Effect of Mud Additives Formula on Rheological Properties of Eco-Friendly Water-Based Mud Used in Fang Oilfield, Thailand

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Abstract

Water-based mud (WBM) is a more environmentally friendly drilling fluid than oil-based mud (OBM), and is commonly used in underground oil and gas wells to avoid serious environmental consequences. However, the effective use of WBM requires the addition of mud additives to adjust its rheological properties to specific drilling conditions. This study aims to assess the impact of mud additive formulations on the key rheological properties of WBM utilized in the Fang oilfield, situated in the onshore northern region of Thailand. Initially, WBM was prepared by blending various concentrations of eco-friendly mud additives, such as Xanthan gum (XG), Carboxymethyl cellulose (CMC), and Dextrinized Starch, along with 3 wt% KCl to prevent clay swelling in shaly sand formations. Subsequently, different WBM formulas were tested using a FANN Model 50SL Rheometer to analyze essential rheological properties including plastic viscosity (μ_p) and yield point (τ_y) for the Bingham Plastic model, as well as flow consistency index (K) and flow behavior index (n) for the Power-law model. Furthermore, the mud filtrate loss of WBM samples was measured using a FANN Series 300 API Filter Press. The experimental results demonstrated that the WBM with an equivalent density of 10-ppg, which is composed of 20-lb/bbl (ppb) Bentonite, 40-ppb Barite, 0.50-ppb Xanthan gum, 0.50-ppb CMC, and 6-ppb starch, exhibited minimum mud filtrate loss of 7.6 mL after 30 minutes. Additionally, the plastic viscosity of this mud formula was 25.7-cP, and the yield point was 24.31-lb per 100 ft^2, both falling within the recommended range for KCl-polymer WBM. Consequently, the study's findings are anticipated to recommend an optimized formula of WBM additives for the use in onshore drilling operations within normally-pressured reservoirs.

Keywords: *Fang oilfield, water-based mud additives, rheological properties, mud filtrate, eco-friendly*

1. Introduction

Drilling fluid, or drilling mud, plays a crucial role in drilling operations due to its various functions including the transportation and removal of cuttings from well formations, cooling and lubrication of the drill bits, supporting wellbore strength and stability, and preventing the influx of formations into the well [1, 2]. Among the types of drilling fluids, Water-Based Mud (WBM) is preferred over Oil-Based Mud (OBM) for its environmental friendliness, especially in underground oil and gas wells where the risk of environmental consequence is significant [2]. However, to enhance the efficiency and safety of drilling operations, the rheological properties of WBM need to be adjusted by adding specific mud additives. These additives include agents for adjusting weight or density, viscosifiers, and filtration control agents, each selected based on varying drilling conditions [1]. Notably, Xanthan Gum (XG) and Carboxymethyl Cellulose (CMC) are considered eco-friendly additives because they are renewable, biodegradable, and environmentally safe [3].

The Fang oilfield, located in the Fang basin within Chiang Mai province in Thailand, is an onshore oilfield lying in the country's smallest intermontane basin, which spans about 600 km². The basin is surrounded by ancient rock formations from the Cambrian and Oligocene periods and is broadly elongated from northeast to southwest. The primary reservoirs in the Fang basin are composed of interbedded shale and sandstones, with significant hydrocarbon production deriving from a sand member featuring layers ranging in thickness from 1.52 to 13.71 meters. These layers exist at depths from about 658 to 687 meters and also from 727 to 758 meters, making them critical to the oilfield's output [4]. Previous studies in this area have determined that the standard pore pressure gradient of 0.494 psi/ft is recommended to design the drilling mud weight, leading to a required mud weight of over 9.50 ppg [5]. Consequently, the optimal density range for WBM used in this oilfield is between 10-11 ppg, with a safety margin of 0.5-1.5 ppg to minimize fluid loss and mitigate formation damage due to excessive overbalance pressure [6, 7]. Therefore, this study aims to evaluate the impact of eco-friendly mud additive formulations on the key rheological properties of

WBM used in the Fang oilfield, located in Thailand's northern onshore region. The goal is to propose an optimal additive formula for safe and effective drilling operations in normally-pressured onshore wells.

2. Materials and Methods

2.1 Raw Material

Each water-based mud formula for the experiment was prepared in the laboratory by mixing various chemicals using a magnetic stirrer. This was done at a constant speed of 1200 rpm for approximately 20 minutes at a temperature of 50°C, until a homogeneous phase was observed. The base composition of all WBM formulas included 20 ppb (pounds per barrel) Bentonite, 40 ppb Barite, and 3 wt% KCl, based on field data sourced from the Fang oilfield. This composition is expected to achieve a mud weight of approximately 10 ppg (pounds per gallon). Following the base mixture, additional chemicals such as Xanthan gum, CMC (Carboxymethyl Cellulose), and Dextrinized Starch were supplemented. The specific compositions of the different WBM formulas used in the experiments are detailed in Table 1.

Tab. 1. Compositions of different WBM formulas used in the experiments.

Formula no.	Composition (lb/bbl)				
	Bentonite	**Barite**	**Xanthan gum**	**CMC**	**Starch**
1	20	40	-	-	-
2	20	40	0.25	-	-
3	20	40	0.50	-	-
4	20	40	1.00	-	-
5	20	40	0.25	0.5	-
6	20	40	0.25	1.0	-
7	20	40	0.50	0.5	-
8	20	40	0.50	1.0	-
9	20	40	1.00	0.5	-
10	20	40	1.00	1.0	-
11					2
12	Optimal Drilling Mud Formulation from Formula no. 1-10				4
13					6

2.2 Rheological Properties Measurement

The rheological properties of each WBM sample were measured at a standard temperature of 30°C using a FANN Model 50SL Rheometer, as illustrated in Figure 1. This equipment enabled the analysis of the relationship between shear stress (τ) and shear rate through a rotational viscometer, facilitating the characterization of rheological phenomena. For the tests, a 52 mL mud sample was placed into a sample cup, which was attached to a rotating bob. Adjustments to the shear rate were made via the Control Interface program connected to a PC. Additionally, to simulate reservoir conditions and examine their impact on rheological properties, the temperature for tests on mud formula no. 11-13 was increased to 65°C, with a corresponding pressure increase to 1000 psig. Equations (1) – (6) were utilized to calculate key rheological parameters, including plastic viscosity (μ_p) and yield point (τ_y) for the Bingham Plastic model, as well as the flow consistency index (K) and flow behavior index (n) for the Power-law model [2, 8]:

$$\mu_p = \theta_{600} - \theta_{300} \tag{1}$$

$$\tau_y = \theta_{300} - \mu_p \tag{2}$$

$$n = 3.322 \log\left(\frac{\theta_{600}}{\theta_{300}}\right) \tag{3}$$

$$K = 510 \frac{\theta_{300}}{511^n} \tag{4}$$

$$\tau = \frac{k\theta}{2\pi r^2 h} \tag{5}$$

where μ_p is plastic viscosity, θ_{600} is dial reading at 600 rpm, θ_{300} is dial reading at 300 rpm, τ_y is yield point, n is flow behavior index, K is flow consistency index, τ is the measured shear stress, k is spring constant, r is bob radius, and h is height of bob.

From the specifications of FANN Model 50SL Rheometer, Eq. (5) could be simplified into Eq. (6):

$$\tau = 0.6996\theta \tag{6}$$

Fig. 1. Photograph of Rheometer used in this study.

2.3 Mud Filtration Measurement

The analysis of mud filtration properties was conducted using a FANN Series 300 API Filter Press. Each WBM sample was placed in a metallic cylinder within the filter press. A hydraulic pressure of 100 psig was then applied to the sample via the inlet line using a dead weight assembly, as depicted in Figure 2. The volume of mud filtrate that accumulated in the graduated cylinder at the outlet was recorded. This volume represented the fluid loss and was measured over a duration of 30 minutes at room temperature. After the completion of the 30-minute filtration test, the thickness of the filter cake that had formed on the filter paper was measured. In accordance with API Recommended Practice 13B-1, the particle retention of the filter paper used was 2.7 μm [9].

Fig. 2. Photograph of Filter Press used in this study.

2.4 Rheological Model Fitting

Shear stress measurements, expressed in $lb_f/100\ ft^2$, were plotted against shear rate (in s^{-1}) for WBM formulas numbered 11-13 because these formulas incorporated all the specified mud additives during preparation. After plotting the data, the slope and intercept of the graph were used to define the parameters of rheological models, specifically the Bingham Plastic and Power Law models. The best fit was achieved by fitting the experimental results to these models and assessing the fit quality through regression coefficients using least squares error (R^2). The Power Law model was modified to show a linear relationship between shear stress and shear rate, denoted as Equation (7). Similarly, the Bingham Plastic model also describes this linear relationship, presented as Equation (8):

$$\log \tau = n \log \dot{\gamma} + \log K \tag{7}$$

$$\tau = \mu_p \dot{\gamma} + \tau_y \tag{8}$$

3. Results and discussion

3.1 Rheological Properties Measurement

This study observed the functional roles of various additives in WBM formulations. Carboxymethyl cellulose (CMC) acts primarily as a viscosifier [10], whereas starch serves as a filtration control agent [11]. Xanthan gum (XG) on the other hand, exhibits dual functionalities by both increasing viscosity and controlling mud filtrate loss. The effectiveness of XG is highlighted by its viscosity, which is nearly eight times higher than that of CMC at the same concentration. Additionally, mud formulated with XG results in only 50% of the filtrate loss observed with CMC-based mud [1]. The rheological properties of different WBM formulas have been quantitatively assessed using a FANN Model 50SL Rheometer, with the results presented in Table 2.

Tab. 2. Rheological properties of different WBM formulas at temperature of 30ºC.

Formula no.	Mud weight (ppg)	θ_{600}	θ_{300}	μ_p (cP)	τ_y (lbf/100 ft²)	n	K (eq. cP)	$\frac{\tau_y}{\mu_p}$
1	10.017	-0.53	-2.14	1.62	-3.76	-2.02	-3.22E8	-2.33
2	9.754	5.29	0.87	4.42	-3.55	2.60	4.02E-5	-0.80
3	9.903	20.02	12.87	7.15	5.72	0.64	123.2	0.80
4	9.994	41.47	31.46	10.01	21.45	0.40	1,336	2.14
5	9.918	45.76	28.60	17.16	11.44	0.68	212.5	0.67
6	9.967	95.81	67.21	28.60	38.61	0.51	1,411	1.35
7	9.976	67.21	41.47	25.74	15.73	0.70	274.5	0.61
8	9.787	97.24	67.21	30.03	37.18	0.53	1,235	1.24
9	9.988	80.08	60.06	20.02	40.04	0.42	2,302	2.0
10	9.902	130.13	97.24	32.89	64.35	0.42	3,605	1.96
11	10.004	27.17	17.16	10.01	7.15	0.66	140.1	0.71
12	10.266	52.91	34.32	18.59	15.73	0.62	356.2	0.85
13	10.007	75.79	50.05	25.74	24.31	0.60	610.3	0.94

When comparing WBM formulas number 2 and 4, the plastic viscosity increased by approximately 126%, from 4.4 to 10.0 cP, as Xanthan Gum (XG) concentration rose from 0.25 to 1.0 lb/bbl without Carboxymethyl Cellulose (CMC). Similarly, a comparison between WBM formula numbers 2 and 5 showed a more significant increase: the plastic viscosity surged by about 288%, from 4.4 to 17.2 cP, when CMC concentration was raised from 0 to 0.5 lb/bbl with a constant XG concentration of 0.25 lb/bbl. These observations suggest that combining XG and CMC in the mud formula is essential to increase the viscosity significantly.

According to the Recommended Practice for Field Testing Water-based Drilling Fluids (API RP 13-B1), the required plastic viscosity (μ_p) should range from 25–40 cP, and the yield point (τ_y) should be between 15–45 lbf/100 ft². Formula number 7, which utilized medium concentrations of XG and CMC, met these API RP 13-B1 requirements with the minimal addition of mud additives and was therefore selected as the base formula for subsequent modifications, including starch concentration variations. Furthermore, the ratio of the yield point to the plastic viscosity (τ_y / μ_p) can serve as an indicator of the drilling mud's carrying capacity, with a recommended ratio of 0.75 or higher [12, 13]. Based on experimental results, a minimum starch concentration of 6 lb/bbl is necessary in WBM additives to satisfy all specified criteria and standards.

Tab. 3. Rheological properties of different WBM formulas at temperature of 65ºC.

Formula no.	θ_{600}	θ_{300}	μ_p (cP)	τ_y (lbf/100 ft²)	n	K (eq. cP)	$\frac{\tau_y}{\mu_p}$
11	18.59	11.44	7.15	4.29	0.70	73.9	0.60
12	38.61	25.74	12.87	12.87	0.58	341.8	1.00
13	55.77	38.61	17.16	21.45	0.53	720.1	1.25

To study the impact of temperature on the rheological properties of water-based mud (WBM) formulas, the test temperature was adjusted to 65°C for formulas numbered 11-13. The experimental results, detailing these rheological properties for various WBM formulas, are presented in Table 3. It was found that key properties such as θ_{600}, θ_{300}, plastic viscosity (μ_p) and yield point (τ_y) decreased with an increase in temperature. This decrease, indicative of shear-thinning behavior, can be attributed to the weakening of hydrogen bonds and van der Waals forces in the polymer-based solutions. Normally, these forces support the formation of macro-molecular tangles, but they diminish as molecular movement increases with rising temperatures [14].

3.2 Mud Filtration Measurement

Table 4 presents the results from using a FANN Series 300 API Filter Press to measure mud filtration properties for various water-based WBM formulations. It highlights how starch and xanthan gum (XG) function as filtration control agents. Initially, formulations no. 2 and 4 were compared, showing a significant reduction in filtrate loss by 56.4%, from 32.6 to 14.2 cm³/30 min, when the XG concentration was increased from 0.25 to 1.0 lb/bbl. The lowest filtrate loss recorded was 7.6 cm³/30 min in formulation no. 13, achieved by increasing the starch concentration to 6 lb/bbl. According to the API Recommended Practice for Field Testing Water-based Drilling Fluids (API RP 13-B1), achieving a mud filtrate loss below 10 mL in a 30-minute test and a mud cake thickness below 2 mm are crucial [9]. Thus, combining these two filtration control agents in the WBM is essential for meeting the API RP 13-B1 standards.

Tab. 4. Mud Filtration properties of different WBM formulas.

Formula no.	Mud weight (ppg)	Filtrate Loss (cm^3/30 min)	Mud cake Thickness (mm)
1	10.017	150.0	12.0
2	9.754	32.6	3.0
3	9.903	22.3	1.5
4	9.994	14.2	1.0
5	9.918	12.2	1.5
6	9.967	9.0	1.0
7	9.976	11.8	2.0
8	9.787	9.0	2.0
9	9.988	10.2	1.5
10	9.902	9.4	1.5
11	10.004	12.0	1.0
12	10.266	9.6	1.0
13	10.007	7.6	1.5

3.3 Rheological Model Fitting

The relationships between shear stress and shear rate from the experimental results were analyzed using the Power Law and Bingham Plastic rheological models. This analysis was conducted through a spreadsheet program utilizing Equations (7) and (8), respectively. The results were gathered for the WBM formulas numbered 11-13 at both test temperatures of 30°C and 65°C. These results are presented in Table 5.

Tab. 5. Bingham Plastic and Power Law Rheological Model of different WBM formulas at test temperature of 30°C and 65 °C.

Formula no.	Rheological Parameters					
	Bingham Plastic			Power Law		
	μ_p	τ_y	R^2	n	K	R^2
Temperature 30°C						
11	13.22	4.94	0.9999	0.23	3.95	0.9502
12	25.47	10.06	0.9994	0.22	7.93	0.9565
13	31.12	19.36	0.9975	0.16	16.83	0.9026
Temperature 65°C						
11	9.43	2.96	0.9999	0.25	2.31	0.9564
12	18.86	7.25	0.9963	0.24	5.51	0.9692
13	24.52	13.23	0.9978	0.19	10.70	0.9547

The analysis revealed that the Bingham Plastic model correlates slightly better with the relationship of experimental values of shear stress and shear rate for these three WBM formulas (formulas including all additives) than the Power Law model. This was evidenced by a higher regression coefficient (R^2) at both tested temperatures. Additionally, when comparing the rheological parameters to those discussed in Section 3.1, the values derived from the Bingham Plastic model were closer to the expected results than those from the Power Law model. These findings indicate that many WBM drilling fluid formulas align more consistently with Bingham Plastic behavior. However, the Bingham Plastic model does not accurately predict the rheological properties at very low or very high shear rates [15].

4. Conclusion

This study analyzed the rheological properties of various water-based mud formulas incorporating environmentally friendly additives such as Xanthan Gum, Carboxymethyl Cellulose, and Dextrinized Starch for drilling operations at Fang Oilfield, a normally-pressured onshore oilfield in Thailand. The investigation identified the optimal WBM formula for use in this oilfield, consisting of 20 pounds per barrel Bentonite, 40 pounds per barrel Barite, 0.50 pounds per barrel Xanthan Gum, 0.50 pounds per barrel CMC, and 6 pounds per barrel Starch. This composition achieved a plastic viscosity of 25.7 centipoise and a yield point of 24.31 pounds per 100 square feet, which meets the API requirements for WBM. Additionally, this formula demonstrated the lowest filtrate loss at 7.6 mL over a 30-minute period and formed a mud cake with a thickness of less than 2.0 mm. Further evaluation using the Bingham plastic model allowed for a precise approximation of rheological parameters under both room temperature and high temperature conditions. Although reservoir conditions vary across different oilfields, the findings from this study provide a useful reference for appropriate concentration ranges of mud additives in WBM for onshore drilling within normally-pressured reservoirs.

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