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Evaluation of a formulated synthetic-based mud properties on its cuttings carrying capacity using factorial design

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ABSTRACT

In drilling mud formulation, evaluating the mud cuttings carrying capacity provides the means of establishing its wellbore hole cleaning potential. Thus, a synthetic-based mud was formulated from derived ester and evaluated for its mud weight and rheological properties: plastic viscosity and yield point. A two level-three factors (2^3) full factorial design was performed to evaluate the cuttings carrying index (CCI) of the formulated synthetic-based mud. This offers the privilege of assessing the combined effect of these factors: plastic viscosity, yield point and mud weight on the cuttings carrying capacity of the mud. The factors' levels (low and high) from the formulated mud properties measurement were 6 and 17cp, 10 and 13lb/100ft^2, and 8.63 and 9.50lb/gal for plastic viscosity, yield point and mud weight respectively. Thus, the experimental design results obtained, resulted ingood cuttings carrying capacity (adequate hole cleaning) as the obtained CCI values were above 0.5. Additionally, the results further revealed main effect from the formulated mud's rheological properties and mud weight on its cuttings carrying capacity. Furthermore, the experimental design result depicted that there was interaction effect between the rheological properties, whilst there was no interaction effect between the rheological properties and the mud weight at the considered factors' level. Therefore, a potential synthetic-based mud with adequate wellbore hole cleaning capacity could be formulated at the considered mud properties.

Introduction

The oil industry is unarguably one of the most complicated industries which faces so many challenges yet functions as efficiently as possible (Agwu and Udoh, 2013). This is because almost every operation during the exploration and production (E & P) process is subject to and influenced by a number of factors thereby making the process complex to describe. Due to these complexities, researchers have in a bid to explain certain phenomena carried out experiments and used the results from such experiments to develop analytical and mathematical models. The widespread use of experiments by researchers highlights the huge regard generally given to information derived from it. However, it has been realized that most of the models developed from the results of these experiments are more often than not inadequate to describe or capture the cause and effect of all the variables involved in a certain phenomenon. Most times, the models capture only the effects of major measured parameters while leaving out the effect and the degree of influence other parameters have on the entire process. This inadequacy in getting at the nuts and bolts of a phenomenon in the E & P process led to the concept of experimental designs. Over time, the successes recorded in describing most down hole events during the E & P process have come from actively manipulating factors involved in the stream of events. The importance of experimental design stems from the quest for inference about causes or relationships as opposed to simple description. For example, the treatment of a drilling fluid that has high filter loss and low yield with two chemical additives (Event A) may cause an observed consequence of X on these problems, but possibly the consequence X may have been derived from another additive used for some other purpose (Event B) instead of emanating from the treatment for Event A or from the treatment for Event A combined with the treatment for Event B. Therefore, it is the pursuit of ambiguous relationships such as this that brings to the fore the need for meticulously planned designs. However, not all of the relevant information that is required can be derived from any given design. Part of the information will be piggy-backed into the study by assumptions, some of which are explicit. Although the knowledge is already available, the task of extracting the exact information needed to solve any research problem is circumscribed (Sytsma, 2009). The purpose of this paper is to use experimental design (design of experiment {DOE}) to evaluate the effect of formulated synthetic-based mud properties: plastic viscosity, yield point and mud weight on cuttings carrying capacity as well as hole cleaning potential during drilling operation.

Materials And Methods

Mud Preparation and Experimental Procedure

The synthetic-based mud used in this experimental design was formulated with palm-oil derived ester using about 100g (MUD-1) of palm fruit pulp to 350mL of water; for detailed preparation of the ester and mud formulation see Udoh *et al.* (2012). The formulated synthetic-based mud (MUD-1) contained no barite ($BaSO_4$) and no soda ash (Na_2CO_3). The drilling mud: MUD-2 was formulated with 5g barite ($BaSO_4$) and 10g soda ash (Na_2CO_3) content per 350mL mud. Thereafter, the formulated muds: MUD-1 and 2 mud weight and rheological properties: plastic viscosity and yield point were determined using mud balance and rotational viscometer respectively. Additionally, the rheological parameters: plastic viscosity and yield point of the formulated muds were evaluated from 300 and

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600 rpm (revolutions per minute) dial reading (presented in Table 1) of the viscometer based on the expanded equations 1 and 2. Thus, API Recommended practices of standard procedure for field testing drilling fluids (Recommended Practice, 1988 in Mahto and Sharma, 2004). Table 2 present the mud weight and rheological properties of the formulated synthetic-based muds.

Table 1: Viscometer Readings of the Formulated Muds

Rotor speed (RPM)	**Dial reading (θ)**	
	MUD-1	**MUD-2**
600	22	47
300	16	33

Table 2: Mud Properties of the Formulated Synthetic-Based Muds

Mud Properties	**MUD-1**	**MUD-2**
Density (ρ_m), lb/gal	8.63	9.50
Plastic Viscosity (PV), cp	6	17
Yield Point (YP), lb/100ft^2	10	13

Mud Properties Measurement Procedure

Density: The mud balance was standardized using distill water. The balance cup was cleaned, dried and filled to the brim with the mud sample to be measured. The lid was placed on the cup as some mud flowed out of the hole on the lid to ensure that there was no trapped air in the cup. The cup and lid were wiped to dry off any mud on the surface in order to obtain accurate measurement as the knife edge was placed on the fulcrum and the rider adjusted until the cup content and the rider were at equilibrium (balance). Later, the density of the mud sample was read on the calibrated arm of the mud balance.

Rheological Properties: The rotational viscometer provides a more meaningful measurement of the rheological characteristics of the drilling mud compared to marsh funnel (Bourgoyne *et al.*, 2003). The formulated mud sample to be measured was poured into the viscometer cup to the scribed mark and placed on the stand of the viscometer as it was lifted to immerse the rotating sleeve. With rotor speed at 300 and 600 rpm (i.e., two point data approach), their respective dial readings were recorded at steady values and used to evaluate the synthetic-based muds' plastic viscosity and yield point using equations 1 and 2.

$$PV = \theta_{600} - \theta_{300} \qquad (1)$$

$$YP = \theta_{300} - PV \qquad (2)$$

Where:

PV = Plastic Viscosity

YP = Yield Point

θ_{600} = *Dial reading at 600 revolutions per minute*

θ_{300} = *Dial reading at 300 revolutions per minute*

Experimental Design of Mud Properties-Cuttings Carrying Index

Design of experiment or experimental design is a systematic approach to investigation of a system or process. Hence, it has more to offer than one change at a time experimental method. Therefore, to examine the main and interaction effects of the formulated synthetic-based mud's mud weight and rheological properties: plastic viscosity and yield point on its cuttings carrying capacity, a two level-three factors (2^3) full factorial design was used. The general mathematical model for 2 by 3 full factorial design is expanded in equation 1. This equation depicts one (1) intercept coefficient (P_O), three (3) main effect coefficients (P_A, P_B and P_C) and four (4) interaction effect coefficients (P_{AB}, P_{BC}, P_{AC} and P_{ABC}).

$$y = P_O + P_A x_A + P_B x_B + P_C x_C + P_{AB} x_{AB} + P_{AC} x_{AC} + P_{BC} x_{BC} + P_{ABC} x_{ABC} \qquad (1)$$

Where:

x_A, x_B and x_C = *Main effects*

x_{AB}, x_{AC}, x_{BC} and x_{ABC} = *Interaction effects*

P_A, P_B and P_C = *Main effect coefficients*

P_{AB}, P_{AC}, P_{BC} and P_{ABC} = *Interaction effect coefficients*

P_O = *Ground mean (intercept)*

y = *Response*

In this study, the following formulated mud properties are represented in the general 2 by 3 factorial design model equation (Eq. 1):

x_A = *Plastic viscosity*

x_B = *Yield point*

x_C = *Mud weight*

y = *Cuttings carrying index (CCI).*

Additionally, the factors and levels selection for this experimental design study was based on the obtained formulated mud properties measurement indicated in Table 2. Hence, the result can be represented as;

Table 4: Level of Factors for the Cuttings Carrying Index study

Factors	**Low Level**	**High Level**
Plastic Viscosity, cp	6	17
Yield Point, lb/100ft^2	10	13
Density, lb/gal	8.63	9.50

The cuttings carrying index (CCI)full factorial design experiment was performed using qimarcos program (software) added to 2007 Microsoft Excel as add-in program, the result of this full factorial design is presented in Figures 1 through 6.

Results And Discussion

Factors Main Effects on Cuttings Carrying Capacity

It is pertinent to establish the yardstick for evaluating the cuttings carrying capacity of the formulated synthetic-based mud forthe experimental design results. Therefore, Table 5 presents this measurement criterion for the cuttings carrying capacity evaluation.

Table 5: ***Criteria for assessing cuttings carrying capacity [Coleman, (online).www.drillingformulas.com]***

Condition	**Assessment**
When the CCI is less or equal to 0.5	Poor hole cleaning and hole problem may be seen
When the CCI is greater or equal to 1	Hole cleaning is good.

Figures 1 through 3 depict the main effects of the formulated mud properties: plastic viscosity, yield point and mud weight on its cuttings carrying capacity based on the obtained CCI values. The steep nature of the line as observed on the figures (Fig. 1 to 3) show that there is main effect of plastic viscosity (x_A), yield point (x_B) and mud weight (x_C) on the cuttings carrying capacity of the formulated synthetic-based mud. In drilling process, cuttings are transported or lifted downhole when the mud flow regime is under turbulent flow. Thence, these formulated mud properties are susceptible to turbulent flow, which explained their main effects on the cuttings carrying capacity of the synthetic-based mud. In Figure 1, it is observed that at low and high levels plastic viscosity (i.e., 6cp and 17cp), a good cuttings carrying capacity would be obtained as their respective CCI values are 1.08 and 1.14 which is greater than 0.5 (based on Table 5). This result shows that the synthetic-based mud's plastic viscosity ranges of 6cp to 17cp are adequate for proper hole cleaning during drilling operation, owing to their susceptibility to turbulent flow during borehole drilling. Figure 2 represents the main effect of yield point on the CCI values of the formulated mud. The result indicates that the yield point of the formulated synthetic-based mud has main effect on its cuttings carrying capacity. However, the obtained experimental design CCI value of the formulated synthetic mud is 1.1 irrespective of the yield point levels (i.e., low and high). This observation may be attributed to the yield point level differences in this study which is 3lb/100ft^2. Thus, the yield point differences would not really impact on the obtained average response (CCI values). Therefore, it can be stated here that there must be a significant difference in the formulated synthetic-based mud yield point to achieve a remarkable cuttings carrying capacity when the need arises during drilling operation. Furthermore, Figure 3 presents the mud weight main effect on the obtained CCI values. The figure indicates higher CCI value at low level mud weight when compared to the obtained CCI value at high level mud weight. This result is expected as a result of pressure loss or drop to overcome the high mud weight in a practical case which may result in less CCI value; indicating inadequate hole cleaning (i.e., poor cuttings carrying capacity). Interestingly, the formulated synthetic-based mud weight ranges of 8.63lb/gal to 9.50lb/gal resulted in adequate cuttings carrying capacity based on the obtained experimental design CCI results.

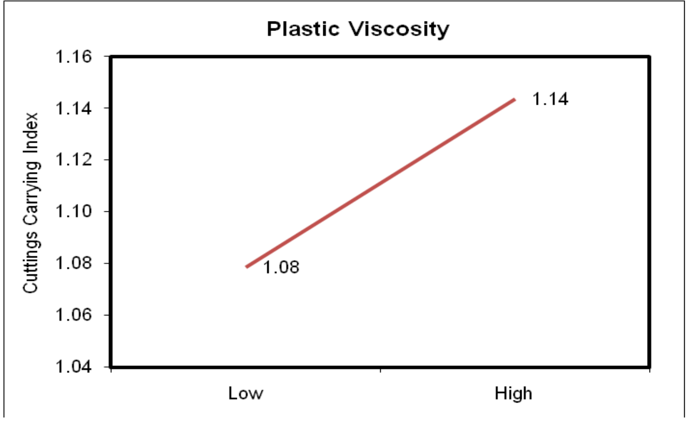

Figure 1: Plastic viscosity main effect on CCI

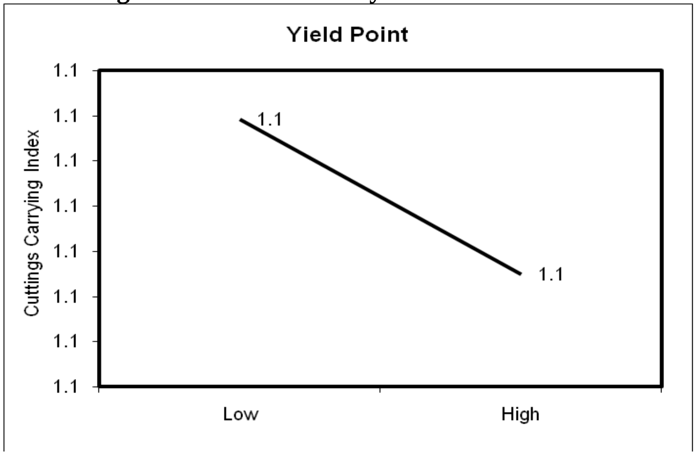

Figure 2: Yield point main effect on CCI

Factors Interaction Effects on Cuttings Carrying Capacity

Figures 4 through 6 show the interaction effects (i.e., x_{AB}, x_{AC}, *and* x_{BC}) of the synthetic-based mud properties on its cuttings carrying capacity. Figure 4 depicts the interaction effect (i.e., x_{AB}) between the formulated mud rheological properties: plastic viscosity and yield point. In that figure, it is noted that there is an intersection of the factors' line (i.e., the lines cross), indicating that there is an interaction effect between the mud's plastic viscosity and yield point on the mud's cuttings carrying capacity. Worth noting in the Figure 4 is that the intersection (lines cross) occurs at high level factors (i.e., high plastic viscosity and yield point values of 17cp and 13lb/100ft^2 respectively).

Figure 3: Mud weight main effect on CCI

This indicates that there is a direct connection between increased mud's rheology and its cuttings carrying capacity as well as hole cleaning potential. Figure 5 presents the interaction effect between the mud's plastic viscosity and mud weight (i.e., x_{AC}) on the mud cuttings carrying capacity since there is no intersection (lines cross) on the figure. This indicates that there is no interaction effect between the mud's plastic viscosity and mud weight on its cuttings carrying capacity. Conversely, it can be deduced from the figure that at a very low factors' level (i.e., lower values of plastic viscosity and mud weight), there might be an interaction effect between the mud's plastic viscosity and mud weight on its cuttings carrying capacity. This assertion is made since at low plastic viscosity and mud weight, drilling muds are susceptible to turbulent flow during drilling operation. In addition to the assertion, the respective factors' line on Figure 5 is not parallel to each other to indicate that there is no interaction effect between plastic viscosity and mud weight on cuttings carrying capacity.

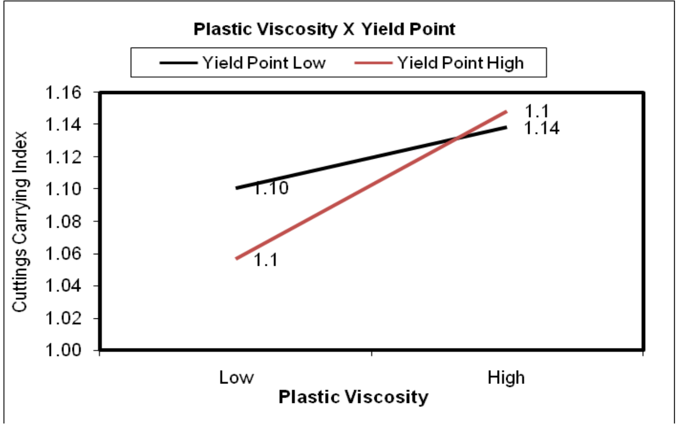

Figure 4: Plastic viscosity and Yield point interaction effect

Figure 6 further presents the yield point and mud weight interaction effect (i.e., x_{BC}) on the mud cuttings carrying capacity of the formulated synthetic-based mud. In this figure, it is observed that there is no factors' line intersection; indicating that there is no interaction effect between the mud's yield point and mud weight at this experimental design factors' level. Apparently, the same observation noted in Figure 5 is also observed in Figure 6, that is, the factors: yield point and mud weight might interact at very low yield point and mud weight on the cuttings carrying capacity of the formulated mud. Therefore, based on Figures 5 and 6, it can be deduced that at low rheological properties and mud weight values, there is an interaction effect between these mud properties on cuttings carrying capacity. Additionally, the experimental design CCI results indicate that there is no direct interaction effect between the mud's plastic viscosity, yield point and mud weight (i.e., x_{ABC}) on the mud cuttings carrying capacity of the formulated synthetic-based mud.

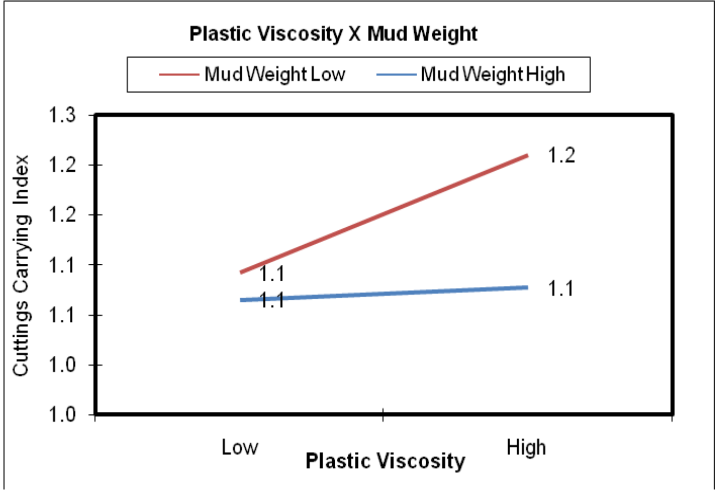

Figure 5: Plastic viscosity and Mud weight interaction effect

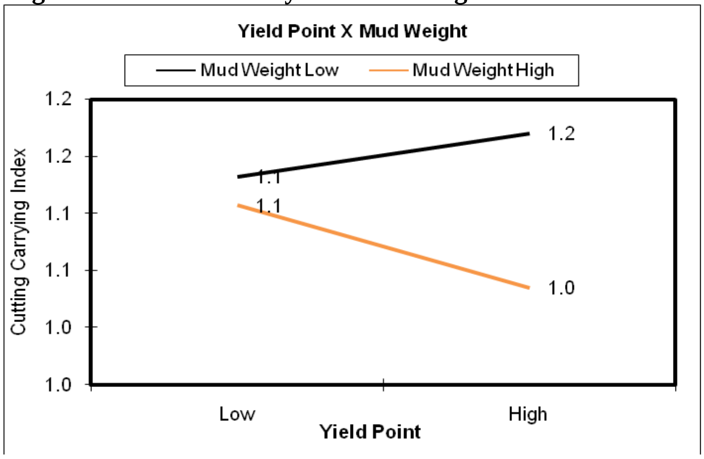

Figure 6: Yield point and Mud weight interaction effect

Conclusion

The importance of adequate wellbore hole cleaning cannot be overemphasized, as its inadequacy can be detrimental during drilling operation. The blood of drilling operation – drilling fluid must accomplish these functions of lifting cuttings to the surface and keeping the wellbore hole clean for a successful well to be drilled. Thus, experimental (factorial) design was utilized to evaluate a formulated synthetic-based mud's properties on its cuttings carrying capacity. Based on the factorial design cutting carrying index (CCI) results, the following conclusion are drawn:

1. The formulated synthetic-based mud has a good cuttings carrying capacity and adequate hole cleaning potential.
2. The formulated mud's rheological properties and mud weight have main effect on the cuttings carrying capacity of the synthetic-based mud.
3. There exist interaction effects between the rheological properties: plastic viscosity and yield point while no interaction effect exists between the formulated mud's rheological properties and mud weight on the mud's cuttings carrying capacity.

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