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Prediction of the Viscosity of a Water – Base Mud treated with Cassava Starch and Potash at varying Temperatures using Factorial Design

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Abstract

In order to monitor and control the properties of drilling fluids, measurements are routinely made at the surface. However, these surface measurements may not be representative of down-hole properties where the desired functions of hole cleaning and other related issues are critical to the success of the drilling operations. Consequently, it is important to make necessary adjustments of the fluid properties obtained at ambient conditions to give estimate of properties at high temperatures and pressures.

The principle and method of factorial design have been used to develop a model, which makes possible the prediction of drilling fluid viscosity at varying temperatures. Cassava starch and potassium carbonate were used as local additives in a water based bentonic drilling fluid after running a quality check. 2^3 full factorial design experiments which consider temperature, starch and potash as factor variables and viscosity as the response variable were conducted.
The main effects as well as the interaction effects were determined and examined. The results were analyzed and a predictive model was obtained. Viscosity values obtained using the model were compared with the experimental results and it was observed that the model has an accuracy of 93.6%.

This method makes possible the prediction of the viscosity of drilling fluids at varying temperatures, hence the treatment of mud systems can be determined ahead of time.

Introduction

Viscosity is one of the important properties of a drilling fluid. It affects hole cleaning as well as the ability of a mud to hold cuttings in suspension when not circulating. Mud viscosity is usually affected by both the additives in the mud and bottom-hole conditions. [1]

It therefore becomes imperative to continuously monitor and control mud viscosity during drilling operations. [2] The usual practice in achieving this purpose is to collect the drilling fluid and subsequently measure its viscosity. The result determines how the mud system is treated for improvement. [3]

To determine the effects of additives, the usual practice is to run an experiment at a time. However, this is cumbersome, tedious, time consuming and expensive. [4]

The factorial design method allows the effects of multiple factors to be investigated simultaneously. The treatments consist of all combinations that can be formed from the different factors. A valuable property of the factorial design is that it makes possible not only the calculation of main effects but also of interaction effects between variables as well. [5]

This technique provides a means of maximizing the information obtained from a minimum number of experimental runs, reduces the number of experimental runs, and saves time and cost. [6]

Apart from giving rise to simple calculations, it is also efficient, and systematic. [7] It provides well-organized estimates of constants.

In this paper, the method of factorial design was applied to a water-based bentonic drilling fluid treated with cassava starch and potash (local additives) to develop a mathematical model for predicting the viscosity of the drilling fluid at different temperatures.

Materials and Method

Locally produced cassava starch and potash were procured at Bodija Market in Ibadan, Oyo State of Nigeria. Normal quality tests were conducted on the materials with satisfactory results.

Experimental Design

A factor of an experiment is a controlled independent variable; a variable whose levels are set by the experimenter. The factors considered in this study were temperature, starch and potash.

Response Variable

The response variable for this experiment is the Viscosity.

Experimental Settings

The number of experimental runs performed in the full factorial design is given as:

$$N = L^K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Since 3 factors were examined at 2 levels the total number of experimental runs is therefore; 8.

Model

Running the full complement of all possible factor combinations means that we can estimate all the main and interaction effects.

In this experiment, there are 3 main effects, 2 two-factor interactions, and 1 three-factor interaction, all of which appear in the full model as follows: [8]

$$\begin{aligned} Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \\ \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \\ \beta_{123} X_1 X_2 X_3 + e \end{aligned} \quad \ldots\ldots\ldots (2)$$

Analysis Matrix for the 3-Factor Complete Factorial

The model or analysis matrix for the 2^3 full factorial design is shown in Table 1. In the design table, "-1" represents the "Low" setting of a factor while "+1" represents the "High" setting of the factor. [9]

Factors and Chosen Levels

The factors and the chosen levels are shown in Table 2.

Transformation of Variables

In factorial design experiments, it is required that the independent variables be transformed from their un-coded values to coded values. This is done using equation (3)

$$X_i = \frac{V_C - V_O}{V_I - V_O} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Randomization

Randomization provides protection against extraneous factors affecting the results. The more freely the experimental runs are randomized the more insurance one has against extraneous factors possibly affecting the results, and hence perhaps wasting of experimental time and effort. [10] Table 3 shows the factor settings in randomized order

Experimental Procedure

Four mud samples were used for the experiments. The composition of the mud samples are shown in Table 4.

The various quantities of the materials as specified in Table 4 were measured and poured into a metallic beaker. With the aid of a Hamilton Beach mixer, the materials were thoroughly agitated until a homogenous mixture was obtained. The mud samples were aged overnight to allow for hydration.

The experiments were conducted in accordance with the randomized order shown in table 3, and was replicated twice, using a rheometer. The rheometer measures the dial reading of 600 rpm and 300 rpm from which the plastic viscosities and the yield points were calculated using equation (4) and (5) respectively.

Plastic Viscosity: $\mu_p = \Phi_{600} - \Phi_{300}$ ………. (4)

Bingham Yield point: $Y_b = \Phi_{300} - \mu_p$ ……….(5)

Results and Analysis

The results obtained from the experiments are recorded in Table 5. Table 6 shows the Model Matrix for the plastic viscosity.

Calculation of Factorial Effects

Yates Algorithm was adopted in this experiment for the calculation of the main and interaction effects. The factorial effects from the Yates algorithm are recorded in Table 7.

Calculation of Coefficients

The coefficient(s) β_i is the change in Y when X_i is changed by 2 units, i.e., from a low level to a high level. Therefore the coefficients are obtained from the result of the Yates algorithm by dividing each of the estimated effect value by 2 except the mean. Results of this operation are shown in Table 8.

Analysis of Variance (ANOVA) for the Factorial Effects

The sums of squares of the main and interaction effects required for the ANOVA process are calculated as shown in Table 9.

The sum of squares of the residual is given as

$$SSQ_{resid} = \sum_{i=0}^{1}\sum_{j=0}^{1}([\sum_{v=1}^{r} Y_{ij}^2] - T_{ij}^2 / r) \quad \text{.........} (6)$$

SSQ_{resid} = 2.125

The sum of squares and the SSQ_{resid} values are substituting into the ANOVA table and the results are presented in Table 10.

Standard Deviation

The standard deviation is given as;

$$S = \sqrt{\text{Residual mean square}} \quad \text{..........} (6)$$

S = 0.515

Variance and Standard Error of Effects

In the analysis of variance, the residual mean square is an estimate of σ^2 for each treatment, because the variance for all treatments is assumed to be equal.

$$\text{Variance of effects} = \frac{4\sigma^2}{2^{k-r}} \quad \text{..............} (7)$$

Thus; Variance of effects = 0.531
Standard error = 0.364
Experimental error = Standard error

Model Development

The model equation is given by equation (2)

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{123} X_1 X_2 X_3 + e \quad \text{..........} (2)$$

The response in equation (2) is the plastic viscosity. Thus substituting the values of the coefficients and the experimental error into the model equation yields

$$\mu_p = 8.094 + 4.156X_1 + 2.219X_2 - 1.469X_3 + 1.906X_1X_2 - 0.656X_1X_3 - 0.469X_2X_3 - 0.281X_1X_2X_3 + 0.364 \quad \text{.................} (8)$$

Equation (8) is the model fitted equation for the prediction of the mud Plastic Viscosity.

The model fitted equation for the Bingham Yield Point is given as equation (9)

$$Y_b = 11.313 + 6.688X_1 + 0.250X_2 - 5.000X_3 + 2.250X_1X_2 - 1.500X_1X_3 + 2.063X_2X_3 + 0.438X_1X_2X_3 + 0.515 \quad \text{.................} (9)$$

Coefficient of Variance (COV)

The COV is given as

$$COV = \frac{\text{Standard Deviation}}{\text{Mean}} * 100\% \quad \text{..........} (10)$$

COV = 6.435%

Comparison of Model Fitted Values and Experimental Viscosity values

To further confirm the accuracy of the model, experimental results were compared with results from the fitted model and the residuals were examined. Table 11 shows the details.

Discussion

The analysis of the factorial design of the mud samples further confirm that the viscosity of the mud sample treated with starch and potash depends not only on the additives but on the down hole temperature as well.

The values of the main and interaction effects (Table 8) suggest that the effects of temperature and starch on a mud viscosity are more than that of potash, with the temperature having the highest value. While the temperature and the starch have a positive effect on the viscosity, the effect of the potash is negative. This implies that an increase in temperature and the quantity of starch in a mud system will increase the viscosity (Fig. 1) where as an increase in the quantity of potash will result in a decrease of the mud viscosity. (Fig. 2)

The interaction effects show that only the interaction between the temperature and the starch can result in an increase in viscosity values. All other interactions involving potash have the effect of reducing the mud's viscosity. This further confirms that potash is a good viscosity reducing agent.

Equation (8) known as the model equation is very satisfactory as confirmed by the COV value (6.35%). This small value is an indicator of the reliability of the model. This result implies that the model accounts for 93.6% (i.e. 1- 0.06435) of the variations in the experiment. This is very satisfactory.

As a further check on the reliability of the model , the plot of the experimental response and that of the fitted model (fig.3) shows that the profile of the fitted model is similar to that of the experimental response with a variation of 0.364 experimental error. Thus equation (8) and (9) provides a means of obtaining very reliable approximations of the viscosity and yield point of water based drilling fluids treated with starch and potash.

Conclusion

The method of factorial design has been used to develop a model that can predict the plastic viscosity of a drilling fluid containing additives and at high temperatures.

The model developed is a faster and cheaper means of obtaining viscosity and maximum information from minimum cost. It enables the estimation of not only the main effects but the interactions as well.

This method can be used to determine the required treatment of a mud system ahead of time. This, no doubt will improve performance as well as save time and cost.

Using this method other equations could be develop to prediction other properties of drilling fluids at various down hole conditions.

Abbreviations

ANOVA = Analysis of Variance
β_0 = Intercept coefficient
β_1 = Main coefficient on factor 1
β_2 = Main coefficient on factor 2
β_3 = Main coefficient on factor 3
β_{12} = Interaction coefficient of factor 1 and 2
β_{13} = Interaction coefficient of factor 1 and 3
β_{23} = Interaction coefficient of factor 2 and 3
β_{123} = Interaction coefficient of factor 1, 2 and 3
COV = Coefficient of Variance
e = Experimental Error.
K = Number of factors
L = Number of levels
N = Number of Experimental Runs.
r = Number of Replications
rpm = Revolutions Per Minute
S = Standard Deviation
SSQ_{resid} = Sum of Squares of Residuals
T_{ij} = Sum of responses for the 1st and 2nd replications
μ_p = Plastic Viscosity
V_c = Current value of variable
V_f = High level value of variable
V_o = Centre of region of interest ((low level value + high level value)/2)
X_i = Coded variables
$X_1, X_2 and X_3$ = Main Effects
X_1X_2 = Interaction Effect between X_1 and X_2
X_1X_3 = Interaction Effect between X_1 and X_3
X_2X_3 = Interaction Effect between X_2 and X_3
$X_1X_2X_3$ = Interaction Effect of factors X_1, X_2 and X_3
Y = Response for the given levels of the main effects X_1, X_2 and X_3
Y_b = Bingham Yield Point
Y_{ij} = Responses for the 1st and 2nd replications
σ = Square Root of Residual Mean Square
Φ_{600} = Rheometer Reading at 600rpm
Φ_{300} = Rheometer Reading at 300rpm

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Tables and Figures

Table 1 – Model or Analysis Matrix for the 2^3 full Factorial Design

RUN	I	X_1	X_2	X_1*X_2	X_3	X_1*X_3	X_2*X_3	$X_1*X_2*X_3$	RESPONSE

NO.									Y
1	+1	-1	-1	+1	-1	+1	+1	-1	
2	+1	+1	-1	-1	-1	-1	+1	+1	
3	+1	-1	+1	-1	-1	+1	-1	+1	
4	+1	+1	+1	+1	-1	-1	-1	-1	
5	+1	-1	-1	+1	+1	-1	-1	+1	
6	+1	+1	-1	-1	+1	+1	-1	-1	
7	+1	-1	+1	-1	+1	-1	+1	-1	
8	+1	+1	+1	+1	+1	+1	+1	+1	

Table 2 - Factor Level Settings

FACTORS	LEVELS		
	LOW (-1)	STANDARD (0)	HIGH (+1)
Temperature (^{o}F)	79.70	127.85	176.00
Starch (g)	5.00	7.50	10.00
Potash (g)	5.00	7.50	10.00

Table 3 – Factor Settings in Randomized Order

RANDOM ORDER	STANDARD ORDER	X1	X2	X3
1	7	-1	+1	+1
2	5	-1	-1	+1
3	2	+1	-1	-1
4	6	+1	-1	+1
5	3	-1	+1	-1
6	4	+1	+1	-1
7	1	-1	-1	-1
8	8	+1	+1	+1

Table 4 – Mud Samples Composition

MUD SAMPLES	BENTONITE (g)	WATER (ml)	STARCH (ml)	POTASH (g)
I	22.50	350.00	5.00	5.00
II	22.50	350.00	5.00	10.00
III	22.50	350.00	10.00	5.00
IV	22.50	350.00	10.00	10.00

Table 5 – Experimental Results

Run No.	Temperature (°F)	Starch (g)	Potash (g)	Fisrt Replication				Second Replication				Average	Average
				Φ_{600}	Φ_{300}	μ_{pI} (cp)	Y_{bI} (lb/100ft^2)	Φ_{600}	Φ_{300}	μ_{pII} (cp)	Y_{bII} (lb/100ft^2)	$\mu_p\ (cp)$	Y_b (lb/100ft^2)
	79.70	5.00	5.00	20.50	16.00	4.50	11.50	20.00	16.00	4.00	12.00	4.25	11.75
2	176.00	5.00	5.00	44.00	34.00	10.00	24.00	43.00	34.00	9.00	25.00	9.50	24.50
3	79.70	10.00	5.00	15.00	10.00	5.00	5.00	15.00	9.50	5.50	4.00	5.25	4.50
4	176.00	10.00	5.00	63.00	43.50	19.50	24.00	63.00	44.00	19.00	25.00	19.25	24.50
5	79.70	5.00	10.00	8.00	4.50	3.50	1.00	7.00	4.50	2.50	2.00	3.00	1.50
6	176.00	5.00	10.00	20.00	13.50	6.50	7.00	20.00	13.00	7.00	6.00	6.75	6.50
7	79.70	10.00	10.00	7.50	4.50	3.00	1.50	7.00	3.50	3.50	0.00	3.25	0.75
8	176.00	10.00	10.00	44.00	30.00	14.00	16.00	43.00	30.00	13.00	17.00	13.50	16.50

Table 6 – Model Matrix for the Plastic Viscosity

RUN NO.	I	X_1	X_2	X_1*X_2	X_3	X_1*X_3	X_2*X_3	$X_1*X_2*X_3$	μ_{pI}	μ_{pII}	Treatment Totals
1	+1	-1	-1	+1	-1	+1	+1	-1	4.50	4.00	8.50
2	+1	+1	-1	-1	-1	-1	+1	+1	10.00	9.00	19.00
3	+1	-1	+1	-1	-1	+1	-1	+1	5.00	5.50	10.50
4	+1	+1	+1	+1	-1	-1	-1	-1	19.50	19.00	38.50
5	+1	-1	-1	+1	+1	-1	-1	+1	3.50	2.50	6.00
6	+1	+1	-1	-1	+1	+1	-1	-1	6.50	7.00	13.50
7	+1	-1	+1	-1	+1	-1	+1	-1	3.00	3.50	6.50
8	+1	+1	+1	+1	+1	+1	+1	+1	14.00	13.00	27.00

Table 7 – Factorial Effects using Yates Algorithm

Run No.	Treatment Totals	1st time	2nd Time	Effect Total 3rd time	Effect Name	Estimated Effect
1	8.50	27.50	76.50	129.50	I	8.094
2	19.00	49.00	53.00	66.50	X_1	8.313
3	10.50	19.50	38.50	35.50	X_2	4.438
4	38.50	33.50	28.00	30.50	X_1X_2	3.813
5	6.00	10.50	21.50	-23.50	X_3	-2.938
6	13.50	28.00	14.00	-10.50	X_1X_3	-1.313
7	6.50	7.50	17.50	-7.5	X_2X_3	-0.938
8	27.00	20.50	13.00	-4.50	$X_1X_2X_3$	-0.563

Table 8 - Factorial Coefficients

Effect Name	Estimated Effect	Coefficient Name	Coefficient Value
I	8.094	β_0	8.094
X_1	8.313	β_1	4.156
X_2	4.438	β_2	2.219
X_1X_2	3.813	β_{12}	1.906
X_3	-2.938	β_3	-1.469
X_1X_3	-1.313	β_{13}	-0.656
X_2X_3	-0.938	β_{23}	-0.469
$X_1X_2X_3$	-0.563	β_{123}	-0.281

Table 9 – Calculations of sums of squares

Contrast = Effect Total	Square of Contrasts $(\text{Contrast})^2$	Sum of squares $SSQ = \frac{(Contrasts)^2}{2^k * r}$
[I] = 129.50	16770.25	1048.141
$[X_1]$ = 66.50	4422.25	276.3906
$[X_2]$ = 35.50	1260.25	78.76563
$[X_1X_2]$ = 30.50	930.25	58.14063
$[X_3]$ = -23.50	552.25	34.51563
$[X_1X_3]$ = -10.50	110.25	6.890625
$[X_2X_3]$ = -7.5	56.25	3.515625
$[X_1X_2X_3]$ = -4.50	20.25	1.265625

Table 10 – ANOVA

Source of variation	Sum of Squares SSQ	Degree of freedom f	Mean Square $S^2 = \frac{SSQ}{f}$	F-Value
X_1 main effect	276.3906	1	276.3906	1040.529
X_2 main effect	78.76563	1	78.76563	296.5294
X_1X_2 interaction effect	58.14063	1	58.14063	218.8824
X_3 main effect	34.51563	1	34.51563	129.9412
X_1X_3 interaction effect	6.890625	1	6.890625	25.94118
X_2X_3 interaction effect	3.515625	1	3.515625	13.23529
$X_1X_2X_3$ interaction effect	1.265625	1	1.265625	4.764706
Residual	2.125	8	0.265625	
Total	461.6094	15		

Table 11 – Experimental results, fitted values from model equation and residuals

RUN NO.	I	X_1	X_2	X_1*X_2	X_3	X_1*X_3	X_2*X_3	$X_1*X_2*X_3$	Experimental Response Y	Fitted Model μ_p	Residuals $\mu_p - Y$
1	1	-1	-1	1	-1	1	1	-1	4.25	4.614	0.364
2	1	1	-1	-1	-1	-1	1	1	9.50	9.864	0.364
3	1	-1	1	-1	-1	1	-1	1	5.25	5.616	0.366
4	1	1	1	1	-1	-1	-1	-1	19.25	19.614	0.364
5	1	-1	-1	1	1	-1	-1	1	3.00	3.364	0.364
6	1	1	-1	-1	1	1	-1	-1	6.75	7.114	0.364
7	1	-1	1	-1	1	-1	1	-1	3.25	3.614	0.364
8	1	1	1	1	1	1	1	1	13.5	13.864	0.364

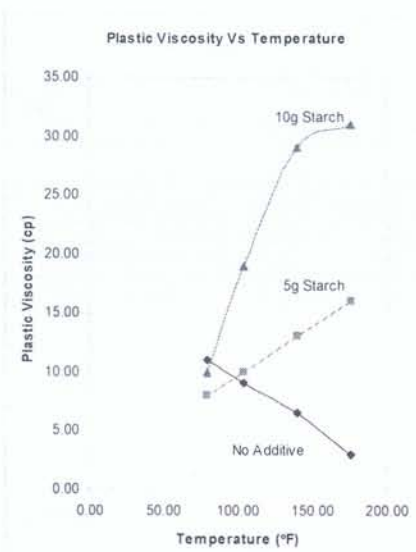

Fig. 1 – Effect of Starch on a mud viscosity

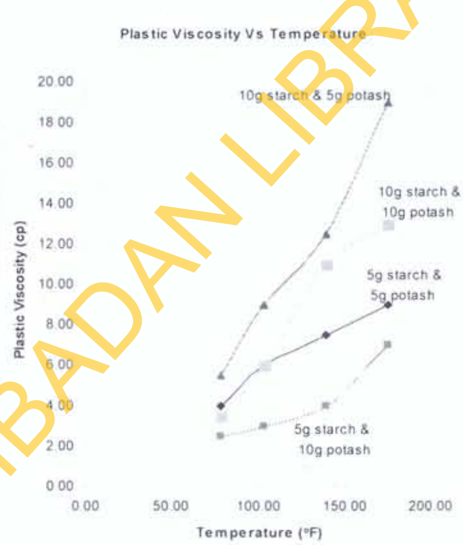

Fig. 2 – Effect of Potash on a mud viscosity

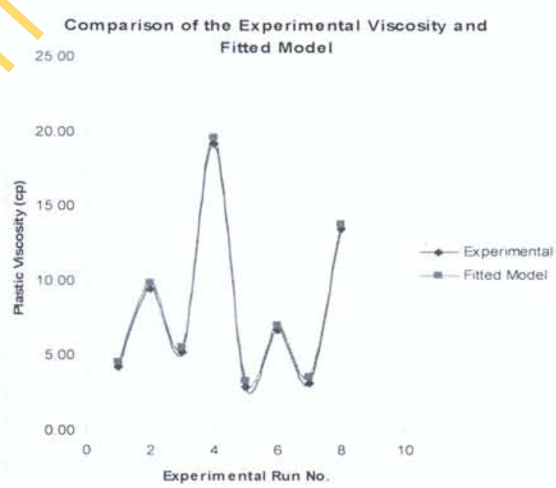

Fig. 3 - Comparison of Experimental Response and Fitted Model