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The Effect of Additives on Rheological Properties of Drilling Fluid in Highly Deviated Wells

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Abstract

The quality of rheological properties like density, viscosity, yield point, gel strength and the volume of the drilling fluids (mud) varies with depth, lithology and conditions associated with a particular location. These environmental conditions downhole affect the rheological properties of the drilling mud, and this always necessitated the introduction of additives to the drilling fluid to reduce, increase or control the rheological properties. The adding of additives can either lead to a kick or the invasion of the reservoir with mud, which may kill the well. This work focused on the effects of Barite and Hematite on the rheological properties of the drilling fluid by considering water base mud (WBM). The effects of field measurement of most rheological properties in cutting transport in highly deviated wells were studied. Water based mud and angles of annulus inclination to the vertical were used, and also the different rheological properties obtained when using Barite and Hematite mud samples were compared. The results obtained showed that Hematite produced a significantly higher density, yield point, gel strength and plastic viscosity when used at the same concentration as Barite. Also, significant changes in the rheological properties were noted, which may be connected to the concentration of the mud additives and as such, Hematite additive performed better than Barite additives at the same concentration. The effects of mud yield and the ratio of yield point to plastic viscosity are more significant for lower fluid velocities or the laminar flow, while in turbulent flow, the cuttings transports are generally not affected by the mud rheological properties.

Keywords: Rheology, additives, drilling, mud

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1.0 Introduction

Highly deviated wells are wells with angles deviated more than 50^0 from the vertical, they are purposely deviated from the vertical by using controlled angles to reach an objective location other than directly below the surface location. A directional well may be the original hole or a directional “side track” hole that deviates from the original bore at some point below the surface. The communication between the surface and the target depth inside the reservoir involves the drilling of a well, which requires the use of drilling fluid (mud). The quality of the drilling fluid determine how reliable and effective your drilling program will be, it also aid in the integrity of the well in terms of the environmental state or impact of these mud down hole and at the surface. The ability of water base mud (WBM) and oil base mud (OBM) as a type of drilling fluid used to clean large diameter wellbore, small diameter and high angle holes depends largely on the rheological properties of the mud. The success of oil base mud in highly deviated well drilling is as a result of its rheological profile and is independent of its calculated yield point and plastic viscosity. Materials that modified this profile tested successful in the laboratory are being used on more than twenty wells. The application of deviated wells in the oil and gas are sometimes for the purpose of performing multiple kick-offs from a single master hole to recapture the cost of re-drilling or coring the overlaying formations above the mineralized zone, which is aimed at maximizing exploration costs. Deviated wells have also been applied to inaccessible surface areas such as lake, rivers and buildings where it is impossible to set a drill down to the zone. Control directional (deviated) wells are drilled for the purpose of increasing the exposed section length of the reservoir by drilling through the reservoir at an angle. It can also be for the purpose of maintaining natural or artificial features already existing in areas where drilling through the reservoir is not possible or certified difficult to drill. Such cases may include; an oilfield under a town or underneath a difficult to drill formation. In some case where inflow of reservoir fluids into the wellbore is noticed, relieve well is drilled to allow the pressure of a well producing without restraint (blow out) to be controlled for the sole aim of starving the blow out. In this scenario, another well could be drilled starting at a safe distance away from the blowout, but intersecting the troubled wellbore. Heavy fluid (kill fluid) is pumped into the relief wellbore to suppress the high pressure in the original wellbore causing the blowout. Offshore platforms have been reduced or in some cases eliminated by the introducing deviated wells from onshore, also to avoid gas cusping or water coning problems.

Drilling fluids are fluids used to aid the ease of drilling from surface to target depth by removing cuttings, lubricating and cooling bits, and also transmit power to the bit. It can also support borehole wall and control formation pressure. Its selection has always been due to the type of well, type of formation and environmental impact. The potency of any mud lies in the rheological properties of the mud, because they determines the ability of the mud to hold cuttings when at rest and in motion. These rheological properties include yield point, plastic viscosity, gel strength, mud density, etc. Darley & Gray (1988) worked on oil base mud (OBM) with respect to drilling production zones, shale’s and other water sensitive formations, as clays do not hydrate or swell in oil but act differently when water is present. Looking at the usefulness in drilling high angle/horizontal wells because of their superior lubricating properties and low friction values between the steel and formation which results in reduced torque and drag. Seeberger (1998) stated that the rheological character of conventional, organophilic clay viscosified oil-base mud can limit their cuttings transport efficiency in large diameter deviated wells. The viscosity of a fluid at low shear rates and its initial gel strength are critical parameters in determining its ability to clean a well. Monitoring low speed VG meter readings is essential in predicting efficient transport and suitable gel structure formation. This research study is aimed at determining the best additives for water base mud to help in cuttings removal in highly deviated wells, by considering some of the rheological properties of water base mud and the cutting transport ability of this mud in selected angles of deviation of the well.

1.1. Drilling Fluid

Drilling fluid is composed of base liquid, active solids and inert solids (Finger &Blankenship, 2010). The liquid constituents can be water which is either brine or fresh water and oil, while the active solids are due to the presence of clays and polymers. Consequently, the active materials combine to form suspended colloids in continuous liquid phase. During the course of drilling the mud collected and other solids from the formation, sometimes the solids it's due to the introduction of weighting materials like barite or hematite for the purpose of increasing the density of the mud. These solids are referred to as inert solids. The sustainability of the rheological properties of drilling fluid is a complex procedure that needs deliberate monitoring of both the mud and all the systems connected to the mud. To achieve effective hole cleaning, the mud viscosity is designed high to be able to lift cuttings out of hole during circulation and also effectively hold these cuttings in suspension when the mud is not in circulation. Furthermore, the presence of high formation pressure necessitates the introduction of weighting materials to increase the density of the drilling fluid. However, the mud should be design light to prevent lost circulation if the formation pressure is low. Formation with high temperature, solids introduced into the mud from the formation as a result of drilling activity retain more of the available water and this leads to viscosity increase because there is water loss. In trying to enhance the properties of drilling fluid through the addition of additives, critical analysis of the impact of the different conditions on the mud must be done so as to avert unexpected complications.

1.2. Drilling Fluid Additives

There are many drilling fluid additives which are used to enhance the key properties of the mud, different additives available give different performance depending on how it is applied, and some of these additives do not give the key properties of the mud systems needed in drilling deviated wells. The complexity is also increasing daily as more difficult and challenging drilling conditions are encountered downhole. The most common types of additives used in water-base and oil-base mud are; weighing materials, viscosifiers, rheological control materials, alkalinity and pH control materials, lost circulation materials, lubricating materials and shale stabilizing materials. Drilling fluid properties are considered depending on the nature of the formations being encountered, when the mud encountered harsh formation, i.e. formation that has an adverse effect on the mud, the ability of such mud to measure up to its purpose becomes very difficult making the investigation of the rheological properties like mud density, viscosity (plastic viscosity, apparent viscosity), gel strength and yield point when Barites and Hematite are added at different conditions to be very relevant. The economical implication involving the conventional vertical well in offshore fields is huge and it is not always cost effective to install the vertical well in such locations. The other alternative to producing from that field is deviated wells to bypass most of the costly obstructions. However, this method is not free of engineering challenges while drilling the deviated and horizontal parts of the hole. Some of the challenges are excessive torque and drag, hindering drill pipe sliding which results in limiting the lateral reach of the well, lost circulation, barite sag, inefficient hole cleaning and frequent sticking. These obstacles directly and indirectly contribute many other problems (Cameron, 2001). A small shift from the vertical due to the angle of deviation will lead to changing of the lifting power of the mud. As the direction of drilling is shifted from vertical to deviated and horizontal orientation, the capacity of the mud in carrying drill cuttings reduces. This happens due to tendency of cuttings to lie down along the low side wall of the annulus rather than being lifted out (Fadairo *et al*., 2009) and this capacity of the mud in carrying drill cuttings determines the quality of performance of hole cleaning. Hence, a comprehensive understanding of hole cleaning is essential and it requires a good understanding of the additives and the effects on the mud rheological properties in order to prevent the unnecessary operational problems.

1.3. Rheological Properties of Drilling Fluid

Some of the rheological properties of mud were enumerated by considering their flow behavior in the formation. One of the most influential properties of the drilling fluid is its viscosity. Understanding the role of viscosity in drilling, and other operations, and being able to match viscosity requirements to the conditions prevalent for that requirement is a key factor in optimizing the efficiency of the fluid. Viscosity is a measure of internal resistance or friction of a fluid to flow; it is also the stress per rate of shear and the resistance to change of form. It is affected by temperature, pressure, and the amount of gas in solution in a liquid and the type and size of molecules in the fluid. Excessive viscosity is undesirable because of the pressures that can be generated by high velocity in the bore hole when pumping horizontally. Newtonian fluids are those whose flow behavior can be fully described by a single term called the Newtonian velocity, μ. For these fluids, examples of which include water and light oil, the shear stress (τ; force per unit area) is directly proportional to the shear rate (γ in time $^{-1}$). This implies that if the shear stress is doubled the shear rate is also doubled vice versa. The fluid begin to flow as soon as a shearing force is applied, the dynamic viscosity of the fluid expressed in poise or centipoise (cp); 1cp = 0.001kg/m (Bourgoyne *et al*. 1986). Non-Newtonian fluids are those whose viscous properties cannot be described by a single term. Moreover, non Newtonian fluids exhibit shear rate dependency; if the apparent viscosity decreases with increasing shear rate they are called pseudo plastic fluids and if the apparent viscosity increases with increasing shear rate they are referred to as dilatants fluids. Bourgoyne *et al*. (1986) mentioned that if the fluid behavior is shear time dependent then they could be classified as thixotropic, if the apparent viscosity decreases with time after shear rate is increased to new constant values; and rheopectic, if apparent viscosity increases with time after shear rate is increased to a new constant value. Shear rate is the condition which changes most throughout the circulation system. Laminar fluid flow is characterized as parallel layers with a profile of changing velocity with distance from the walls. The shear rate is an average representation of the movement relationship of the layers of fluid in a cross section of the flow path.

Bingham (1922) initially recognised plastic fluids which are now commonly referred to as Bingham plastic fluids and are distinguished from Newtonian fluids as they require a finite stress to initiate flow. Bingham plastic fluids, do not flow until the applied shear stress τ, exceeds a certain minimum value (τ_y) known as yield points. Once the yield point has been exceeded, changes in shear stress are proportional to changes in shear rate and the constant of proportionality is called plastic viscosity, μ_p. (Clark 1995).

Plastic viscosity is part of the flow resistance of the fluid caused by mechanical friction within the fluid. The friction is due to interaction of individual solid particles, the interaction between solid and liquid particles and the deformation of the liquid particles under shear stress. Yield point is also part of flow resistance of fluid caused by electrochemical forces within the fluid (Azar & Samuel, 2007). Yield point is expressed in unit of dynes per square cm, or in field units of pounds per 100 square feet. However, the Bingham plastics model over values the low shear rate viscosity for most drilling fluid (Growcock & Harvey, 2005).

2.0. Methodology

The properties of drilling fluid can be enhanced to perform adequately in highly deviated well, to this end two weighting materials were adopted for this study which was limited to some properties that include density, plastic viscosity, yield point and 10-sec gel strength. Monitoring these properties daily helps to sustain the ability of the mud in effectively cleaning the hole of cuttings when the mud is in circulation or holding the cuttings when circulation stops. Some of the essential factors in field management of drilling fluid rheology are; a quick recognition of any deviation from the specification, distinguishing the type and degree of changes noticed, identifying the probable cause and the remedial action for the change. The major properties of the fluids should be measured and reported daily on the drilling morning report. Each mud property contributes to the character of the fluid and must be monitored regularly to show trends, which can be used to ascertain what is happening to the mud whilst drilling. This work captured some of the experimental analyses to ascertain the impact of the weighting materials (Barite & Hematite) on the mud at different conditions and the major analyses are explained below.

2.1. Sampling and Experimental Procedure

The materials for this study were sourced and collected locally; consequently, all the data generated were obtained from laboratory experiments. Mud balance was duly calibrated for the purpose of obtaining accurate results, however, if gases are entrapped in the mud either sourcing the mud directly from the field or during the formulation stages air may be trapped in it which can lead to high weights or thick mud, then a pressure balance should be used. Each should be calibrated at the start of the job to weigh 8.33*ppg* with fresh water. Marsh Funnel was calibrated to read 26 ± 0.5 seconds when testing fresh water. The Fann V-G Viscometer or Rheometer was used to measure the viscosity and yield point of mud. The plastic viscosity (PV) is measured by taking the difference between the dial readings taken at two highest speeds of 600 rpm and 300 rpm.

$$Plastic\ Viscosity, (cp)\mu_p = \theta_{600} - \theta_{300} \qquad (1)$$

Same equipment used for measuring of plastic viscosity. Both PV and yield point (YP) are mathematical values which are used to calculate the pressure loss in the circulating system. When plastic viscosity rises, this is usually an indication that the solids control equipment are running inefficiently. Bingham plastic fluids flow behavior for laminar flow is described by the equation:

$$\tau = \tau_y + \mu_p Y; \quad \tau \geq \tau_y \tag{2}$$

Ideally the yield point should be just high enough to suspend the cutting as they are circulated up the annulus and also hold the cuttings when not in circulation. Yield point (YP) is calculated from

$$Yeild\ Point, \left(\frac{Ib}{100} sq\ ft\right) \tau_y = \theta_{300} - \mu_p \tag{3}$$

There are two reading for gel strengths, 10 seconds and 10 minutes with the speed of the viscometer set at 3 rpm. The fluid must have remained static prior to each test, and the highest peak reading will be reported. The laboratory data were analysed based on existing models and theories, taking into consideration the assumptions that govern them.

2.2 Hole Inclination Effect on Cuttings

The three possible scenarios under deviated wells were investigated with water based mud being the drilling fluid and the angles of annulus inclination to the vertical considered as the activity areas of the cuttings in the drilling fluid. Experimental data were processed to exposes the cuttings transport quantitatively through annular cuttings concentration (Vol. %) at steady state. Three separate regions of hole inclinations can be identified regarding cuttings transport, they are 0^o – 40^o, 45^o – 55^o and 55^o – 90^o, and these inclinations were critically and skillfully analyzed with regards to the cuttings transport through these hole inclinations and the flow pattern experienced in these regions.

2.3 Mud Density

The density of mud which is commonly referred to as mud weight is the density of the drilling fluid and it is measured in pounds per gallon (ppg) or in pound cubic feet (pcf). Barites or hematite can be used to increase the density of the drilling fluid, varying weight percentage were formulated by adding barites and hematite to the mud and the corresponding density were obtained by applying the mud balance. Meanwhile, mud balance or pressure balance or mud scale can be use in the field to determine the drilling fluid density and if the hydrostatic head is available equation 4 can be used to obtain the mud density.

$$P = 0.052\ \rho D \tag{4}$$

where P is the hydrostatic pressure or hydrostatic head in (psi), ρ is the mud density in (lb/gal) and D is the depth in (ft). All materials present in mud contribute to its density. The resulting mud mixture from all the additives and water is assumed to be ideal; hence the total volume as stated in equation 5 is equal to sum of the component volume.

$$V_t = V_1 + V_2 + V_3 + \cdots V_n \quad (5)$$

where, the volume V_i of the given additives, having density, ρ_i and sample mass of m_i is given by equation 6.

$$V_i = \frac{m_i}{\rho_i} \quad (6)$$

Hence, the resulting density can be computed using the following expression as stated in equation 7.

$$\rho = \frac{m_1 + m_2 + m_3 + \cdots m_n}{V_1 + V_2 + V_3 + \cdots V_n} \quad (7)$$

If $$X = 1470 \frac{w_2 - w_1}{35 - w_2} \quad (8)$$

Volume increase using barites is given as,

$$V = 100 \frac{w_2 - w_1}{35 - w_2} \quad (9)$$

where X is the number of 100 pounds sacks per 100 bbls and V is the number of bbls increase per 100 bbls. W_1 is the Initial mud weight (ppg), W_2 is the desired mud weight (ppg)

2.4. Viscosity

In terms of viscosity dial reading, Θ_N and the rotational speed, N (in rpm), the mud properties like the plastic viscosity and yield point were calculated using the following expressions 10 to 15

$$\tau = \mu\gamma \quad \text{(Newtonian fluid)} \quad (10)$$

$$\mu = \frac{300\,\theta_N}{N} \quad (11)$$

where, μ is the Newtonian or apparent viscosity in centipoises (cp) and Θ_N is the viscometer dail-reading at any rotational speed of N, the plastic viscosity of the mud is usually obtained by

$$\mu_p = \frac{300\,\theta_N}{N - 300\,\tau_y} \quad (13)$$

For N = 300 rpm, 600 rpm.

$$\mu_p = \theta_{600} - \theta_{300} \quad (14)$$

where Θ_{600}, Θ_{300} are the viscometer dial readings at N = 600 rpm and N = 300 rpm respectively. The yield point (τ_y) in unit lb/100sq ft is obtained using

$$\tau_y = \theta_{300} - \mu_p \quad (15)$$

The gel strength in unit lb/100 sq ft is measured by taking the maximum dial deflection when the rotational viscometer is turned at low rotor speed (i.e. 3 rpm) after the mud has been static for a period of time which is generally 10 seconds or 10 minutes. The gel strength quantifies the thixotropic behavior of a fluid, its ability to have strength when static in order to suspend cuttings, and flow when put under enough force. Ideally the two values of gel strength should be close rather than progressively far apart. The more the mud gels during shutdown periods, the more the pump pressure will be required to initial circulation again.

3.0. Results and Discussion

Rheology test results have been divided into 4 sections, namely mud density results, plastic viscosity test results, yield point test results and 10-sec gel strength test result. These results presented are a true representation of the two additives (barite and hematite) and are presented in the Table 1.0 and Table 2.0. The graphical representation of each section is shown in the Figure 1 to 4 below;

Table 1 Rheological Properties of Barite Mud Sample at Varying Concentration of Barite

Mud Sample	Weight of Barite (%)	Density (lb/gal)	Plastic Viscosity (cp)	Yield Point (lb/100ft^2)	10-Sec Gel Strength (lb/100ft^2)
A	0.00	8.56	18.00	18.00	4.00
B1	5.00	8.70	24.00	26.00	7.00
B2	10.00	9.00	26.00	31.00	9.00
B3	15.00	9.58	29.00	33.00	11.00
B4	17.50	9.87	35.00	35.00	14.00
B5	20.00	10.10	37.00	43.00	17.00

Table 2. Rheological Properties of Hematite Mud Sample at Varying Concentration of Hematite

Mud Sample	Percentage Weight of Hematite (%)	Density (lb/gal)	Plastic Viscosity (cp)	Yield Point (lb/100ft^2)	10-Sec Gel Strength (lb/100ft^2)
A	0.00	8.56	18.00	18.00	4.00
H1	5.00	9.00	23.00	48.00	15.00
H2	10.00	9.60	31.00	69.00	16.00
H3	15.00	9.90	33.00	79.00	24.00
H4	17.50	10.00	35.00	102.00	31.00
H5	20.00	11.40	44.00	117.00	57.00

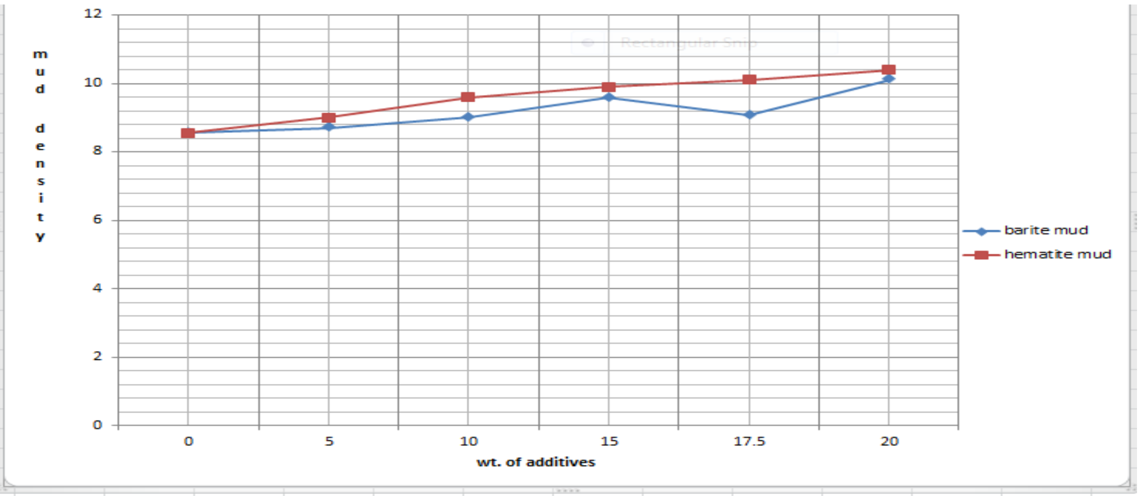

Fig. 1 Effect of Additives on the Density of Mud Sample

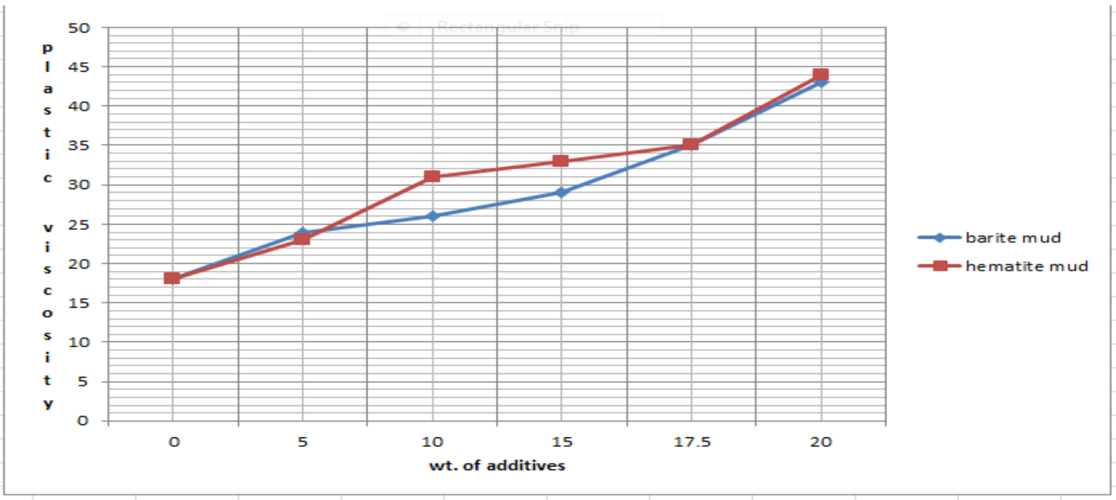

Fig. 2 Effects of Additives on the Plastic Viscosity of Mud Samples

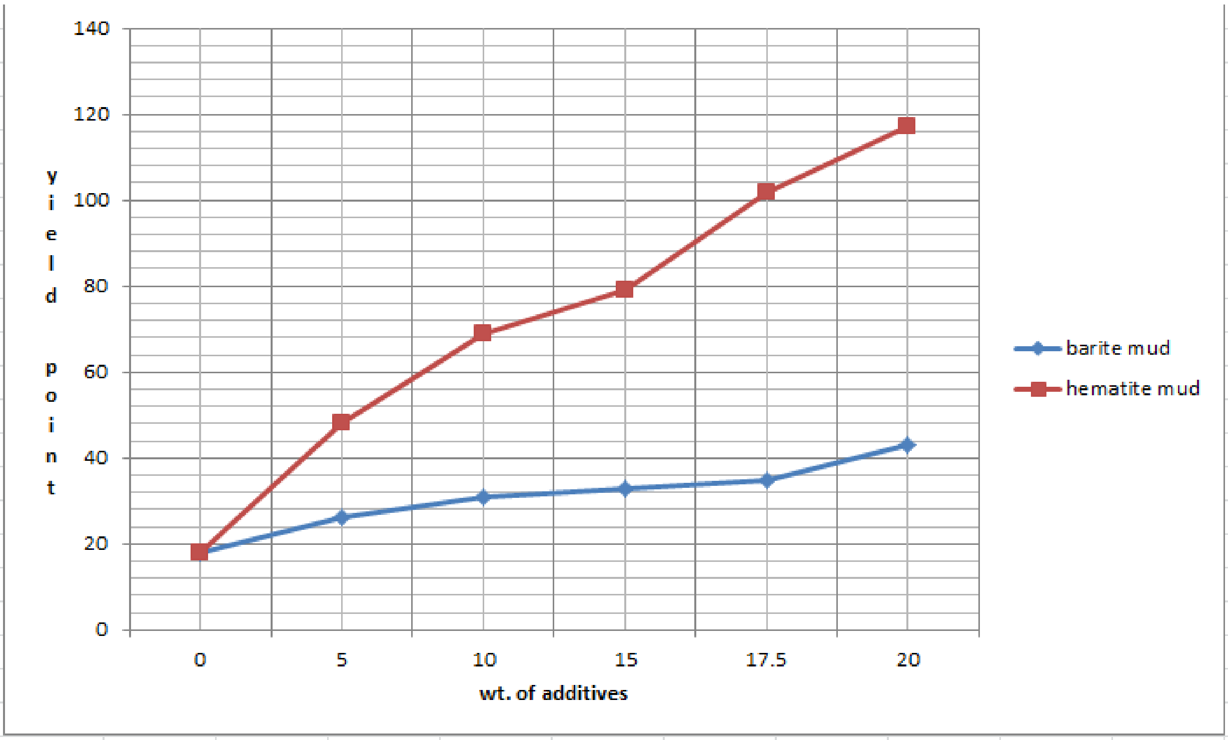

Fig. 3 Effects of Additives on the Yield Point of Mud Sample

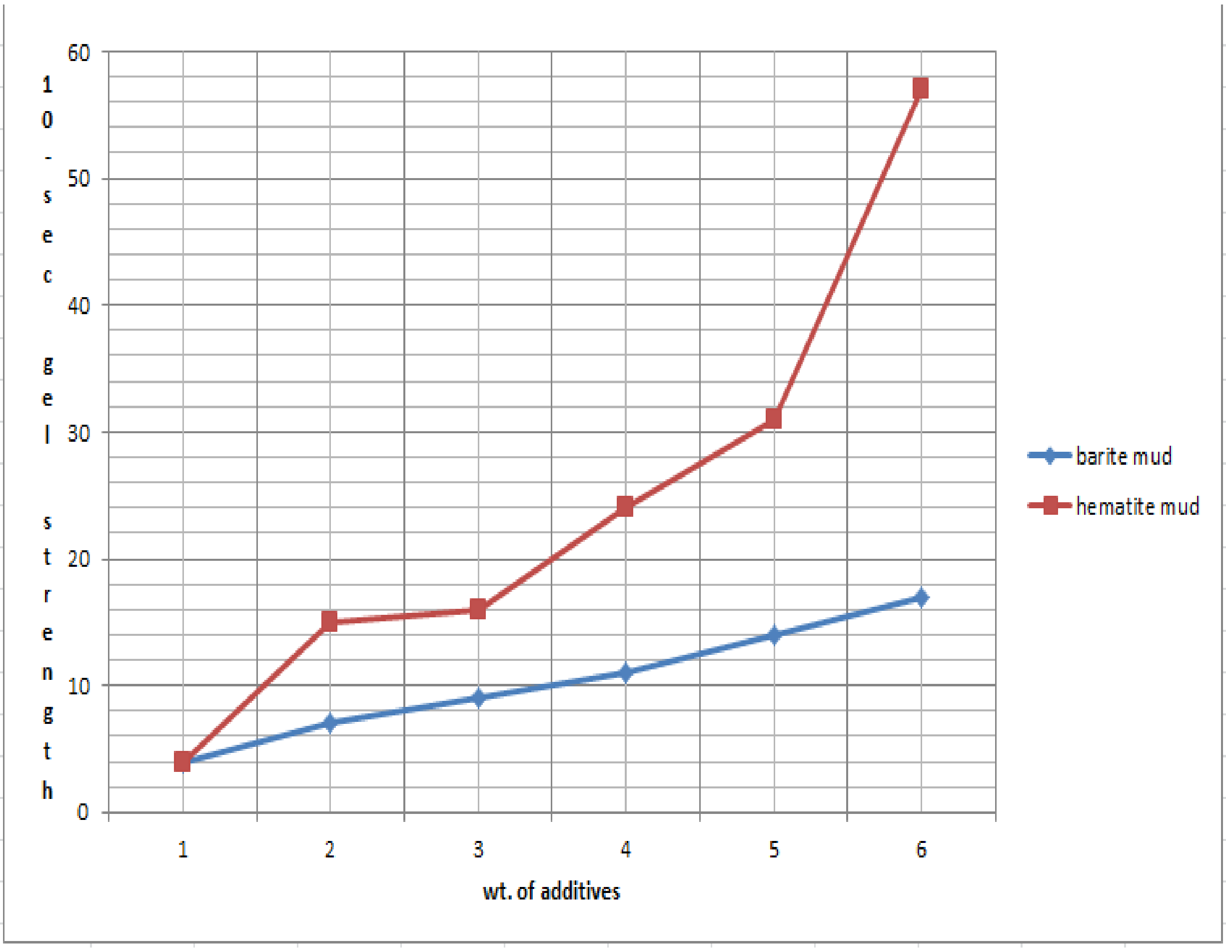

Fig. 4 Comparisons of Barite and Hematite in 10-Sec. Gel Strength

3.1. Discussion

The presented suggest that the additives make a very significant impact on the four different sections, which are the mud density, plastic viscosity, yield point and 10-sec. gel strength. Drilling fluid properties are directly or indirectly related to most of drilling problems. Even a slight variation in the properties of drilling fluid can cause unpredictable problems. In this experiment, rheological properties of drilling mud additives were studied Mud samples with varying concentration of additives were prepared; their properties were studied and compared.

Rheological properties of drilling fluids with a varying concentration of additives are graphically represented. The results indicate that rheological properties vary with a varying concentration of additives. The mud density comparison of barite mud and hematite mud indicate that a similar amount of hematite will give a higher mud density than barite. This can be attributed to the specific gravity of hematite as it is greater than that of barite. The other rheological parameters tested showed that hematite gave better values than barite when using the same concentration. These laboratory results supported by Menzel (1973) who mentioned that mud weighted with iron oxide gives better rheological properties and have lower rate of sedimentation than with barite.

According to this study, increasing the plastic viscosity of the mud resulted in a remarkable increase in the amount of recovered cuttings. Surprisingly enough, the surplus amount of viscosity inverses the result. As far as cuttings transport in highly deviated wells is concerned, researchers offer various ideas about the effect of viscosity on hole cleaning. Some researchers such as Zeidler (1972), Okrajni & Azar (1986), Pilehvari *et al*. (1999), Jawad (2002), Kelessidis *et al*. (2007) and Mohammadsalehi and Malekzadeh (2011) believed that raising viscosity of the drilling fluid deteriorates hole cleaning, because type of flow regime changes from turbulent flow to laminar flow; and it has been proved that cuttings can be better displaced in turbulent flow than laminar flow. On the other hand, there are also some investigators, for instance, Ford *et al*. (1990), Iyoho and Takahashi (1993), Belavadi and Chukwu (1994), Shou (1999), Li *et al*. (2004) claimed that improvement in hole cleaning occurs as viscosity increases.

The effects of field measurement of most rheological properties in cutting transport in highly deviated wells drilling were studied. Water based mud were used and angles of annulus inclination to the vertical. Experimental data were processed to exposes the cuttings transport quantitatively through annular cuttings concentration (Vol %) at steady state. Three separate regions of hole inclinations can be identified regarding cuttings transport: 0 - 40^0, 45-55^0 and 55 - 90^0. The effect of laminar flow dominates cuttings transport in low-angles wells (0^o – 45^o) because inclination is assumed to experience laminar flow, while the effect of turbulent flow predominates high-angles wells (55^o – 90^0), in the range of intermediate inclination (45^o – 55^o), turbulent and laminar flow generally have similar effects and this regions may also be called the transition zone. In laminar flow, higher mud yield point values and yield point/plastic viscosity (YP/PV) ratio provide better cuttings transport. The effect of mud yield point value is significant in the range of 0-45^0 hole inclination and becomes small or even negligible in the range of 55-90^0. The effects of mud yield and YP/PV ratio are more significant for lower fluid velocities. In turbulent flow, the cuttings transports are generally not affected by the mud rheological properties.

4.0. Conclusions and Recommendation

This experiment studied the effect of drilling mud additives on rheology of drilling mud. Studies compared the rheological properties of barite and hematite additives. The following conclusions can be drawn from this study:

i. The concentration of mud is vital to control the rheological properties of drilling mud. Significant changes in mud density, plastic viscosity, yield point, and gel strength were noted to correspond to changes in the concentration of mud additives.
ii. Hematite gave a significantly higher value of density, yield point, gel strength and plastic viscosity when used at the same concentration as barite.
iii. The density, plastic viscosity, yield point and 10-sec. gel strength have direct relationship due to the percentage weight of the individual sample.
iv. The specific gravity of the barite and hematite additives determines the performance of the mud in terms of their plastic viscosity, yield point, 10-sec. gel strength and density.
v. The effects of mud yield and the ratio of yield point to plastic viscosity are more significant for lower fluid velocities or the laminar flow, this make the regions experiencing laminar flow to depend on the properties of the mud in terms of cutting transport. While in turbulent flow, the cuttings transports are generally not affected by the mud rheological properties.

Basic mud engineering knowledge dictates the requirements for good hole cleaning, reducing friction between the drill string and casing and/or formation, and maintaining hole stability. These requirements become critical when a highly deviated well is drilled.

Inhibited mud with low solids content provides a stable hole and, at the same time gives good rheology (relatively low plastic viscosity). Yield points must be maintained high so the mud will have good carrying capacity. Inverted rheology is desirable for good hole cleaning (yield point higher than plastic viscosity), although that is difficult to obtain at high angles. High pump rates assist in cleaning cuttings from the hole in the area considered.

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