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Improvement of Anti-Sag and Rheological Properties of Water Based Muds Using Nano-Barite

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Abstract

Barite Sag is an adverse phenomenon observed in horizontal drilling or Extended Reach Drilling (ERD) operations. It has been reported to occur majorly due to settling of weighing material such as barite on the lower side of directional wells. The barite sagging has been reported to cause drilling operational problems such as induced well-bore instability, mud losses and pipe stuck up leading to well control problems. In this context, an attempt has been made to address the barite sagging problem through application of laboratory synthesized nano-particles of barite as they are known to posses' high area to volume ratio, hence required in low quantities in formulating optimum gravity drilling fluid. However, low quantities of barite nano-particles aids in lowering Plastic-Viscosity (PV) and increasing Rate Of Penetration (ROP) due to low solids concentration associated with it. Further, the larger surface area of barite nano-particles also aids in improved heat dissipation from bottom hole, thereby increasing the life of bits. The sagging test results have projected a reduction in sagging phenomenon with the application of nano-barite particles. However, the rheology analysis results have projected a decrease in PV with unchanging filtration-loss properties meeting the API standards. Further, the rheological behaviour at various temperatures better fits with Herschel-Bulkley model establishing its shear thinning characteristics. The present work aids in formulating efficient drilling fluids for economical directional drilling operations.

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Keywords: Nano-Particle, Barite, Weighting Agent, Barite Sagging, Rheology modelling.

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1. Introduction

Sag is found to be associated with several potential problems like wellbore instability, lost circulation, stuck pipe, problems in getting logging tools to bottom, well control problems. The situation gets worsen in case of highly deviated wells where there is very small difference between fracture pressure and formation pressure [3]. The phenomenon of sagging has been mainly reported in all type of muds, one such study demonstrated that differences between the maximum and minimum mud weight in Gulf of Mexico was more than 4 ppg [1]. Further, the mechanism of barite sagging was demonstrated by Boycott [4], who observed that blood corpuscles in narrow tube settle at a faster rate if the tube was inclined rather than vertical. As the particle starts to settle on one side of an inclined tube, the density variations thus generated imposes pressure variations which leads to induced convective flow from top to bottom of the tube until equilibrium is attained.

The mechanism of particle sedimentation in vertical tube is referred as "hindered Settling". Fig. 1 depicts various regimes of settling: clarification regime, hindered regime and compaction regime. Clarification regime is the region where few particles settle independently with much less interference from the tube wall and nearby particles. The concentration is notably higher than surrounding particles in hindered regime and interferes with individual particles settling, thereby slowing the settling rate below free settling. If the particles coagulate to form clusters the settling rate increases in the regime due to increased size. However, in the compaction regime layer the particles that have reached the bottom and expel excess slowly upwards as beds compacts.

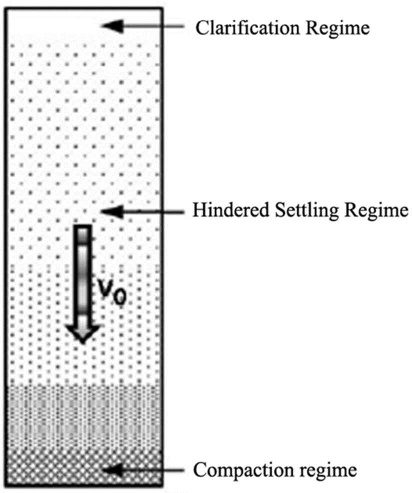

Fig. 1 Hindered settling under static conditions [2]

When the tube is inclined the mechanism changes completely and Boycott settling comes into play. However, particles still settle vertically and form a slumping bed. The settling rate is increased in the clarified layer. A clear fluid layer is formed quickly on higher side of the tube due to buoyancy. Hindered settling also applies for horizontal tubes due to increased surface area available to fluid.

A case study by Bern et al [5] of 8½ inch interval of a well inclined at 60^o drilled with 13.2ppg oil based mud reported that the mud had sagged after the well was kept in static condition for 5 days and tripping. The mud projected a density variation between 12.7- 13.7ppg at the previous casing shoe. Mud loss and difficulties in running in the open hole were encountered. To overcome the problem, the mud is reported to be treated with low shear rheology modifier, which resulted in increasing the low shear rate yield point from 8 lb/100 ft^2 to 11 lb/100 ft^2. However, the low shear rheology modifier was ineffective in mitigating the problem and sagging continued. The interpretations established the reason that low initial concentration of the organophillic clay was the reason behind sagging. Another case study of an HPHT well was presented by Bern et al. [5]. The well was an S-shaped directional well with 17.9ppg OBM. The tangent angle was 40°. Sag and lost circulation were encountered in the well and samples taken at the shale shaker showed that sagging had occurred with mud density variations ranging from 16.6ppg to 20.7ppg. To control the sag clay based gelling agents were used which resulted in decreasing the extent of sagging but not completely diminishing it.

However, many case studies have been reported on application of nano-technology for improving the performance of water based drilling mud such as use of multi-walled carbon nano tubes (MWCNT) and nano metal oxides (titanium oxide, aluminum oxide and copper oxide) [6]. The study has projected an improvement in plastic viscosity characteristics and gel strengths through application of nano-particles.

It can be observed from the case studies that the problem of barite sag is crucial and cannot be tackled effectively by using external chemical agents like gelling agent and rheology modifier. However, nano-particles have been reported to address the improvement in drilling mud properties owing their larger surface area. Nano technology was prominent in the oil and gas industry over the last few decades, use of nano-particles due to their fine size (<100 nm) and maximized surface area facilitate us in modifying the rheological characteristics of drilling fluid which can be done by altering the magnitude of either the size, composition or dispensation of the sampled nano-particles [13-14]. During this notable period of nano usage numerical studies were complied in order to implement nano-particles as additives for an ideal drilling fluid assembly [15-17].

Adding to the experimental work to prove how effective a nano-barite is in the drilling industry, a theoretical approach is always appreciable, As it is not possible to determine by visual observation of which rheological model is most reliable to describe the flow behaviour, regression analysis was carried out to find the best fitting model. Rheological modelling is a crucial part of designing a drilling mud, the behaviour of drilling fluids can be described by their fluid characterization either Newtonian or Non-Newtonian, the later division is further classified into four sub classifications i.e. Bingham plastic, power law, polynomial and Herschel-bulkley [18-19]. Analysing the behaviour of fluid gives us a lot of insights into how a fluid will behave at different surrounding temperatures and pressures, and hence help in maintaining the ability, reliability, and timely management of the rheology of the drilling fluid with different variations in temperatures.

In this context an attempt has been made to address barite sagging problem through application of nano-barite particles. In order to achieve the objective, a synthetic water based drilling fluid with laboratory synthesised nano-barite-particles as weighting component has been formulated, tested with sagging test and compared with conventional barite chemical based drilling fluids for its improved gravity property and reduction in sagging phenomenon and is measured for its rheological compatibility.

2. Methodology

2.1 Preparation of $BaSO_4$ Nano particles

The nano-particles of barite ($BaSO_4$) are synthesized based on the precipitation in pure water method adopted by Yoskhikawa et al.[7] and Ramaswamy et al [8]. The precipitation reaction for the synthesis of is as in Eq. 1. For the preparation of nano $BaSO_4$ particles, equal quantities of 0.1M sodium sulphate (Na_2SO_4) and 0.1M barium chloride ($BaCl_2$) were taken into 50 ml burettes. Then 200 ml of double distilled water was taken into a beaker and placed on magnetic stirrer. Both $BaCl_2$ and Na_2SO_4 solution was added drop wise into the beaker while stirring the solutions at 1000 rpm for 30 minutes. The solutions are maintained at room temperature (~30°C) while stirring. After completion of the stirring process, the beaker was removed from the magnetic stirrer and allowed to precipitate under stable conditions. The precipitate was collected into another beaker, repeatedly washed with double distilled water until the other solvents are removed from the precipitation and filtered through Whattman no.1 filter paper. Thus obtained sample was kept in a hot air oven at 100°C for 6 hours and is used for barite sag tests.

$$BaCl_2\,(aq) + Na_2SO_4\,(aq) \longrightarrow BaSO_4\,(s) + 2NaCl\,(aq) \qquad (1)$$

2.2 Barite Sag Test

A dynamic Barite test has been carried out using the rotational viscometer test procedure adopted by Amighi and Moghadam [9]. The rotational viscometer test (RVT) has been used to analyze dynamic barite sag characteristics at laboratory conditions [10]. The test uses 6-speed standard viscometer as shown in Fig. 2 and consists of inner bob, inner rotating sleeve and outer wall of cup which forms two concentric cylinder sets [11].

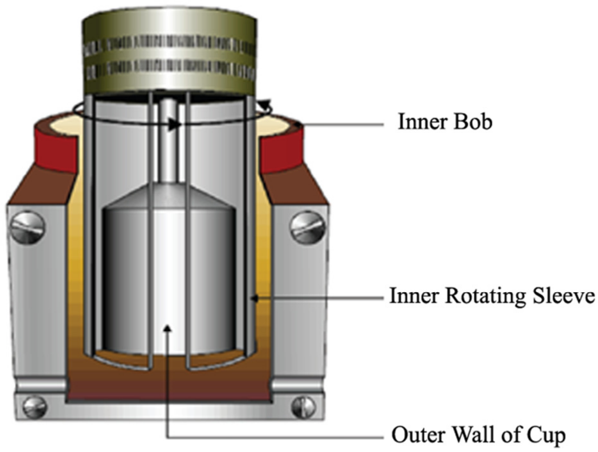

Fig. 2. Dynamic Test Set-up [9]

The method for estimation of dynamic sag consists of subjecting the drilling mud sample to shear rates in viscometer by rotating at 100 rpm. The mud weights are calculated before and after rotating the sample in viscometer for 30 minutes. The change in thus mud weight is quantified as dynamic sag.

2.3 Filtrate loss Analysis

The formation of optimum size filter cake and hence barrier between fluids in well bore (filtrate) and reservoir to control loss of liquid filtrate from mud is of importance at par with rheological properties. Therefore filtrate loss test has been carried out using standard API Filter Press to estimate the thickness of filter cake formed in a filter cell through subjecting the formulated drilling mud to 100 psi for a period of 30 min and hence the volume of filter lost through the cake formed on the bottom side of the cell. Thickness of the filter cake is measured to the nearest 1/32 in.

2.3. Rheological Modelling

Rheological modelling of drilling muds are known to play vital role in their economical formulation for commercial applications. In this context the data evaluated at various temperatures has been tested to fit into various non-Newtonian models such as Bingham plastic, power law, polynomial and Herschel-bulkley models. Error analysis has also been carried to asses accuracy of the model in fitting the rheology data.

Bingham plastic fluids behave like an elastic solid till they reach their yield point and beyond that they approach a Newtonian behaviour. The bingham plastic modelling of a fluid requires rheological parameters such as yield strength, plastic viscosity and shear rate, given by eq (2)

$$\tau = \tau_o + \mu_p \gamma \quad (2)$$

where τ = shear stress, lb/100ft, τ_o = yield stress, lb/100ft, μ_p = plastic viscosity, cP and γ = shear rate, s^{-1}.

Power law precisely demonstrates the behaviour of fluids under low shear rates assuming that all fluids are pseudo plastics, but as it doesn't include yield stress it becomes highly difficult to predict results at an extreme low condition of shear rates and is given by eq (3)

$$\tau = \tau_o + K\gamma^2 \tag{3}$$

Where, τ_o = yieldstress,1b/100ft^2, K = consistency index ,Pa-s^n, γ = shearrate,s^{-1} and n = flow behaviour index (dimensionless).

Herschel Bulkley model is known to reasonably define the behaviour of yield pseudo-plastics and is the most widely used model in oil field applications. The pseudo plastic curve model is defined by a non-linear relation of bentonite shear rate and shear stress, given by eq (4)

$$\tau = K\gamma^n \tag{4}$$

where τ = shear stress 1b/100ft^2, K = consistency index, Pa-s^n, γ = share rate , s^{-1} and n = flow behaviour index (dimensionless).

3. Results and Discussion

3.1. Characterisation of Nano-barite particles

The SEM micrographs of the Barite-Nano-particles are used to analyze the size and morphology of the particles. The HITACHI S-3700N SEM instrument manufactured by HITACHI high-technologies Ltd, India is used to take the micrographs. The accelerating voltage of 15000V and the magnifications from 10,000X to 30,000X are maintained. The obtained micrographs are presented in Figure 3.

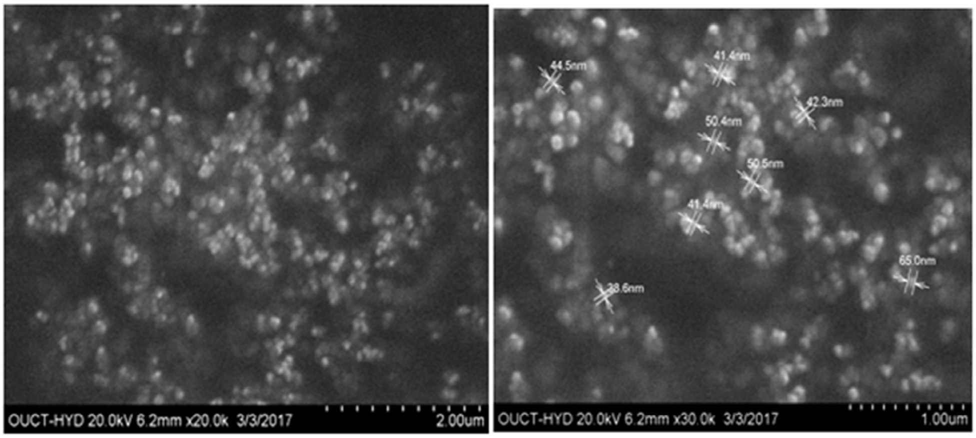

Fig. 3. SEM Images of Nano-Barite Particles (~40-65 nm)

From the image, it can be clearly noticed that the particles are in the spherical shape and are of uniform size between 40 to 65 nm. The main advantage of this adopted method over other synthetic methods is that the process adopts no reducing or capping agents which would result in extremely high purity of the particles with satisfactory production yields. Thus prepared barite-nano-particles are used in carrying out the sagging characteristic study of water based drilling mud.

3.2. Characterization of Nano-Barite based drilling mud

A water based mud with 7% (w/v) of bentonite has been chosen as base mud for the present study. This mud has been named as sample-A in sagging test analysis. The mud is prepared using hamilton beach mixer and allowing it to stand for 20 hrs. The characteristics of the sample-A are presented in Table 1 and its average density (mud weight) is found to be 1035 kg/m^3.

Table 1: Drilling Fluid Parameters in Barite Sag study

Base Fluid Description	Mud Density, ρ (kg/m^3)	Yield Stress, τ_o (lb$_f$/100ft^2)	Plastic Viscosity, μ_p
Water based mud with 7% bentonite	1035	12	4.8

Two other samples of water based mud added with barite chemical are prepared with 3% (w/v) of conventional and synthesized-nano-barite-particles of particle sizes 25-30 μm and 70-90 nm respectively. The samples are named as sample-B and sample-C respectively; their rheological properties are tabulated in Table 2. The average densities of samples B and C are found to be 1070 kg/m^3 and 1068 kg/m^3 respectively.

Table 2: Rheological Properties of Drilling Fluids

Mud Type	A	B	C
Mud Density (kg/m^3)	1035	1070	1068
Temperature (°C)	35	35	35
θ_{600}	16.8	21.2	23.4
θ_{300}	12.01	16	17.8
θ_{200}	10.2	14	16.5
θ_{100}	7.8	12	14
θ_6	6.1	11.5	13.5
θ_3	5.05	10.2	12.4

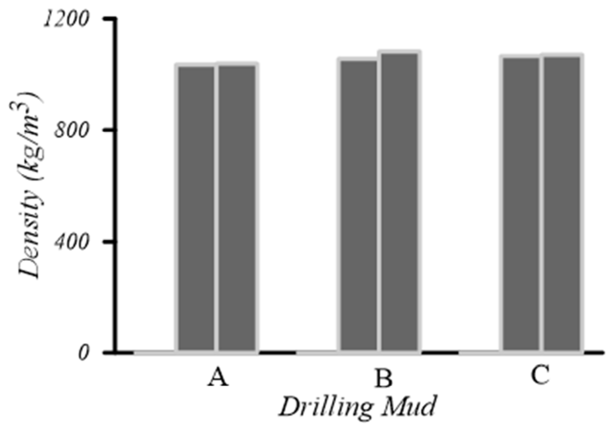

Fig. 4. Effect of Nano-Barite Particles on Density of Drilling Mud

Fig. 4 presents the effect of barite sagging on the average density of drilling mud in the sag test. It is evident from the plot that the drilling mud sample-C prepared from nano-barite-particles has projected minimum variation in density measures before and after sagging test in comparison with the conventional barite. It can be contributed to the better interaction between the nano-barite and the base mud due to higher surface areas of the nano-barite-particles. However, the conventional barite based drilling mud sample has projected much variation in densities of mud collected from top zone and bottom zone of the viscometer cup.

Once the anti-sag characteristics of the nano-barite based drilling fluid has been established, the fluid is analysed for its rheological properties such as plastic viscosity and yield point, and fluid-loss characteristics.

Fig. 5 shows the effect of nano-barite-particle on plastic viscosity of the water based drilling mud. The results project an increase in plastic viscosity for drilling mud when added with conventional and low particle sized nano-barite-particles. However, the drilling mud sample-C with nano-barite-particle has projected slightly higher plastic viscosity than samples A and B. This can be contributed to the improved surface to volumes of nano-barite that provides additional sites for bonding with base mud. This would allow for better interaction between the nano-barite and the base mud, causing an increase in plastic viscosity [12].

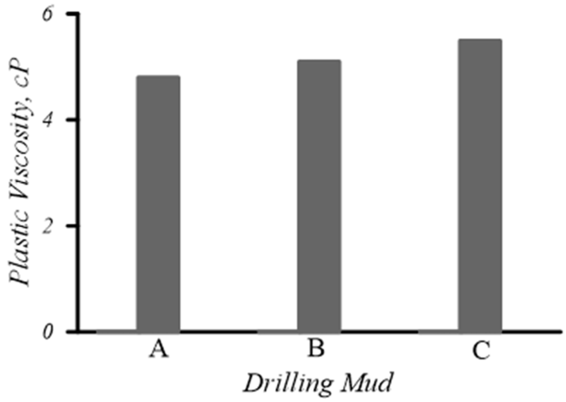

Fig. 5. Effect of Nano-Barite Particles on Plastic Viscosity of Drilling Mud

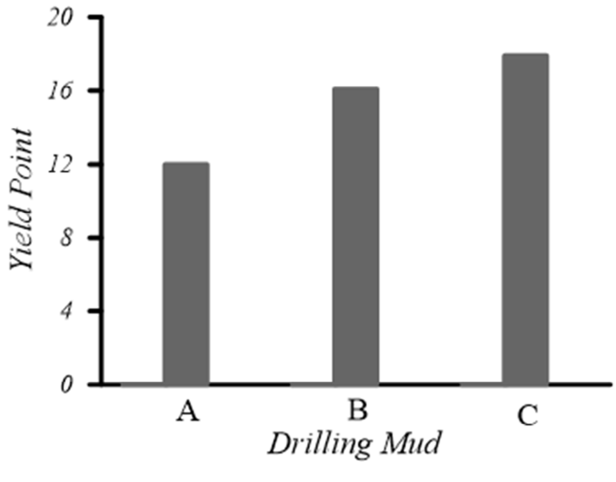

Fig. 6. Effect of Nano-Barite Particles on Yield Point of Drilling Mud

Fig. 6 presents the effect of nano-barite-particles on yield point of drilling mud. The results project higher yield points for nano-barite based drilling mud sample-C in comparison with sample-A and B. This improved property of nano-barite-based drilling mud is known to impart better cutting carrying ability (dynamic suspension) and effective well bore cleaning characteristics to the drilling mud.

It is evident from the table and regression analysis that the polynomial and Herschel-Bulkley models fits better than the other models available for rhelogy model. However, the Herschel-Bulkley model projects the best fit with the conventional and nano-barite based data as seen in Figures 8 and 9 respectively.

Drilling fluids are commonly non-Newtonian fluids, which are not independent of shear rate. It is evident from the figures 7 and 8 that the drilling fluids project decreasing viscosity with increasing shear rate confirming the shear thinning behaviour and establish best fit between the experimental and modelled data with minimal error for applied shear rate using Herschel-Bulkley model.

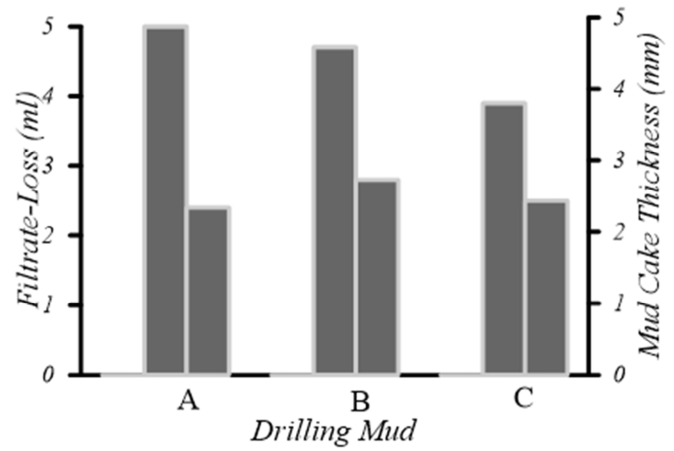

Fig. 7. Effect of Nano-Barite Particles on Filtrate-loss characteristics of Drilling Mud

Figure-7 presents the effect of nano-barite-particles on filtrate loss of drilling mud. The filtrate loss and mud cake for sample-A is observed to be 5.2 ml and 2.4 mm and for sample-B is 4.7 ml and 2.8 mm respectively. However, the filtrate loss and mud cake for nano-barite based drilling mud (sample-C) is found to be 3.9 ml and 2.5 mm meeting the API standards.

3.3 Rheological Models

Table 3: Rheological model data of conventional and nano-barite based drilling fluids

Mud Sample	Temperature °C	Bingham Plastic			Power law			Polynomial				Herschel-Bulkley		
		τ_o	μ_p	R^2	K	N	R^2	a	b	c	R^2	τ_o	K	n
B	30	14.37	0.185	0.978	13.51	0.2086	0.944	0.0004	0.273	13.17	0.997	12.32	0.927	0.697
	60	14.74	0.151	0.961	13.81	0.184	0.933	0.0005	0.241	13.47	0.996	12.42	1.113	0.626
	80	14.80	0.185	0.964	13.74	0.209	0.933	0.0006	0.301	13.`9	0.996	11.96	1.362	0.626
	95	17.76	0.173	0.933	13.31	0.185	0.994	0.0007	0.311	15.82	0.994	13.84	2.107	0.534
C	30	13.34	0.177	0.983	12.68	0.208	0.937	0.0003	0.243	12.42	0.996	11.80	0.68	0.746
	60	12.56	0.156	0.975	11.83	0.203	0.928	0.0004	0.231	11.46	0.997	10.78	0.781	0.698
	80	16.46	0.173	0.966	15.54	0.185	0.933	0.0005	0.271	15.13	0.996	14.41	1.125	0.649
	95	18.95	0.185	0.957	17.76	0.178	0.931	0.0006	0.303	17.29	0.997	16.06	1.413	0.621

Table 3 presents the rheology of the drilling mud with conventional barite (Sample-B) and the nano-barite (Sample-C) as the weighting agent at various temperatures of 30, 60, 80, and 95°C and modelled using Power Law model, Bingham Plastic model, polynomial model and Herschel Bulkley model respectively as shown in fig. 8.

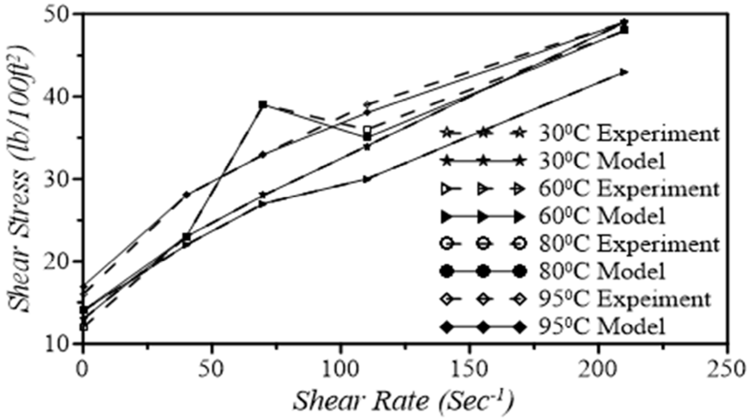

Fig. 8. Herschel-Bulkley model for conventional barite based mud formulation

4. Conclusion

The present work illustrates the study on barite sag control through application of nano-technology. Nano-based barite particles have been synthesized at laboratory using precipitation method and added to the conventional water-based-drilling with bentonite. Based on the rheological and sag test the following conclusions can be drawn:

- Negligible mud weight and filtrate-loss variation in nano-barite based mud in comparison with the high particle size barite based mud confirm the barite sag control through application of the nano-particles of barite.
- Improvement in plastic viscosities and yield points of nano-barite based drilling mud confirms improved rheological characteristics required for an effective drilling mud.
- The rheology of both conventional and nano-barite based drilling fluids fits better with Herschel-Bulkley model and project shear thinning behaviour.
- The present work aids in formulating efficient nano-based drilling fluids for effective drilling operations.

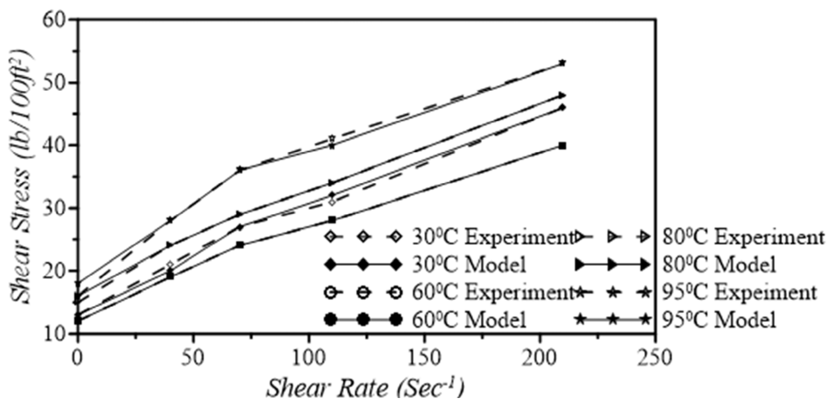

Fig. 9. Herschel-Bulkley model for nano-barite based mud formaulation

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