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ABSTRACT:

This work investigated and characterized the rheological model that best describes the shear stress-shear rate relationship of stabilized cassava-starch bentonite mud. Rheology has undoubtedly become one of the most important parameters in characterizing drilling fluids. The accuracy in the rheological parameter determination enables a corresponding effective fluid hydraulics evaluation. This in turn addresses the frequent challenges of frictional pressure losses in drilling operations. Fluid rheology failures could result in problem as kicks, stuck pipes, loss of circulation, mud pump failure or a blow-out amongst others. In this study, two local cassava cultivar starches; TMS 92/0057 and TMS 98/0581 were stabilized by the addition of salts of benzoate, sorbate and propionate as preservatives and mixed with bentonite. The rheology tests were carried out at 800F, 1200F, 1500Fand 1900F. The experimental data was applied to four rheological models. The Herschel Bulkley model presented the best correlation to the experimental data, to be followed by the Casson model. Bingham Plastic model overestimates the shear stress while Power Law model does underestimation. The yield stresses showed positive and progressive temperature dependence. The flow behaviour indexes did not indicate any clear or patterned temperature relationship. The mud rheology presented pseudo-plastic and shear thinning profiles and good thermal stability which is desirable features for productive drilling campaigns. Therefore, applying the Herschel-Bulkley model to predict shear stress-shear rate relationships for drilling muds of this cassava-starch formulation is an opportunity to be explored in furtherance of the local content drive in the Nigerian oil and gas industry.
Keywords: *Cassava starch, drilling mud, model parameters, preservatives, rheology.*

1.0 INTRODUCTION

Rotary drilling has been the standard approach in the oil and gas drilling operations. The drilling fluid is one of the most important components of any successful drilling campaign because of its unique functions. In the formulation of the fluids, important activities and challenges such as the following must be addressed; drill cuttings suspension, formation pressure control, drill string cooling and lubrication, hydraulic energy transmission to the drill bit, checking wellbore stability, transporting of the cuttings from the borehole to the surface, easy separation of these cuttings within the surface equipment, data logging, minimizing fluid losses, amongst others (Mohammed, 2007).

Drilling fluids have since witnessed substantial technological evolution from the earlier simple clay and water mixtures to the modern-day combination of complex mixtures of both inorganic and organic substances which were formulated with the peculiarities of the formation in mind (OGP, 2003). Today, the science and art of drilling fluids formulation has a life of its own because of its importance and it has been reported that drilling fluids represent between 15-18% of the entire drilling costs, but has the potential of causing 100% of drilling challenges (Hossian and Al-Majed, 2005).

Rheology is the study of the flow and deformation behaviour of a fluid, and it has undoubtedly become one of the most important parameters in characterizing drilling fluids (Amjid et al., 2013). It describes the response of fluid materials to stress and this response is a function of the complexity or otherwise of the fluid. Fluids can be classified broadly into simple fluids such as water, pure substances and structured ones such as mixtures, dispersions and solutions (John, 2005). Simple fluids have uniform phase as in solutions and pure substances. However, fluids of heterogeneous phase such as emulsion and solid particles dispersed in a liquid are considered structured fluids and drilling fluid belong to this group.

When a fluid is subjected to this stress, the nature of the response of the body rheologically can be classified into three categories; reversible elastic deformation (solids), irreversible viscous flow (liquids) or a combination of both (viscoelastic-polymers) (Godwin & Hughes 2000). In the industrial world, a good understanding of rheology is very critical in the production, handling and application of many products, drilling fluids inclusive. In broad terms, the rheological and filtration properties are the key indicators used to characterize muds (Neff et al., 2005). The rheology addresses the transport ability, suspension capability and gelatin properties while the filtration property measures the fluid loss. Specifically, mud plastic viscosity, density, pH, gel strength, and fluid loss are constantly monitored and controlled as the drilling lasts (Okumo and Isehunwa, 2007)

Viscosity is an important index in the flow characterization of drilling fluids. It is a measure of the resistance to flow and factors such as nature, size, shape, concentration and chemical properties of the solid affect its value (Coghill, 2003). It is a measure of the thickness of the fluid and is commonly expressed in stokes, poise or centipoise. This resistance to flow is caused by the friction between these suspended particles as well as by the viscosity of the continuous liquid phase (water or oil) in which it is dispersed. For simple fluids, their viscosity remains constant at the same temperature and pressure for all shear rates. However, structured fluids are referred to as non-Newtonian fluids because they are not subject to a linear relationship between shear stress and shear rate but their viscosity is a function of the rate of shear and sometimes on the shear history (Skalle, 2011).

Drilling fluid has starch as one of its formulation components. Starch is a viscosifier and is a thixotropic material that is used in drilling fluid formulations (Winson, 2012). The abundance of starch in nature is underscored by the report of it occupying an enviable second position besides cellulose (Herman et al., 2002). Starch is also a polysaccharide consisting of long chains of sugar glucose molecules (Wing, 1988 as cited by Wami et al., 20015). The two components of the starch molecule; the crystalline, linear low molecular weight amylose and the amorphous branched high molecular weight amylopectin account for its rheological and filtration properties in water-base drilling fluids (Bergthaller and Hollmann, 2007).

In non-Newtonian fluid rheological characterization and hydraulic estimations, several mathematical models have been established such as the Bingham Plastic, Power Law, Casson, and Herschel-Bulkley models amongst others (Seyssieq and Ferasse, 2003, Mackley, 2011). The Bingham Plastic is a two-parameter model that has gained some applications in the simple drilling operations in the industry. It describes the combination of flow characteristics of a material with a yield stress term and constant viscosity at stresses above the yield stress (Bingham, 1922 as cited by Folayan et al., 2017).The Power Law Model is also referred to as the Ostwald Model. The model generally characterizes flow behaviour of materials that are shear-thinning in nature but has no yield stress (Pevere et al, 2006).

The consistency index is a measure of the fluid viscosity for a Newtonian fluid, the flow behaviour index is a measure of the degree of departure from Newtonian fluid and when its value is unity, the fluid characterizes a Newtonian fluid. When the value of n is above unity and below unity, the fluid exhibits shear thickening and shear thinning characteristics, respectively. The Herschel-Bulkley model has found good and wide applications on fluids with a yield stress and non-linear characteristics (Xiuhua and Xiaochun, 2010). According to Pevere and Guiband, 2006, the presence of three constitutive parameters in its rheological equation makes it a precise model of acceptable wide application. This model is seen as an extension of the Bingham plastic model because of the presence of a shear rate dependent term in its constitutive equation. According to Kalili-Garakani et al, 2011, this model does a correction of the inherent deficiency of the Bingham plastic model by the substitution of the constant plastic viscosity term of the latter with that of the Power-law model term. The Casson Model is a structured model that is used in the rheological characterization of the flow behaviour of visco-elastic fluids (Casson, 1959 as cited by Folayan et al., 2017). It is also a two-term model unlike the Herschel-Bulkley model

A flow curve generated by plotting shear rates and shear stress is called rheogram (Guibao et al, 2005). There are several rheological models in the industry that have been used successfully in the characterization of the flow behaviours of various fluids such as Bingham, Power-law, Casson and Herschel Bulkley models (Shah et al., 2010, Vipulanandan & Mohammed, 2014). These models are used essentially to predict the viscous flow behaviour of non-Newtonian fluids under the varying condition of shear stress and shear rates and sometimes also to the time of the shear application. However, in practical terms, some of these models have proved deficient in their predictive capability to define the fluid rheological characterization and hydraulic behaviour over the full spectrum of shear rates (Barnes and Walters, 1985 as cited by Folayan et al., 2017).

Folayan et al, 2017 posited that the power-law model predicts a better rheological characterization of synthetic-based drilling muds at the onset of the low shear rate regimes quite unlike the Bingham plastic model. The power-law model was used to estimate the flow behaviour under dynamic conditions for corn starch under varying amylose content specifications (Xie et al, 2009). Also, in relating the shear stress to shear rate, Mepba and Ademiluyi, 2007 showed that the power-law model reasonably predicts the rheological flow behaviour of coconut milk yoghurts, with the consistency index having strong temperature dependence. On the other hand, the Herschel - Buckley model showed a good predictive rheological capability for polymer muds (Kevin and Bala, 2014), especially at very low shear rate viscosities. Low shear rate viscosities regime is predominantly prevailing in the annulus and as such is very critical to the hole cleaning capacities of the drilling mud (Thivolle, 2004). Further credence was laid to this position by Harry et al., 2017 in their study on the rheological modelling of cassava starch-bentonite muds for the drilling operation. Mellak, 2007, studied the rheological characterization of sludge-based muds and postulated that the consistency index and the flow index behaviour of the mud were closely modelled by the Herschel Buckley model equation.

Also, Folayan et al, 2017 in their works on synthetic-based mud, established that the Casson rheological model fully characterizes the mud behaviour over the wide spectrum of shear rate regimes, reasonably attributable to the correction factors in the model equation. The obvious drawback of the Bingham plastic model is that its rheological equation cannot satisfactorily describe the flow behaviour of fluids with viscosity and shear rate or shear stress dependencies.

Although copious works have been done previously on the evaluation and rheological characterization and modelling of local cassava starch-bentonite muds, not much is available in the literature concerning such muds that have been stabilised with the addition of preservatives (Ademiluyi et al., 2011, Wami et al., 2015, Harry et al, 2016. The major drawback to the optimal use of cassava and cassava products such as starch for wider applications is their ready susceptibility to post-harvest physiological damages (PPD) (Versino, 2015, Zidenga, 2012). A preservative is a substance that is added to a product to maintain an existing condition or prevent decomposition by microbial attacks or degradation through other undesirable changes. However about food preservation which starch belongs to, preserving what is, may not be just adequate as additional requirements of improving flavour, texture and visual appearance may also be imposed (Leistner, 2000). Therefore, the objective of this study was to investigate the modelling and rheological characterization of such muds formulated with cassava starches that were treated with the benzoates, propionates and sorbates, which are common food preservatives. The resulting rheogram and the constitutive model parameters will be valuable tools in the deterministic prediction of shear stress-shear rate relationship of stabilised cassava starch enriched bentonite muds for the Nigerian oil and gas industry.

2. MATERIALS AND METHODS.

Two 12-months old cassava cultivars TMS/92/0057 and TMS98/0581 were obtained and processed at the National Root Crop Research Institute (NRCRI), Umudike, Umuahia, Nigeria. Salts of the benzoates, propionates and sorbates which were applied as the preservatives were procured from an industrial chemicals supply company in Port Harcourt, Rivers State, Nigeria. The preservatives are products of BDH Chemicals.
Each of the two cassava cultivars was subjected to starch extraction process as described by Ibekwe et al, 2006; Eke et al 2007. Freshly harvested tubers were generously washed with potable water, peeled with a knife and washed thoroughly to remove all dirt and sand. The tubers were ground and sieved with the addition of a small quantity of portable water to facilitate the sieving operation. The filtrate was allowed to settle for 4 hours and then decanted. This leaves a white, tasteless and odourless starch at the bottom of the container. The wet starch was spread thinly over an aluminium tray for open-air drying at atmospheric conditions of 27 oC - 30 oC for about 6hours to minimize damage to native starch granules. The starch was further dried in an air oven for about 6 hours at 60 oC. The dried starch was finally milled in blenders to fine particles and sieved with 150-micron mesh.

2.1 Experimental Protocol

The Bentonite-starch muds were formulated as per the basic recipe shown in Table 1, according to API 13A 2010, using the two cassava starch cultivars and the three preservatives. Muds A1 to A15, B1 to B15 and C1 to C15 were treated with the benzoate, propionate and sorbate salt preservatives, respectively. Cassava starch cultivar mixed with the preservative and the bentonite were weighed with AD electronic weighing balance into a beaker containing distilled water while stirring with Hamilton Beach mixer for five minutes. The mixer was stopped, the beaker removed from the beach mixer and with the aid of the spatula, all the materials clinging to the beaker walls were dislodged back into the beaker. This process was repeated four times making a total stirring time of 20 minutes, to obtain a homogenous mixture of the suspension.
Each of the mud suspension was poured into a viscometer cup and subjected to a multi-speed model 800 OFITE Fann Viscometer which was used to carry out the viscosity test at the shear speeds of 600, 300, 200, 100, 60, 30, 6 and 3 rpm, respectively. The tests were done separately for each sample at temperatures of 80, 120, 150 and 1900F, and the viscometer dial readings were recorded.

Table 1: Basic Mud Recipe

Mud Type	1% Starch(TMS92/0057)	Bentonite	Distilled Water	% Benzoate salt preservative
A1	0.23g	22.5g	350ml	0
A2	0.23g	22.5g	350ml	0.05
A3	0.23g	22.5g	350ml	0.1
A4	0.23g	22.5g	350ml	0.5
A5	0.23g	22.5g	350ml	1.0

The results from the viscometer were used to calculate those rheological properties as per the following equations (Caenin *et al*., 2016).

Shear rate (sec^{-1}) = rpm x 1.703 (1)

Shear stress (Pa) = Dial reading x 1.065 (2)

Viscosity (Poise) = Shear stress /Shear rate (3)

2.2 Rheological Model Parameters

Four rheological models were considered in this study and their constitutive model parameters were determined by applying their respective model equations. The Bingham Plastic Model is given by

$$\tau = \tau_o + \mu_p \quad (4)$$

Where τ = shear stress

τ_0 = yield stress (shear stress at zero shear rate)

μ_p = apparent viscosity

The Power Law Model equation is expressed as;

$$\tau = k\Upsilon^n \quad (5)$$

where τ = shear stress

k = consistency coefficient

Υ = shear rate

n = flow behaviour index

The Herschel-Bulkley Model is represented as

$$\tau = \tau_{0H} + k\Upsilon^{Nh} \quad (6)$$

where τ = shear stress

τ_{0H} = yield stress

Υ = shear rate

k_H = consistency index

n_H = flow behaviour index

The Casson Model is represented as;

$$\tau = \tau_{0C}^{0.5} + k_C^{0.5}\Upsilon^{0.5} \quad (7)$$

where τ_{0C} = Casson yield stress

k_c = Casson plastic viscosity

Υ = shear rate

Non-linear regression analysis was applied to determine the rheological model parameters using the EXCEL SOLVER software. The validation of the model was done in terms of the coefficient of determination (R^2) statistical tool.

3 RESULTS AND DISCUSSION

3.1 Rheogram of Mud Formulations

The shear stress – shear rate relationship of all the formulations was determined according to equations (1) and (2) and only five of the mud formulations met the API RP 13B1 threshold. They are muds A2, A7, A8, B7, and C7, with their rheogram shown as Figures 1 to 5. A common feature of all the muds rheology was that they were non-Newtonian, possessing a yield point value at zero shear rate. Also in general terms, their shear stress increases with increasing shear rate per the Newtonian law. They also exhibited pseudo-plastic profiles which are in tandem with starch-bentonite mud formulations (Harry et al., 2017; Dankwa et al., 2018). Mud A2 posted largely non-linear shear stress – shear relationships at low shear rates for all the temperatures. However, as the shear rate increases, the relationship tends to be more linear except for the indication at 80°F. Mud A7 indicated similar features except that at 80°F, it showed better linearity and trends. This near linearity at higher shear rates may be attributable to the dwindling effects of terminal yield stress with increasing shear because the intermolecular forces within the fluid exhibit flow profile that approaches a Newtonian fluid behaviour.

The shear stress range at 600 rpm was 34.08 Pa to 40.47 Pa at 80°F and 190°F, respectively, indicating good thermal stability. Mud A8 trends similarly except that unusual phenomena occurred at a shear rate of 510 sec^{-1} where the shear stress at 80°F was higher than that of 120°F with values of 29.82 Pa and 28.76 Pa respectively. The mud posted a thermally stable shear stress range of 34.08 Pa to 40.47 Pa at 80°F and 190°F respectively. The interaction of the preservatives and the mud components may explain this result.

The presentation of mud B7 profile trended alike with non-linear low shear rates section, followed by a largely linear section. The exception being at 80°F where the linear section of the shear stress – shear rate profile was shorter occurring at higher shear rates of 340.60 sec^{-1} and upwards. It had the best thermal stability with a range of 40.47 Pa to 42.60 Pa at temperatures of 80°F to 190°F respectively.

Mud C7 indicated similar presentation like mud B7 with a shear stress range of 34.08 Pa to 38.34 Pa at temperatures of 80°F and 190°F respectively. The existence of two distinct sections of non-linear and linear parts on the rheogram, with the non-linear section found around the low shear rate values, in addition to terminal yield stress at zero shear rate were the phenomena in all the muds considered. This indication was in agreement with the works of other researchers on the rheology of starch – bentonite muds **(**Hemphil et al., 1993 as cited by Folayan et al., 2017: Harry et al., 2017**).**

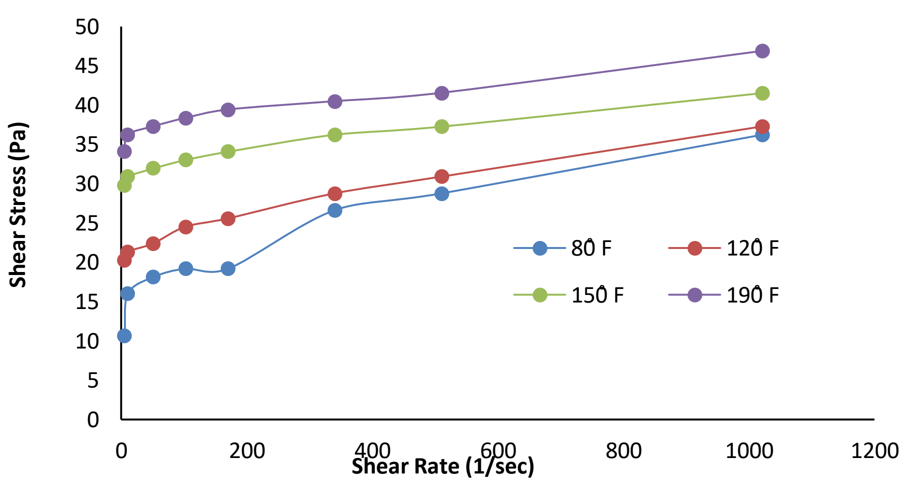

Fig. 1: Rheology of Mud A2 @ different temperatures

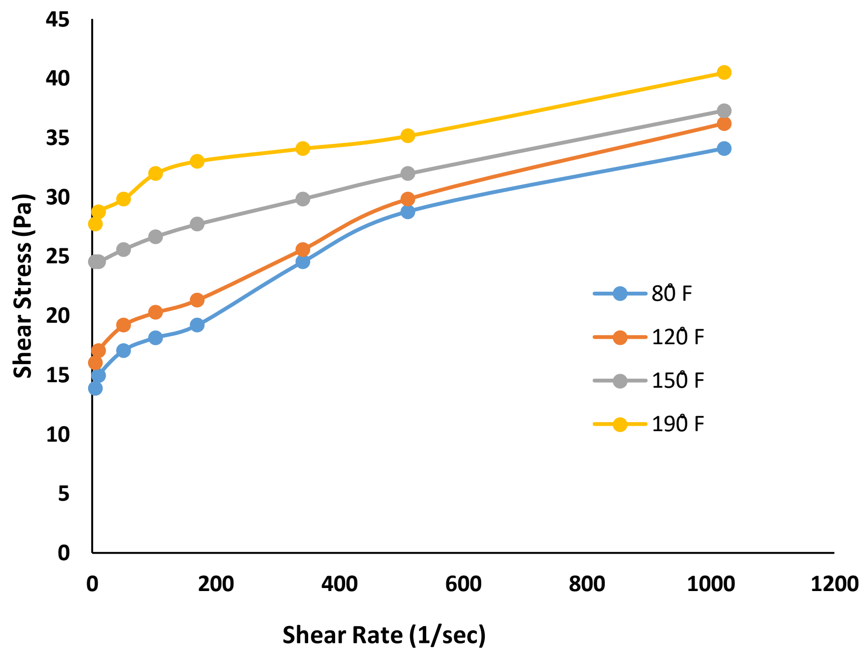

Fig. 2: Rheology of mud A7 @ different temperatures

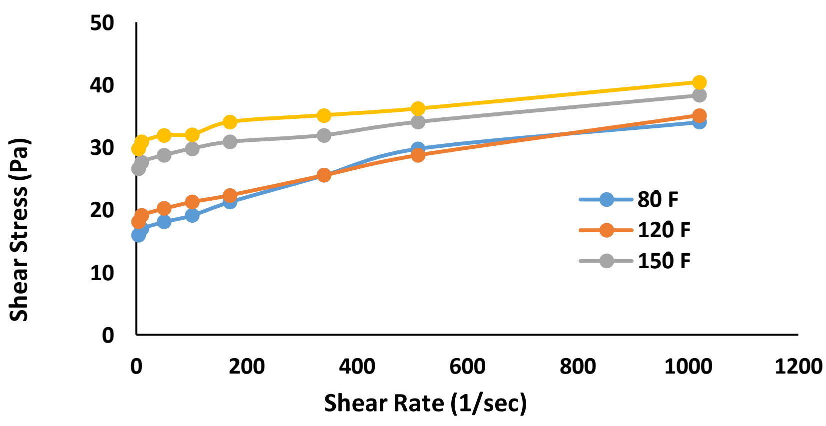

Fig. 3: Rheology of mud A8 @ different temperatures

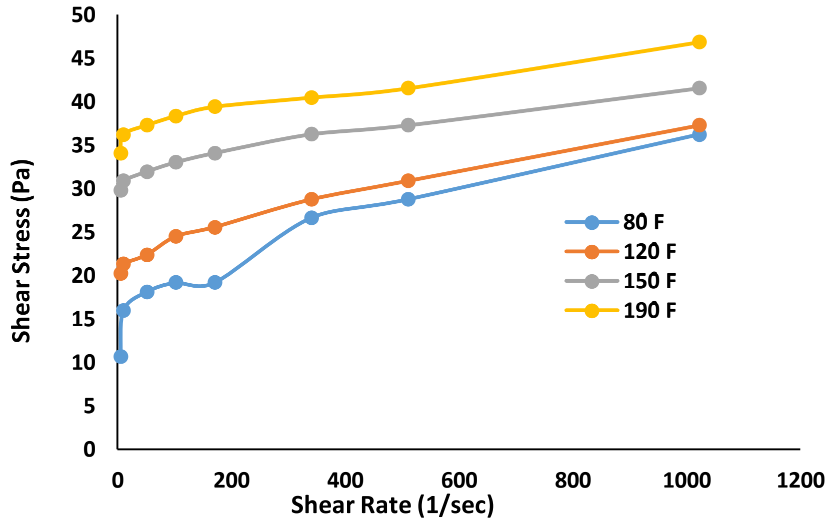

Fig. 4: Rheology of mud B7 @ different temperatures

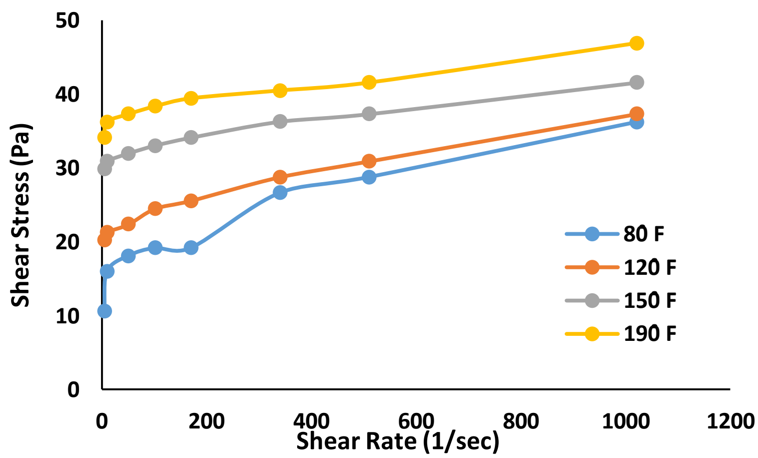

Fig. 5: Rheology of mud C7 @ different temperatures

3.2: Comparative Rheological Performance

The rheogram of the comparative performance of the muds A2, A7, A8, B7, and C7 at various temperatures were shown in Figures 6 to 9. At 80°F muds, A2 and B7 posted the least (10.65 Pa) and the highest (40.47 Pa) shear stress values, respectively. Mud B7 had consistent high shear stress all through its profile with a clear linear section of the shear stress – shear rate plot. Muds A2 and A8 showed more irregular profile. At 120°F muds, A7 and C7 paired in having the least shear stress value while mud B7 had the highest value of 15.98 Pa and 38.34 Pa, respectively. All the muds posted a fairly uniform profile for both the linear and non-linear segments of their rheogram.

At 150°F mud, A2 indicated the highest consistent shear stress profile while the least low shear rate stress value of 22.37 Pa was indicated by mud C7. A stable profile was posted by all the muds at this temperature. The 190°F rheogram of the muds had a similar feature as in the 150° profile with muds C7 and A2 having the least and highest shear stress values of 24.50 Pa and 46.86 Pa, respectively. Therefore, apart from at 80°F where mud B7 indicated the highest shear stress values, mud A2 led in the remaining temperatures while mud C7 largely had the least values in all the temperatures. The general trend, therefore, is that the shear stress increases with temperature as corroborated by Harry et al., 2017.

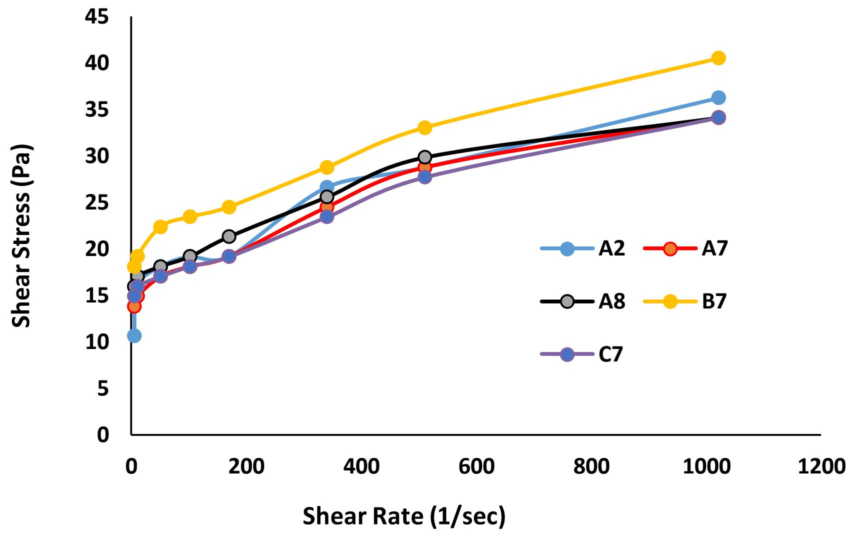

Fig. 6: Comparative rheogram of all the muds @ 80^0F.

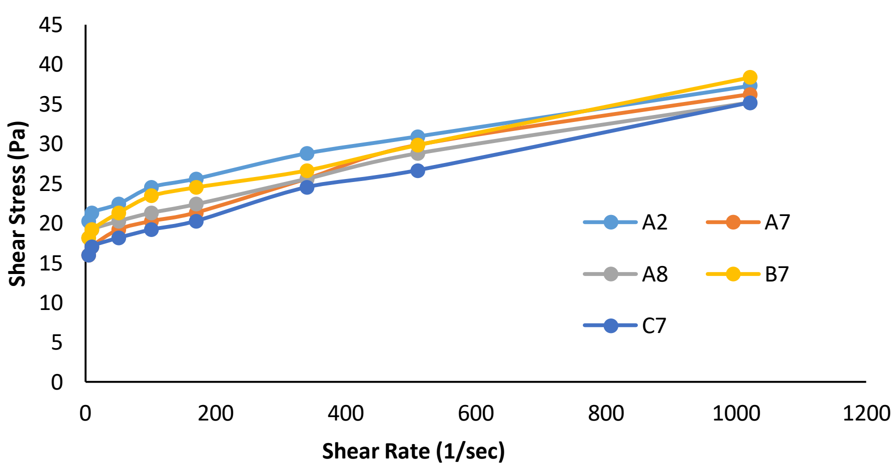

Fig. 7: Comparative rheogram of all the muds @ 120^0F.

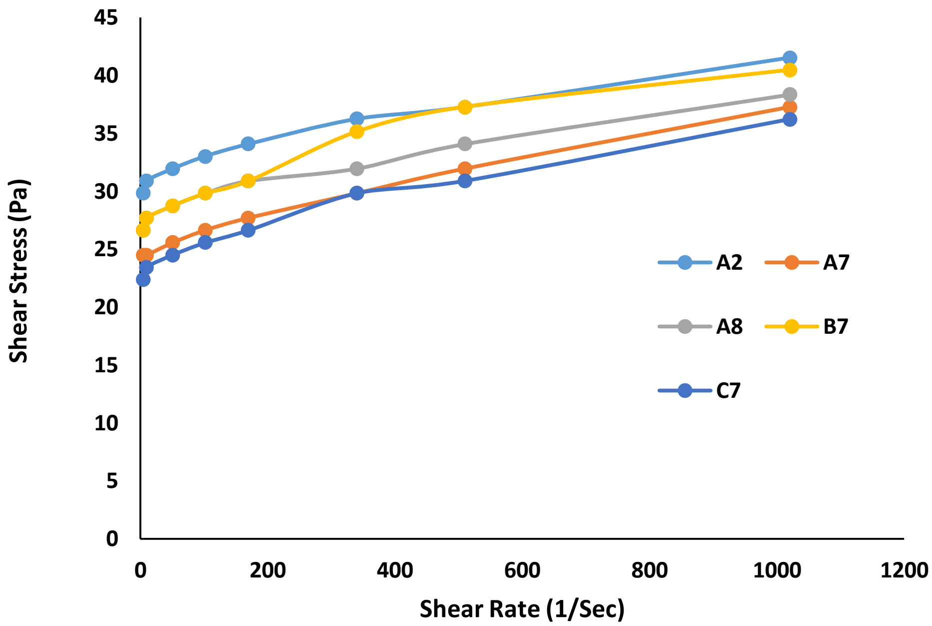

Fig. 8: Comparative rheogram of all the muds @ 150^0F.

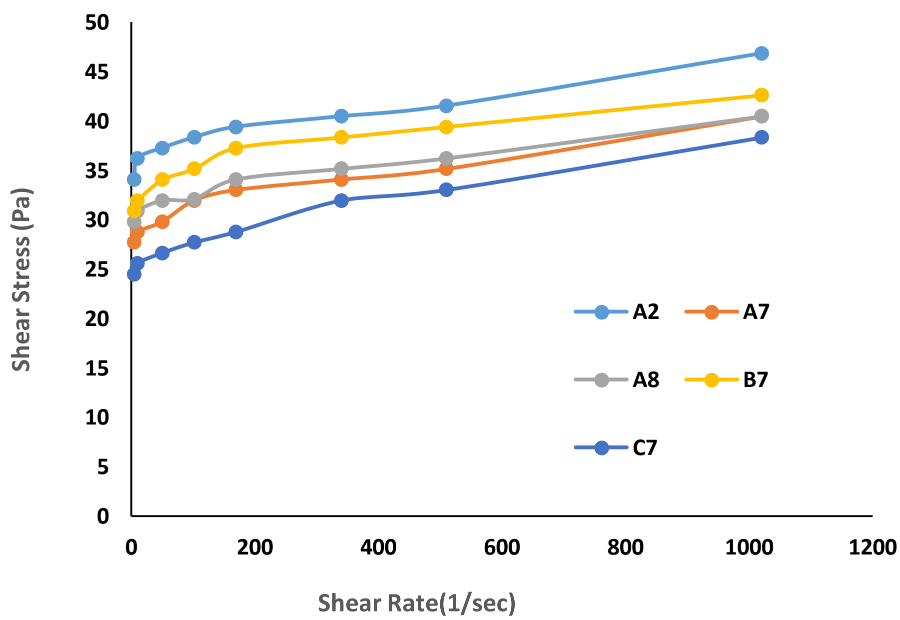

Fig. 9: Comparative rheogram of all the muds @ 190^0F.

3.3 Prediction of Rheological Model Parameters

The four rheological models of Bingham Plastic, Power Law, Herschel- Bulkley and Casson models were considered in this presentation. The constitutive parameters of these models as shown in Table 1 were firstly determined and subsequently applied in the prediction of the shear stress and shear rate relationships.

3.3.1 Bingham Plastic Model

The yield stress factor showed consistent positive gradient with increasing temperature for all the mud, with mud A2 posting the highest value of 36.323 Pa at 190^0 F. The plastic viscosity value showed neither strong nor clear pattern of temperature dependence for all the muds.

3.3.2. Power Law Model

The flow behaviour index n_{pl}, largely showed a progressively negative temperature dependence for all the mud. The muds have their flow behaviour indices values of less than unity which suggests a non-Newtonian and thixotropic shear thinning properties. However, the consistency index which is a viscosity term depicted a strong positive and progressive temperature dependence ranging from 7.451 - 30.984 Pas. Both limits were shown by mud A2 at 80^0 F and 190^0 F respectively. The Power law model equation has inverse shear stress – consistency coefficient relationship and, therefore, its highest and lowest shear rate regimes were exhibited by mud A2. The concept of starch gelatinization at temperatures of 143 ^{0}F upwards could readily explain the increasing values of the consistency coefficient with temperature as this factor is also a viscosity term (Ademiluyi et al, 2011, Samavati et al, 2014, Ashaye et al, 2010, Akintola and Isehunwa, 2015).

3.3.3 Herschel- Buckley Model

This model quite unlike the Bingham plastic, Power-law, and Casson models is a three-parameter model which largely accounts for the deficiencies of the former in terms of rheological parameter predictions. The yield stress showed progressively positive temperature dependence with a range of 11.124 - 34.490 Pa at 80^0F and 190^0F respectively, and both values were posted by mud A2. The consistency coefficient K_{HB} has the lowest and highest ranges of 0.071 posted by mud C7 AT 150^0F and 2.052 by mud B7 at 190^0F, respectively. All the values of the flow behaviour index n_{HB} were below unity and hence a non- Newtonian shear thinning property was described (Harry et al, 2017)

3.3.4 Casson Model

This model, like the Bingham plastic and the Power-law model, has a two-parameter model equation. Mud A2 trended the least and highest yield stress values of 12.425 Pa at 80 ^{0}F and 34.359 Pa at 190 ^{0}F respectively. As aforetime, the yield stress largely exhibited positive and progressive temperature dependence. The consistency coefficient showed neither a strong nor clear patterned relationship with increasing temperature.

Table 2 Rheological Model Parameters of the Mud

MUD	Temp ^{0}F	Bingham Model		Power Law Model		Herschel Bulkley Model			Casson Model	
		t_0	u_p	k	n	t_{0h}	k_h	n_h	t_{oc}	k_c
A2	80	15.721	0.022	7.451	0.219	11.124	0.813	0.494	12.425	0.006
	120	21.923	0.016	14.986	0.119	19.911	0.242	0.617	19.256	.003
	150	31.392	0.010	26.097	0.059	29.455	0.309	0.527	29.414	.001
	190	36.323	0.011	30.984	0.051	34.490	0.283	0.537	34.359	.001
A7	80	15.800	0.012	8.173	0.196	13.066	0.347	0.596	12.791	.005
	120	17.890	0.019	10.395	0.165	15.425	0.306	0.604	14.967	.004
	150	24.421	0.013	19.631	0.079	24.167	0.077	0.740	22.927	.002
	190	29.497	0.011	23.917	0.066	27.198	0.406	0.497	27.430	.001
A8	80	17.611	0.018	10.225	0.164	15.032	0.332	0.590	14.375	.004
	120	19.318	0.016	12.743	0.131	18.184	0.101	0.741	29.434	.001
	150	28.083	0.011	23.034	0.064	26.641	0.187	0.593	16.740	.003
	190	31.182	0.010	26.522	0.052	29.971	0.185	0.581	26.183	.001
B7	80	20.386	0.021	11.922	0.163	17.792	0.309	0.620	17.081	.005
	120	20.045	0.019	12.564	0.145	18.343	0.172	0.683	17.131	.004
	150	28.324	0.014	21.763	0.082	25.687	0.430	0.516	25.845	.002
	190	33.362	0.010	27.467	0.059	27.811	2.052	0.283	31.256	.001
C7	80	16.089	0.019	8.994	0.177	14.731	0.122	0.734	13.272	.005
	120	17.050	0.018	10.159	0.161	16.183	0.071	0.806	14.311	.004
	150	23.849	0.013	17.980	0.090	22.193	0.202	0.611	21.610	.002
	190	25.979	0.013	20.046	0.083	24.323	0.202	0.611	23.719	.002

3.4 Analysis of Rheological Models

Having determined the rheological model parameters as in Table 3, the values were applied in the prediction of the shear stress – shear rates relationships at temperatures of 80°F, 120°F, 150°F and 190°F using non-linear regression analysis method. The five muds A2, A7, A8, B7 and C7 were considered and the four rheological models of Bingham Plastic, Power-law, Herschel Bulkley and Casson models were applied in this comparative analysis as shown in Figures 10 to 14.
At 80°F, for mud A2, the Bingham model underestimates the shear stress at low shear rates while overestimating same at higher shear rates. The Power model underestimates the shear stress all through the rheogram profile. Herschel Bulkley and Casson models showed closely better predictions to the experimental data. For muds A7, A8, B7 and C7, the presentation were similar with the Bingham model, consistently showing overestimation of stress values both at low and high shear rates while the Power model was the opposite, showing under predictions at both regimes. The Herschel Bulkley and Casson models posted closer correlations.
At 120°F, 150°F and 190°F, all the muds presented similar features as afore-mentioned; overestimation and underestimation at both low and high shear rates regimes by the Bingham and Power models respectively. Herschel Bulkley and Casson had a close and good correlation. Previous researchers have corroborated similar presentations (Simon, 2004; Hary et al., 2017).

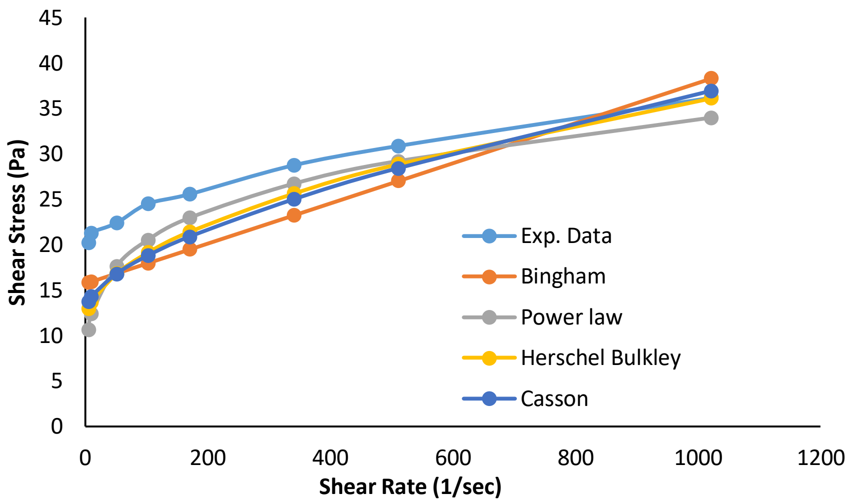

Fig. 10: Rheology models predictions for mud A2 at 80^{0}F

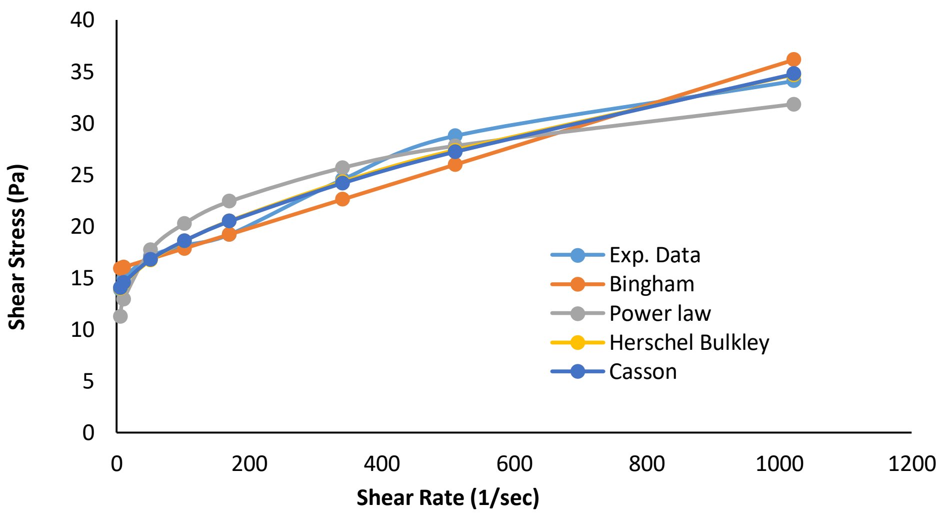

Fig. 11: Rheology models predictions for mud A7 at 80^{0}F

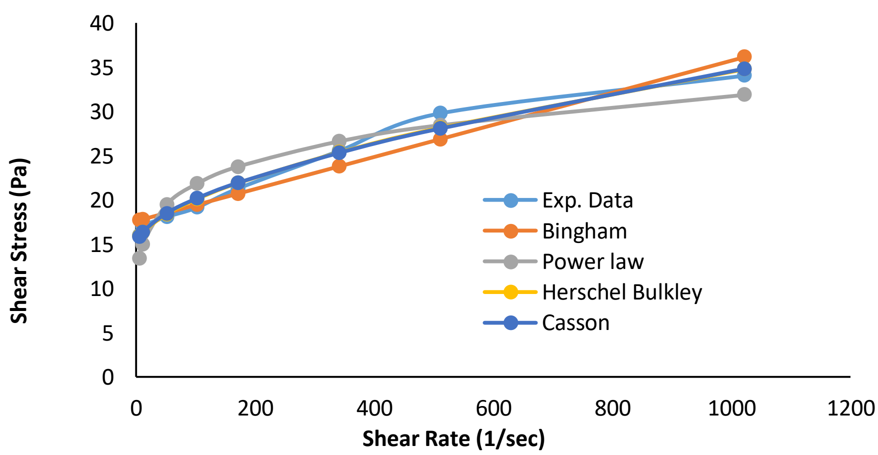

Fig. 12: Rheology models predictions for mud A8 at 80^{0}F.

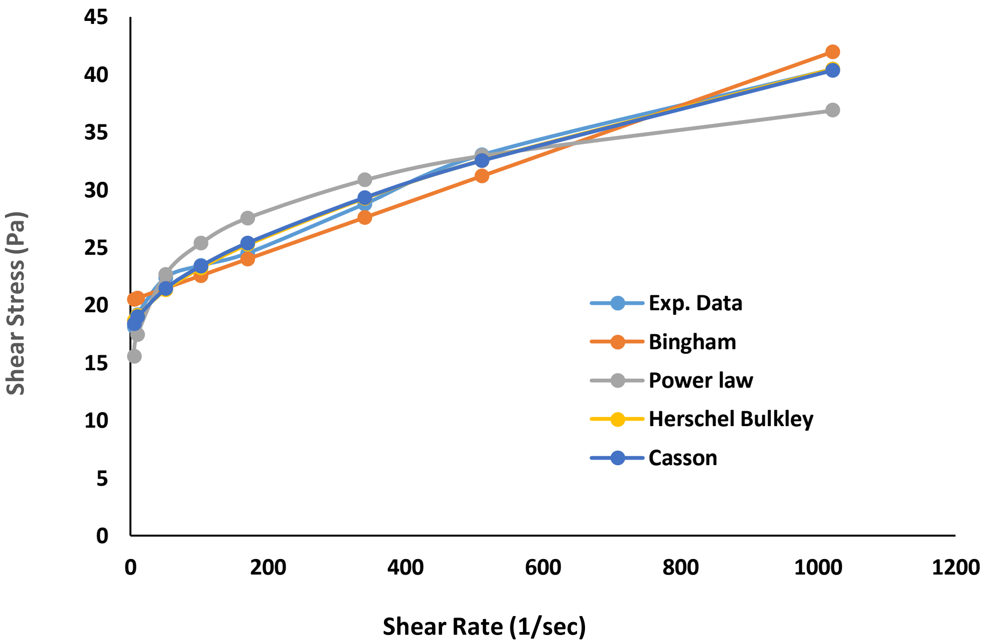

Fig. 13: Rheology models predictions for mud B7 at 80^{0}F

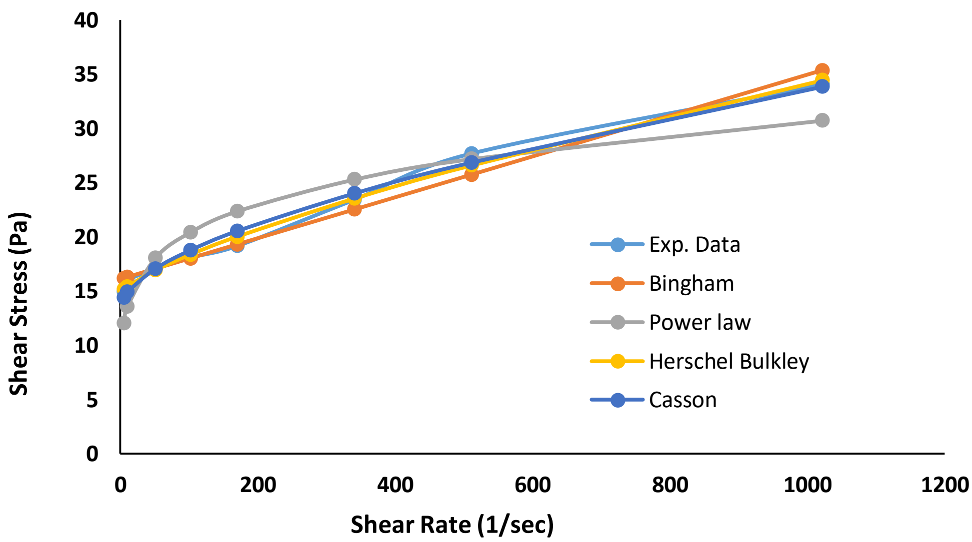

Fig. 14 Rheology Models Predictions for Mud C7 at 80^{0}F

3.5 Validation of Rheological Model

The empirical model validation adopted in this work is the coefficient of determination (R^2) statistical tool. It shows the correlation between the experimental results and the model predictions. The charts for the determination coefficient were shown in Figures 3.35 to 3.39. Mud A2 showed the least correlation for the Power model at all temperatures but for 80°F where the Bingham model posted 0.895 while the Herschel Bulkley model had the highest correlation except at 80°F where the Casson model had the lead. Mud A7 had the Bingham model with the least correlation at all temperatures, while the Herschel Bulkley posted the highest values of 0.999, 0.991 and 0.987 at 150°F, 120°F and 80°F respectively. The Casson model led at 190°F with a value of 0.977. Mud A8 also had the least correlation for the Power model at all temperatures. Herschel Bulkley model posted best correlations at all temperatures but for 190°F where the Casson had the lead. Mud B7, however, showed a slight variation as the Bingham model had the least correlation only at 190°F valued 0.831 while the Power model maintained the record as aforetime. Hershel Bulkley model had the record of best correlation at all temperatures, peaking with a value of 0.994 at 80°F. Mud C7 indicated the Power model maintained the least correlation and the Herschel Bulkley model the highest correlation at all temperatures. The least value was 0.835 and the highest was 0.997. Statistically, a coefficient value of 0.99 and above satisfactorily describes a model and in this work, both the Herschel Bulkley and Casson models demonstrated this requirement for starch-bentonite mud rheological model characterization (Seasan, 2000).

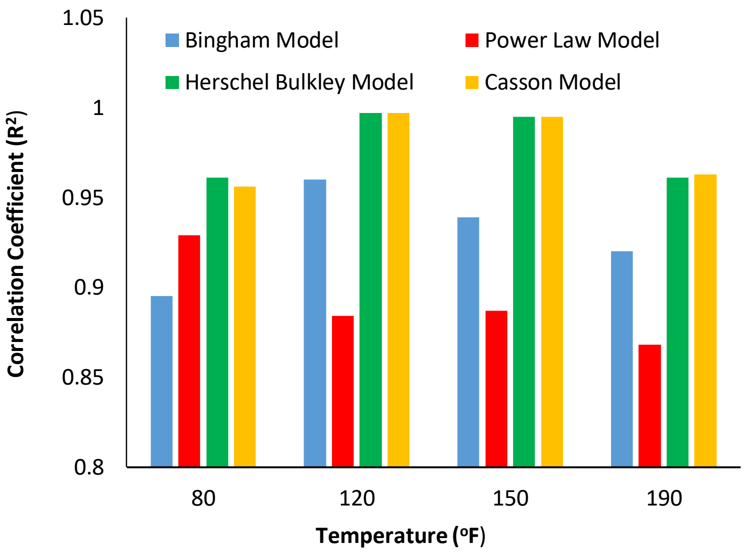

Fig. 15: Mud A2 coefficient of determination (R^2) charts.

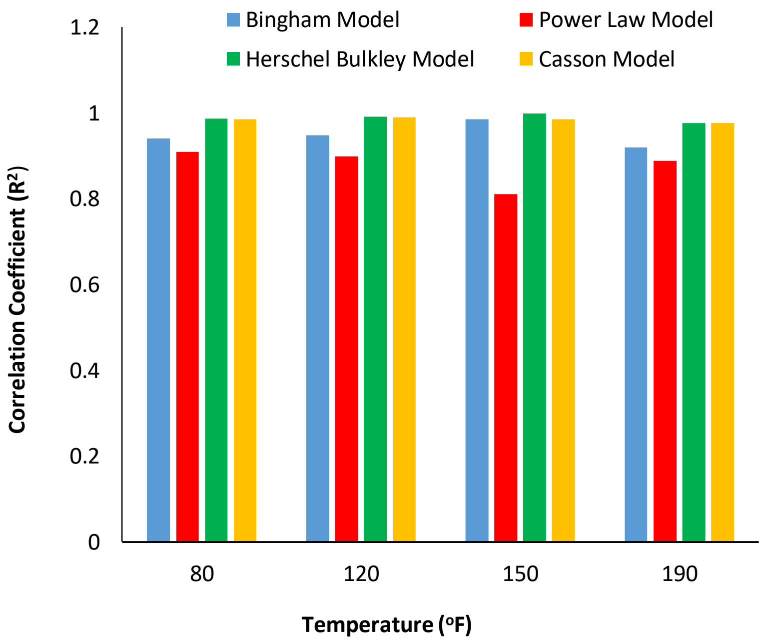

Fig. 16: Mud A7 coefficient of determination (R^2) charts.

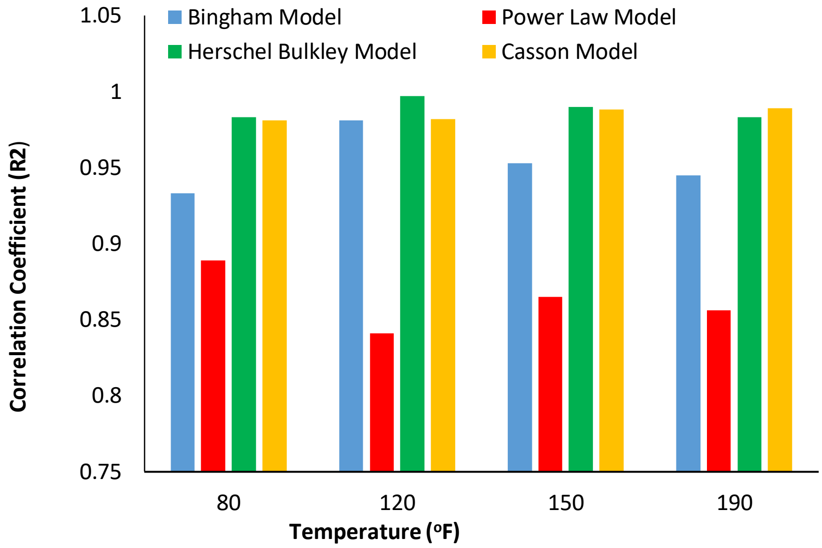

Fig. 17: Mud A8 coefficient of determination (R^2) charts.

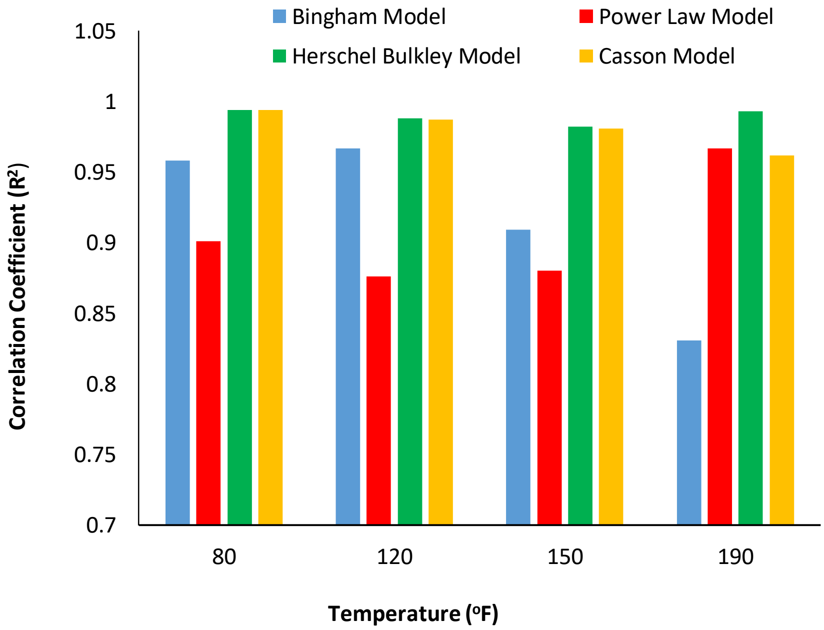

Fig. 18: Mud B7 coefficient of determination (R^2) charts.

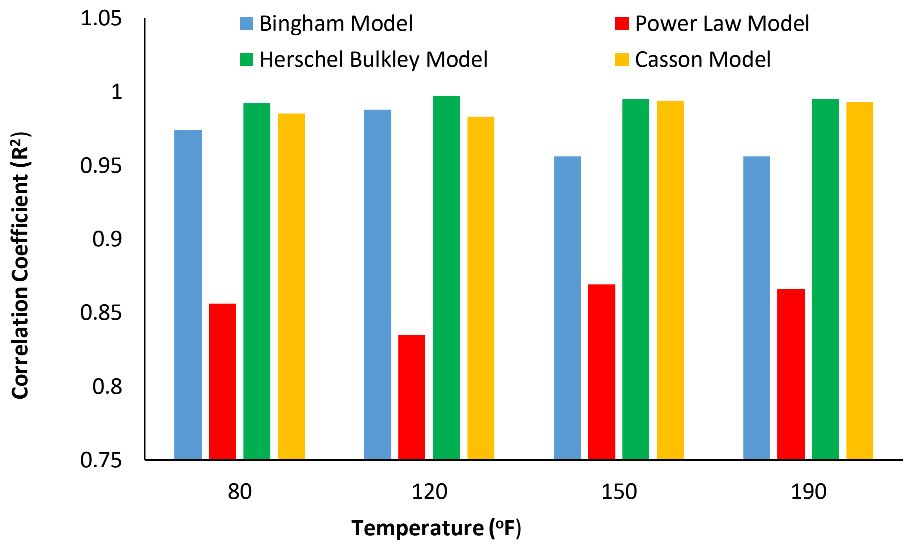

Fig. 19: Mud C7 coefficient of determination (R^2) charts.

4. CONCLUSION:

The determination of the rheological model parameters of two stabilized cassava starch-bentonite mud formulations with the four models of Bingham Plastic, Power Law, Herschel Buckley and Casson models were made and the following conclusions were presented from the analysis:

- The muds were pseudoplastic with shear-thinning profiles and the muds showed good thermal stability which hugely supports productive drilling operations.
- Rheogram of the muds presented two distinct sections; an initial non-linear section within the low shear rate region and a largely linear section over the wider spectrum of the shear rate.
- The shear stresses of all the muds and the consistency index of the Power-law model showed positive and progressive temperature dependence over the entire shear rate regime.
- The flow behaviour indexes for all the models presented no clear or patterned dependence on temperature.
- The Herschel Buckley model showed the best correlation to the experimental data, followed by the Casson model. The Bingham Plastic model overestimates the parameter especially at low shear rates while the Power law indicated underestimations.
- The Herschel Buckley model could be used to predict the shear rate-shear stress relationship for these water base mud formulations and, therefore, presents huge opportunity to be explored in furtherance of the local content mandate. The predictive shear stress is very crucial for the accurate evaluation of pressure drops, along the drilling campaign profiles. The domestication of this drilling fluid additive in Nigeria will readily come with a better specific cost of oil production, a reduction in import bills, more industrialization, reduction in youth unemployment and restiveness and especially in these times of dwindling oil fortunes.

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