Lightweight biopolymer drilling fluid for underbalanced drilling: An optimization study

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ABSTRACT

This paper presents an optimization of a lightweight biopolymer drilling fluid for underbalanced drilling (UBD) using Response Surface Methodology (RSM). Concentrations of four raw materials (glass bubbles, clay, xanthan gum and starch) were varied to analyze their effects on three vital responses: density, plastic viscosity (PV) and yield point (YP) of the fluid. Based on the results, the optimum condition was achieved at concentrations of glass bubbles, clay, xanthan gum and starch of 24.46% w/v, 0.63% w/v, 0.21% w/v and 2.41% w/v, respectively. The results showed that it is possible to predict the three response parameters using models generated by RSM since the experimental values were found to be in good agreement with the predicted values (error < 1.0, standard deviation < 0.5 and accuracy > 98.5%).

1. Introduction

Underbalanced drilling (UBD) is a drilling technique where the pressure inside the wellbore is maintained to be lower than reservoir pressure while drilling (Garrouch and Lababidi, 2001; Wong and Arco, 2003). UBD is applied in under-pressured or depleted reservoirs to prevent lost circulation and stuck pipe which occurs during conventional overbalanced drilling (Kutlu, 2013; Marbun et al., 2012; Rafique, 2008). This makes UBD a suitable choice when drilling in formations that are sensitive to rock–fluid or fluid–fluid interactions to prevent permeability damage. UBD is also used in formations with consolidated sands of high permeability. Furthermore, it is also known that UBD could increase the rate of penetration (ROP) by up to 10 times of the conventional drilling process. It plays an important role to reduce formation damage in horizontal drilling as the drilling fluid is prevented from flowing into the target formation (Arco et al., 2000; Marbun et al., 2012; Rafique, 2008). High pressure losses due to decrease in flow area of the annulus caused by drill cuttings settling out from the drilling fluid by gravitational force could be reduced during UBD in a horizontal well (Kutlu, 2013).

Lightweight fluids may be used in drilling using UBD technique. The density of the drilling fluid is intentionally reduced to ensure the hydrostatic pressure in the wellbore to be lower than the pore pressure of the target formation (Babajan and Qutob, 2010). Hence, drilling fluids with densities below 6.9 lb/gal, which usually contains air or gas including foam, mist and aerated muds, are suitable for UBD (Arco et al., 2000; Medley et al., 1995; Rafique, 2008). In the past, air drilling was used due to the realization of the advantages in using UBD for drilling a reservoir. These advantages include increased ROP, faster drill cuttings removal from under the drill bit, improved bit life, prevention of lost circulation, reduction of differential sticking and most importantly, formation damage reduction (Caenn and Chillingar, 1996). However, numerous problems arise because air drilling may increase drilling cost, cause drill string corrosion, lead to risk of fires and explosions, cause serious drill string vibrations, excessive drag and torque, require special equipments, post additional works, etc. (Arco et al., 2000; Khalil and Badrul, 2012a, 2012b; Kutlu, 2013; McDonald et al., 1998; Medley et al., 1995; Wong and Arco, 2003).

Moreover, new drilling fluid systems have also been developed to substitute toxic chemicals and non-biodegradable substances due to environmental restrictions (Caenn and Chillingar, 1996). It is reported that the usage of diesel as base fluids in drilling has been reduced because environmental regulations consider diesel as harmful to the environment (Galate and Mitchell, 1986; Khalil and Badrul, 2012a, 2012b). Non-toxic and biodegradable oil based muds from edible vegetable grade oils and plant seed oil are being developed as alternatives. Studies have shown that the use of more water makes the drilling fluid less costly as it reduces the formulation costs

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(Apaleke et al., 2012). It is a challenge to reduce the oil/water ratio in vegetable and seed oil fluids due to stability issue of the formulated drilling fluid and its relatively high viscosity values (Apaleke et al., 2012). In addition, industries have not been able to reduce the oil/water ratio beyond 85/15 (Apaleke et al., 2012). Therefore, water-based drilling fluids are still the preferred choice. As such, this research focused on the development of a water-based drilling fluid that is lightweight for UBD application. This drilling fluid can have low density even without the use of gas or air. Since pneumatic drilling fluids may experience many problems, therefore, by incorporating glass bubbles into this fluid formulation, the fluid can be kept lightweight and suitable for UBD. In addition, most water-based drilling fluids formulated with glass bubbles are incompressible which can reduce several limitations of aerated fluids, while retaining the advantages of UBD technique (Wong and Arco, 2003). Recent research by Kutlu (2013) and Kutlu et al. (2014) investigated on lightweight drilling fluids, which incorporated glass bubbles. Kutlu (2013) used a modified version of Einstein's relative viscosity model to predict the rheological behaviour of the water-based drilling fluids. Lightweight drilling fluids were also developed for coalbed methane application to reduce pollution (Zuo et al., 2012). The application of glass bubbles in different types of drilling fluids has been successfully tested in the field by many researchers (Arco et al., 2000; McDonald et al., 1998; Medley et al., 1997; Wong and Arco, 2003; Zuo et al., 2012). In addition, the used glass bubbles could also be recycled and reuse which further reduce drilling cost (McDonald et al., 1998; Medley et al., 1995; Wong and Arco, 2003).

Furthermore, many types of polymers have also been used for various applications in the oilfield such as in drilling operations, polymer-augmented water flooding, chemical flooding and profile modification (Taylor and Nasr-El-Din, 1998). However, the use of partially hydrolyzed polyacrylamide (HPAM) by some researchers in lightweight drilling fluids (Medley et al., 1995) is found to have many disadvantages. HPAM is toxic to the environment as it remains in the produced water of oilfields, making oil–water separation more difficult. It is also observed that groundwater may also be contaminated with HPAM during drilling, as residual HPAM in wastewater tends to slowly degrade into the toxic acrylamide monomer naturally. Costs of water treatment will increase due to these factors (Bao et al., 2010; Khalil and Badrul, 2012a). Since HPAM has many disadvantages in its use, natural polymers are often preferred. For instance, an exocellular biopolymer, xanthan gum, which is secreted by *Xanthomonas* sp. (Casas et al., 2000). It is reported that solutions of xanthan gum exhibits thickening properties with a pseudoplastic behavior (Casas et al., 2000) which is very stable in a wide range of pH, pK (ionic concentration) and temperature. Therefore, it could be used as a thickener to stabilize suspensions and emulsions in many industries such as in the upstream oil and gas industry (Casas et al., 2000; Khalil and Badrul, 2012a, 2012b). Furthermore, another type of natural biopolymer that is frequently used in drilling fluid formulations is starch, which is a polymer made up of glucose molecules in two different forms; amylose and amylopectin linked together. Both xanthan gum and starch are used for polymer flooding and oil displacement process in EOR to improve production of oil. In drilling fluids, they are usually used as rheological control agents in aqueous systems and also in fluid loss control (Khalil and Badrul, 2012a). In recent studies, a novel lightweight biopolymer drilling fluid was developed based on these two biopolymers (Khalil and Badrul, 2012a, 2012b). The study involved investigating the effects of the concentrations of starting materials on the drilling fluid rheological properties and its viscoplastic behavior (Khalil and Badrul, 2012a, 2012b). Then, additional work was carried out to determine the effects of the starting materials concentrations on the density, plastic viscosity and yield point of this drilling fluid formulation (Lim et al., 2014). This information is deemed important to mud engineers when selecting the right drilling fluid and equipment for a myriad of field conditions.

As a continuation from our previous studies (Khalil and Badrul, 2012a, 2012b; Lim et al., 2014), this paper presents a study on the application of RSM in the optimization of the formulation of a lightweight biopolymer water-based drilling fluid. RSM was applied to fit and to exploit mathematical models that represent the relationship between the responses (i.e. density, plastic viscosity and yield point) and variables (i.e. glass bubbles, clay, xanthan gum and starch concentrations). The objective of this study is to optimize the formulation of the fluid composition (i.e. glass bubbles, clay, xanthan gum and starch concentrations), to achieve the best formulation condition in formulating the lightweight biopolymer drilling fluid with the lowest possible density achievable and acceptable viscosity and yield point. The typical range of acceptable plastic viscosity for clay/water muds are approximately 5 to 50 cP for low range and 12 to 70 cP for high range (Bourgoyne et al., 1991).

2. Materials and methods

2.1. Raw materials

The lightweight biopolymer drilling fluid contains two biopolymers, namely xanthan gum from Sigma-Aldrich and starch from SYSTERM®. Glass bubbles (3M Scotchlite hollow-glass spheres (HGS), [3M, St. Paul, Minnesota, USA] rating of 4000 psi) were added as density reducing agent. Clay (Wyoming, USA) was used to enhance fluid rheological properties. Sodium chloride (NaCl) purchased from R&M Chemicals was used as an additive. A bactericide from Sigma-Aldrich was added to protect the biopolymers against parasites.

2.2. Lightweight biopolymer drilling fluid formulation

To formulate the fluid, xanthan gum, starch, glass bubbles, clay, sodium chloride and a bactericide were mixed in distilled water using the IKA RW20 digital mixer at 500 rpm. To optimize the drilling fluid formulation, the concentrations of starting materials were varied while the concentrations of sodium chloride and bactericide were maintained constant.

2.3. Density and rheological measurements

The optimized drilling fluid should have the lowest possible density and acceptable plastic viscosity (PV) and yield point (YP). In this study, all the measurements were taken at ambient temperature and pressure. Density measurements were taken using a 25 ml pycnometer at ambient conditions. A rotational viscometer (Haake Viscotester Model VT550, with repeatability and accuracy: ±1%, comparability: ±2%) equipped with MV2P spindle was used to measure the respective shear stress values in correspondence to various applied shear rates. The applied shear rates ranges from 2.639 to 528 s^{-1} for all samples except for a fluid sample with 10% w/v clay and another with 1% w/v xanthan gum where the applied shear rate was only up to 264 s^{-1}. The rheological parameters (PV and YP) were calculated based on the Bingham-plastic model. The

Table 1
Summary of experimental domain of central composite design (CCD).

Variables		Factor levels				
Code	Name	−2	−1	0	1	2
A	Glass bubbles concentration (% w/v)	10	15	20	25	30
B	Clay concentration (% w/v)	0.5	1.75	3.0	4.25	5.5
C	Xanthan gum concentration (% w/v)	0.1	0.2	0.3	0.4	0.5
D	Starch concentration (% w/v)	0.5	1	1.5	2	2.5

relationship between shear stress and shear rate are represented by the Bingham model in Eq. (1):

$$\tau = \tau_0 + \mu_0 \gamma \tag{1}$$

where τ is the shear stress, τ_0 is the yield point, μ_0 is the plastic viscosity and γ is the shear rate. The Bingham-plastic model is one of the conventional rheological models widely used for drilling fluids (Maxey, 2007; Vipulanandan and Mohammed, 2014). This model can determine the yield point exhibited by most drilling fluids and cement slurries to predict the minimum force needed for the fluid to start flowing (Vipulanandan and Mohammed, 2014; William et al., 2014). This value is referred to as the Bingham yield point, τ_0 (Khalil and Badrul, 2012b; Khalil et al., 2011). It is also more suitable to describe fluid rheology at high shear rates (Baumert et al., 2005; William et al., 2014). However, it does not function so well at low shear rates; giving overly high values of the yield point (Baumert et al., 2005). Like most models, it also does not represent the limit on the maximum shear stress of drilling fluids (Vipulanandan and Mohammed, 2014).

Table 2
Range of independent variables experimental runs by CCD.

Run	Factors			
	A	*B*	*C*	*D*
1	15.00	1.75	0.40	1.00
2	20.00	3.00	0.30	1.50
3	20.00	3.00	0.30	1.50
4	20.00	3.00	0.10	1.50
5	25.00	1.75	0.20	2.00
6	20.00	3.00	0.30	1.50
7	15.00	4.25	0.40	2.00
8	25.00	4.25	0.40	1.00
9	25.00	1.75	0.40	2.00
10	20.00	3.00	0.50	1.50
11	20.00	3.00	0.30	1.50
12	25.00	4.25	0.20	1.00
13	20.00	3.00	0.30	2.50
14	20.00	0.50	0.30	1.50
15	30.00	3.00	0.30	1.50
16	20.00	3.00	0.30	1.50
17	20.00	5.50	0.30	1.50
18	15.00	4.25	0.20	2.00
19	10.00	3.00	0.30	1.50
20	20.00	3.00	0.30	0.50
21	15.00	1.75	0.20	1.00

A: Glass bubbles concentration, *B*: Clay concentration, *C*: Xanthan gum concentration, *D*: Starch concentration.

Table 3
CCD of the independent variables and responses parameters.

Run	Factors				Responses		
	A	*B*	*C*	*D*	Density (lb/gal)	PV (cP)	YP (Pa)
1	15.00	1.75	0.40	1.00	7.0534	58.8	9.8265
2	20.00	3.00	0.30	1.50	6.7876	70.7	10.2148
3	20.00	3.00	0.30	1.50	6.7839	70.8	10.3247
4	20.00	3.00	0.10	1.50	6.7798	62.2	2.8124
5	25.00	1.75	0.20	2.00	6.4618	75.8	6.3041
6	20.00	3.00	0.30	1.50	6.7876	70.7	10.5728
7	15.00	4.25	0.40	2.00	7.2075	65.4	12.4862
8	25.00	4.25	0.40	1.00	6.5587	95.9	24.1190
9	25.00	1.75	0.40	2.00	6.4743	110.6	18.3668
10	20.00	3.00	0.50	1.50	6.7965	95.1	22.2386
11	20.00	3.00	0.30	1.50	6.7869	70.5	10.0034
12	25.00	4.25	0.20	1.00	6.5338	80.9	10.4125
13	20.00	3.00	0.30	2.50	6.8088	81.1	10.4246
14	20.00	0.50	0.30	1.50	6.7123	68.4	7.1171
15	30.00	3.00	0.30	1.50	6.2658	120.0	18.3536
16	20.00	3.00	0.30	1.50	6.7866	70.7	10.3036
17	20.00	5.50	0.30	1.50	6.8746	73.1	14.2923
18	15.00	4.25	0.20	2.00	7.1816	53.7	5.1994
19	10.00	3.00	0.30	1.50	7.5402	38.5	5.3068
20	20.00	3.00	0.30	0.50	6.7787	69.8	9.5908
21	15.00	1.75	0.20	1.00	7.0726	53.1	2.7580

2.4. Experimental design and data analysis

The software used for the statistical design of experiments and data analysis was the Design Expert software (Version 8.0, Stat-Ease Inc., Minneapolis, USA). Central Composite Design (CCD) was employed to generate mathematical models that can be used to describe the relationship between the responses (i.e. density, PV and YP) and variables (i.e. glass bubbles, clay, xanthan gum and starch concentrations). Table 1 presents the range and center point values of four independent variables.

In this study, the experimental design consists of eight factorial points, eight axial points at a distance of ± 2 from the center and five replicates of the center point. The four variables were set at five levels which are -1, $+1$, 0, $-\alpha$ and $+\alpha$. Table 2 presents the combination of the independent variables experimental runs of the CCD analysis. To minimize the effect of unexpected variability in the observed responses, all experimental runs in this study were carried out in random arrangement.

The Analysis of Variance (ANOVA) was used in the statistical diagnostic checking test which is able to evaluate the adequacy of the generated model. To check the quality of the generated polynomial models, the R^2 value was determined and its statistical

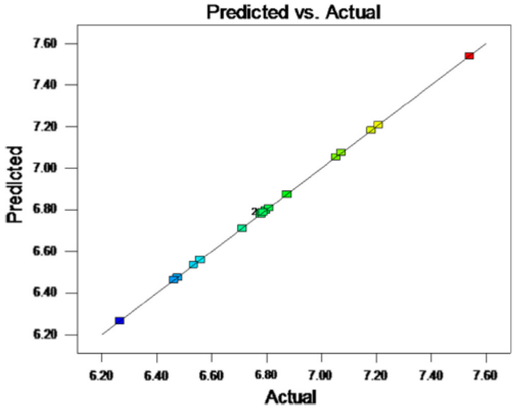

Fig. 1. Predicted versus actual values plot from Design Expert for the drilling fluid density.

Table 4
Analysis of variance (ANOVA) results for first response (density).

Response	*F*-value	*P*	R^2	Adj. R^2	AP	SD	PRESS
Density (Y_1)	26055.62	< 0.0001	1.0000	0.9999	709.958	2.124×10^{-3}	1.646×10^{-3}

P: probability of error; AP: adequate precision; SD: standard deviation; PRESS: predicted residual error sum of squares.

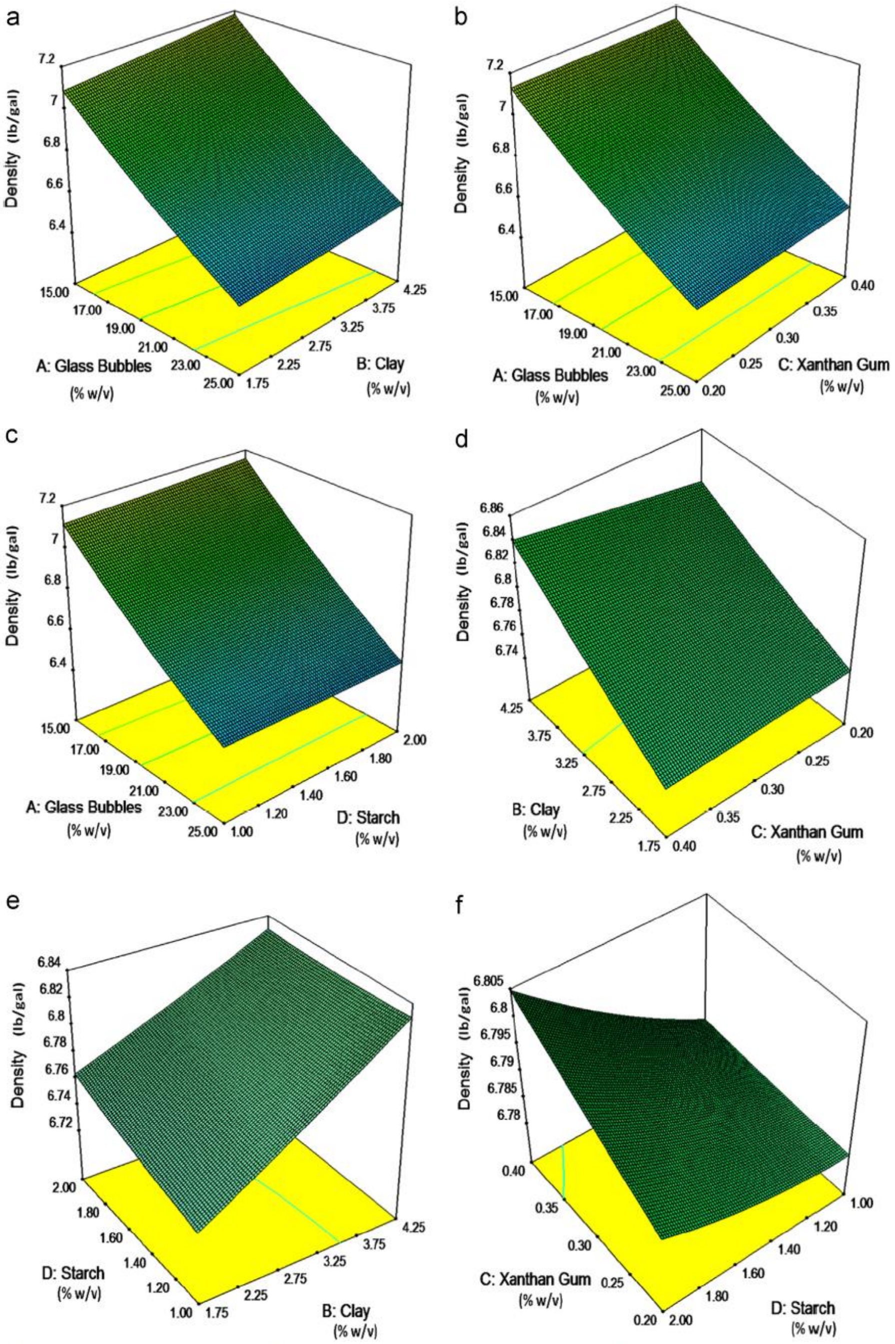

Fig. 2. 3D response surface plot from Design Expert for density versus (a) A and B, (b) A and C, (c) A and D, (d) B and C, (e) B and D, (f) C and D.

Table 5
Analysis of variance (ANOVA) results for the second response (plastic viscosity).

Response	*F*-value	*P*	R^2	Adj. R^2	AP	SD	PRESS
PV (Y_2)	35441.19	< 0.0001	1.0000	1.0000	851.961	9.705×10^{-5}	2.948×10^{-6}

P: probability of error; AP: adequate precision; SD: standard deviation; PRESS: predicted residual error sum of squares.

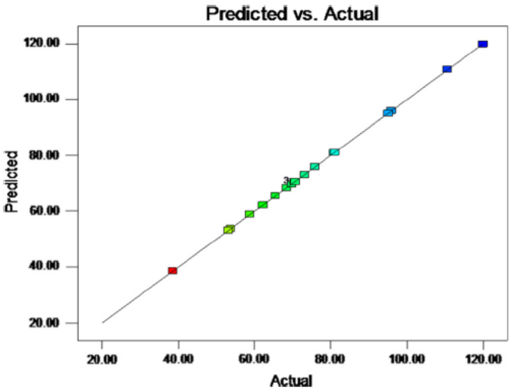

Fig. 3. Predicted versus actual values plot from Design Expert for the drilling fluid plastic viscosity.

significance was determined by the Fisher's *F*-test using the similar program. In addition, *P*-value (probability of error) with 95% confidence level was also used to evaluate the model terms. Furthermore, three-dimensional plots and their respective contour plots were also investigated to determine the optimum condition.

2.5. *Validation of experiment*

To validate the mathematical models generated by the software in the statistical analysis, test experiments were conducted in the laboratory based on the generated optimal setting from RSM. After the experiment, the error and accuracy between the predicted and experimental values were calculated.

3. Results and discussion

3.1. *Statistical analysis (ANOVA) and process analysis*

In this study, RSM was used to investigate the relationship between the four independent variables (i.e. concentrations of glass bubbles, clay, xanthan gum and starch) and the three responses (i.e. density, PV and YP), which depend on the variables to obtain various mathematical models that represent these correlations. The CCD design in RSM, predicted and generated mathematical models for each of the responses. The results are presented in Table 3. These results were used to assess the predicted responses for density, PV and YP as a function of glass bubbles, clay, xanthan gum and starch concentration.

3.1.1. *Density*

Experimental results for the first response (density) were fitted into the equation by the Analysis of Variance (ANOVA). The best equation that fits the results was quadratic in nature. ANOVA was used to assess the "goodness of fit" of the model obtained. The best fitted quadratic model for density (Y_1) in terms of coded factors are represented by Eq. (2):

$$\begin{aligned} Y_1 = {} & 6.79 - 0.32A + 0.041B + 4.844 \times 10^{-3}C + 7.525 \times 10^{-3}D \\ & - 5.813 \times 10^{-3}AB + 3.837 \times 10^{-3}AC - 0.012AD + 7.187 \times 10^{-3}BC \\ & - 7.787 \times 10^{-3}BD + 4.088 \times 10^{-3}CD + 0.029A^2 + 1.529 \times 10^{-3}B^2 \\ & + 2.044 \times 10^{-4}C^2 + 1.604 \times 10^{-3}D^2 \end{aligned} \tag{2}$$

where *A* represents glass bubbles concentration; *B* represents clay concentration; *C* represents xanthan gum concentration and *D* represents starch concentration.

The results of ANOVA for the response surface quadratic model were shown in Table 4. The Model *F*-value given by ANOVA was 26055.62, which imply that the model is significant and has only a 0.01% chance to occur due to noise. The data presented in Table 4 depicts that the mathematical model is significant at the 5% confidence level since the value of Probability of Error (*P*) is far lesser than 0.05. According to Noordin et al. (2004), high R^2 value, close to 1 is desirable and having a reasonable agreement with the adjusted R^2 value is necessary. High R^2 value indicates a satisfactory adjustment of the quadratic model to the experimental data (Ahmad et al., 2009; Ghafari et al., 2009). Based on the results, the high calculated R^2 value of 1.0000 for this response as illustrated in Table 4, showed that the quadratic model is able to fit perfectly the variability of the responses obtained from the experimental data. The adjusted R^2 value of 0.9999 is very close and in good agreement with R^2. The Lack of Fit *F*-value of 3.79 implies that it is not significant relative to the pure error. A non-significant lack of fit is considered good as it shows that the model fits. A lack of fit value this large needs 11.93% chance to occur due to noise.

Furthermore, from the ANOVA results, it is also possible to measure the signal to noise ratio of the experimental data by analyzing the adequate precision (AP). AP value compares the range of the predicted value at the design points (Ghafari et al., 2009; Khalil et al., 2010). A ratio greater than 4 is desired and indicates model discrimination which means the model can be used to navigate the design space (Beg et al., 2003). Based on the results in Table 4, the response for density gave a very high AP value of 709.958 (greater than 4). This showed that the predicted model could be used to navigate the design space defined by the CCD. To support these results, a diagnostic plot between the predicted and actual values can also be used to justify the model satisfactoriness. Fig. 1 illustrates the diagnostic plot of the predicted versus actual values for density. This graph shows that the actual values for this response were in an adequate agreement with the ones obtained from the model (predicted values). This is a comparison between actual experimental results and the estimated values from regression models, which will show the reliability and adequacy of the empirical models from the responses, respectively. The meaning of this plot lies in the position of the points. Points that are above the diagonal line indicate that the values were over-estimated while those below were under-estimated (Ahmad et al., 2009). It was observed in Fig. 1 that the points mostly lie along the line which shows that the model gives a very good estimation of the predicted values. The predicted values are close to the actual experimental values.

Furthermore, Fig. 2 shows the relationship between density, as a function of glass bubbles, clay, xanthan gum and starch concentrations. Based on the figures, density of the drilling fluid decrease with the addition of glass bubbles. However, it tends to increase

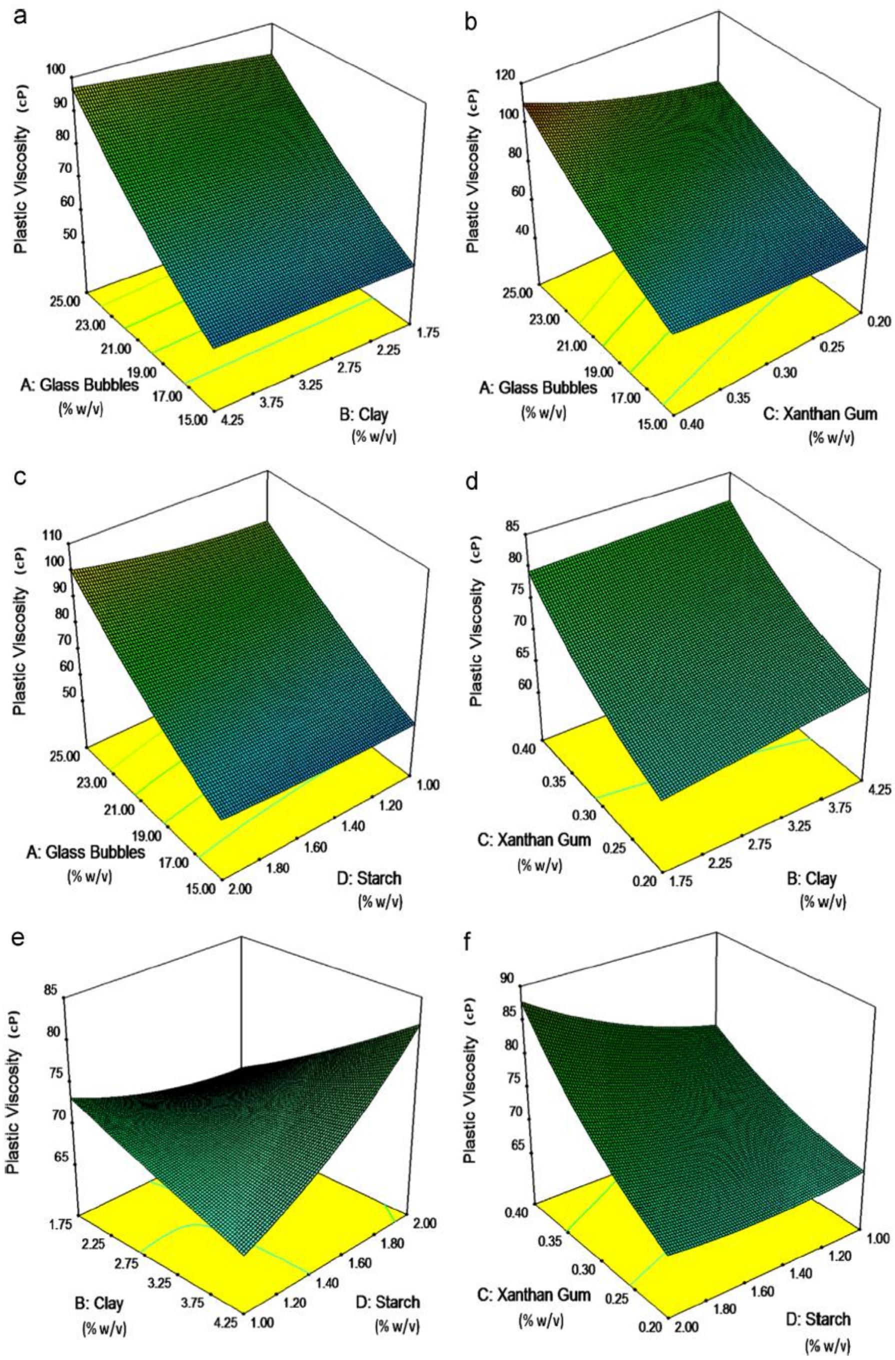

Fig. 4. 3D response surface plot from Design Expert for plastic viscosity versus (a) A and B, (b) A and C, (c) A and D, (d) B and C, (e) B and D, (f) C and D.

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