Rheological Behavior of Bentonite-Water Mud Under Elevated Temperatures: Insights for Predicting Fluid Performance

Masoumeh Amiri, Arild Saasen, Mahmoud Khalifeh, Alf Kristian Gjerstad

Department of Energy and Petroleum Eng., Faculty of Science and Technology, University of Stavanger, 4036, Stavanger, Norway

ABSTRACT

During well construction, control of drilling mud rheology is required at elevated temperature and pressure. Therefore, understanding the influencing factors on water-base mud (WBM) rheology characteristics, as one of the most commonly used drilling fluids, is essential to maintain a firm control over rheological properties of elevated temperature WBM. Due to changing the rheological properties of some additives at elevated temperatures, selecting appropriate additives for WBM is challenging.

This study focuses on the behavior of a typical bentonite mud utilizing a state-of-the-art viscometer to measuring drilling fluids properties at different concentrations of bentonite and temperatures. Sensitivity of the mud to shear stress at different temperatures and concentrations was examined. The experimental approach involved mixing distilled water with bentonite and conducting experiments including preparation, and hot rolling to simulate aging of mud during circulation. Rheological properties of the mud were measured at various concentrations (8 and12 g) across temperatures (10 to 90°C) and shear rates (5 to 1021 s^{-1}) to identify patterns for predicting the mud behavior.

The results show that the rate of shear stress increase is a strong function of temperature in the applied shear rate range. Plastic viscosity decreased with temperature, being highest at 10°C and lowest at 90°C. Additionally, temperature increase leads to increased yield stress. It is believed that at higher temperature face to face repulsive electrostatic energy between particles is higher. Additionally, higher temperatures led to an increased yield stress due to stronger particle interactions. It is proposed that, as a result of these enhanced interactions at higher temperatures, a more robust gel structure would be formed. The experimental data closely fit the Herschel-Bulkley model, confirming its suitability for predicting bentonite mud behavior under varying temperatures and shear rates.

This study provides deeper understanding of how temperature and bentonite concentration influence the rheology of bentonite muds. Also, these findings highlight the complexity of maintaining mud rheology at elevated temperatures, as viscosity changes can affect mud stability and drilling efficiency. Moreover, it offers practical insights for optimizing bentonite concentrations to ensure efficiency in field applications for elevated temperature conditions.

Key words: Rheology characteristics; temperature effect; Bentonite muds

Introduction

Understanding the rheological properties of drilling fluids under elevated pressures and temperatures is crucial for any drilling operation. In deeper formations where such conditions are encountered, predicting the rheological characteristics of drilling fluids is essential to ensure their performance and stability[1]. One of the key components in top hole water-based fluid systems is bentonite clay, due to its cost-effectiveness, environmental advantages, swelling capacity, and gel-structure formation [2]. Acquiring knowledge about the rheological properties of bentonite is critical for improving drilling fluid performance in terms of wellbore cleaning efficiency, managing pressure losses, and controlling equivalent circulation density[2].

Several studies have shown that the effect of pressure on the rheology of water-based drilling fluids is negligible[3]. However, temperature can significantly influence the rheological properties of water-bentonite dispersions in various ways[4].

For instance, Mohammed et al.,[5] investigated the rheological characteristics of three different bentonite concentrations (2, 4, and 6 wt%) at three temperatures (25°C, 55°C, and 85°C), both with and without nano-Fe_2O_3. Their results showed that yield stress decreased with increasing temperature at all concentrations. Generally, higher bentonite concentrations resulted in greater plastic viscosity and apparent viscosity. However, both plastic viscosity and apparent viscosity decreased as temperature increased.

In a separate study, Vryzas et al.,[4] examined the rheology of Wyoming sodium bentonite at a 7.0% mass concentration (45.16 g bentonite in 600 ml deionized water) across a wide temperature range (25°C to 80°C) under ambient pressure. Contrary to prior studies, they observed that at low shear rates, shear stress increased with temperature, whereas at high shear rates, the shear stresses converged to similar values. Their samples, analyzed using the Herschel-Bulkley model, revealed that yield stress increased with temperature, while the flow consistency index decreased, and the flow behavior index increased with temperature. Similarly, Lin et al.,[6] studied the temperature dependence of the yield stress in clay suspensions (kaolinite and bentonite mixed with distilled water) at various concentrations (15, 20, and 30 wt%) and temperatures (2°C and 25°C). They reported a significant increase in yield stress with increasing temperature, particularly at higher clay concentrations.

This behavior was attributed to the increase in electrostatic repulsive potential between charged clay particles with temperature.

This study focuses on investigating the rheological behavior of bentonite based mud with varying properties at elevated temperatures and different concentrations using a state-of-the-art rheometer. Understanding the combined effects of high temperature and bentonite concentration sensitivity is crucial to maintaining consistent drilling fluid properties, ensuring optimal performance in challenging environments.

Drilling fluid design and preparation

The composition of bentonite muds is presented in **Table1** including the order and duration of mixing:

Table 1: Mix design of WBDF

Ingredients	Function	Content by Weight (g)	Mixing time (min)
Distilled Water	Base fluid	350	-
Bentonite	Elevate viscosity and reduce filtration loss	8 and 12	10

Experimental Procedure

The methodology is divided into two steps: before hot rolling (BHR) and after hot rolling (AHR).

In the first step (BHR) the mentioned compositions were mixed using Silverson L4RT- a high-speed mechanical homogenization and emulsification shown in **Fig. 1**.

FIGURE 1: Blade used to shear the fluid during drilling fluid preparation

To avoid agglomeration the process of adding bentonite should be done very slow. Also, mixing time plays an important role in water base mud mixing.

The pH of drilling fluid was measured by a pH meter). To improving chemical solubility and performance of drilling mud, as well as for protecting drilling and completion tools from corrosion, pH of water-base drilling muds is generally maintained in the 8 to 12 [6].

To investigate the flow behaviour of this drilling mud, rheology parameters like yield stress and apparent viscosity were recorded using a versatile rheometer-model MCR302.

In the second step to simulate a wellbore mud circulation in the laboratory a roller oven and mud aging cell were used. Hot rolling is conducted to assess changes of mud properties after a mud circulation at a specific temperature. The mud samples were hot rolled at 90 ºC for 16 hours at atmospheric pressure.

After hot rolling the mud sample placed in the rheometer cell at the mentioned temperature. To reduce the effect of evaporation pressure cell was used. Shear stress readings were taken in 5, 10, 51, 102, 170, 340, 510 and 1021 s^{-1} in ascending order with 10 seconds between each measuring point in order to wait for equilibrium and to measure in a permanent state. The viscosity of the drilling fluids was measured with the same viscometer configuration.

Results

Temperature Effect on Shear Stress at Ambient Pressure

8 grams of bentonite

Rheograms for all six samples containing 8 g of bentonite at the tested temperatures are presented in Fig. 2. As shown, shear stress increases with increasing shear rates across all temperatures. Notably, higher temperatures result in a greater yield stress. At 10°C, the shear stress was 0.079 Pa at the lowest shear rate and 8.6 Pa at the highest. While, at 90°C, the shear stress ranged from 2.01 Pa at the lowest shear rate to 6.01 Pa at the highest. It shows at elevated temperatures and higher shear rates, the observed shear stress values are lower compared to those at lower temperatures.

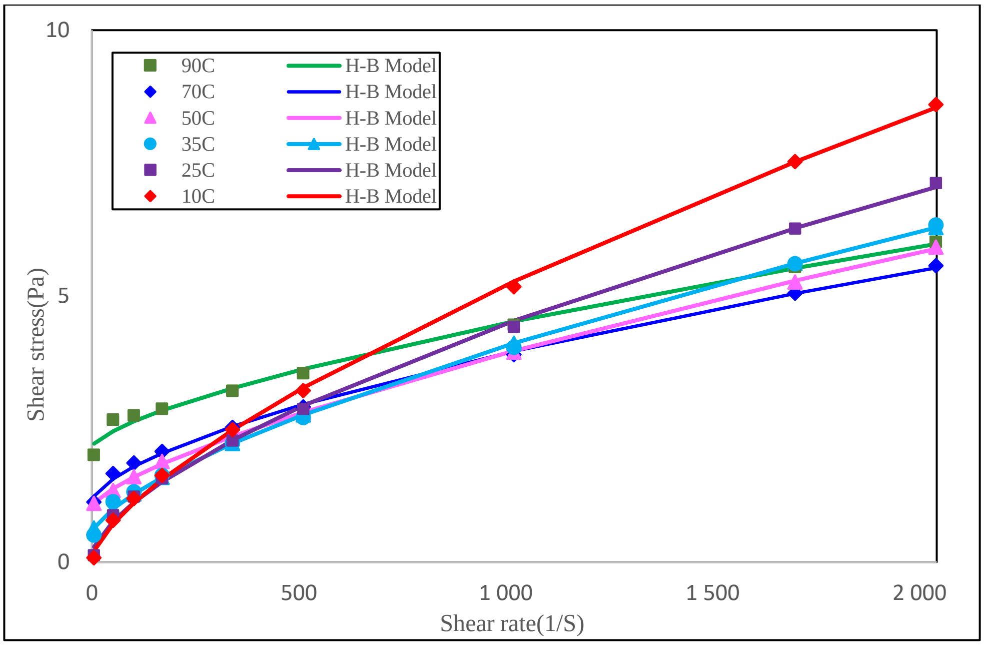

Figure 2. Rheograms of 8 grams of sodium bentonite in water at different temperatures

Table 2. presents the data obtained from fitting the data to the Herschel-Bulkley rheological model. This model demonstrated a strong fit for all sample rheograms, and the corresponding rheological parameters. It is obvious with increasing the temperature yield stress increased. No discernible pattern was observed for the flow consistency index and flow behavior index.

TABLE.2. Herschel-Bulkley rheological parameters of 8 g water- sodium bentonite suspensions at different temperatures.

Herschel- Bulkley Model				
T (ºC)	τ_o	k	n	R^2
10	0.08414	0.03972	0.7035	0.9993
25	0.1486	0.04765	0.6529	0.9984
35	0.5441	0.03108	0.6849	0.9986
50	1.05	0.01884	0.7281	0.9997
70	1.141	0.03469	0.6352	0.9981
90	2.165	0.01955	0.692	0.992

12 grams of bentonite

The relationships between shear stress with shear rate for 12 g bentonite drilling mud have been graphed (Fig. 3). The same trend was observed for 12 grams of bentonite. In other words, at lower temperatures (e.g., 10°C), the shear stress is lower (1.48 Pa) compared to higher temperatures like 90ºC which shows shear stress of 7.77Pa at the same shear rate (5 1/s). However, at all shear rates, shear stresses were higher than 8 rams of bentonite.
Also, at lower shear rates, the yield stress exhibits higher values as the temperature increases.

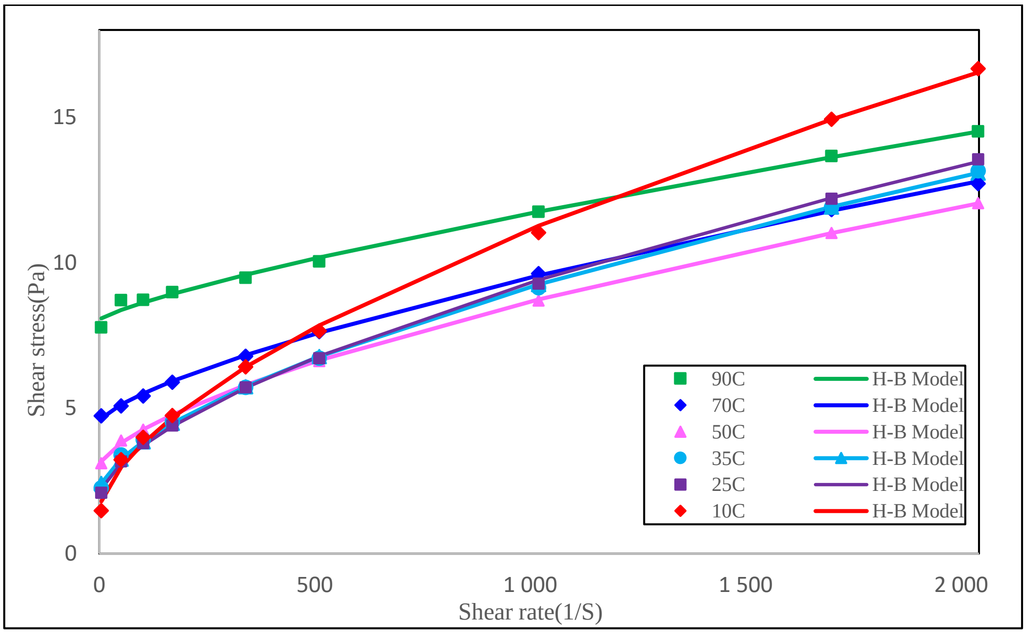

Figure 3. Rheograms of 12 grams of sodium bentonite in water at different temperatures

The Herschel-Bulkley model was found to fit all sample rheograms very well, especially at higher shear rates and the rheological parameters, are shown in Table 3. An increase of yield stress with temperature was observed Also, flow consistency index decreased with temperature while the flow behavior index increased with temperature and tends towards the value of 1.0, indicating that the dispersions become Bingham plastic at higher temperatures.

TABLE 3. Herschel-Bulkley rheological parameters of 12g water- sodium bentonite suspensions at different temperatures.

Herschel- Bulkley Model				
T (ºC)	τ_o	k	n	R^2
10	1.428	0.1348	0.6193	0.9986
25	1.963	0.09558	0.6287	0.9996
35	2.154	0.0954	0.6222	0.9994
50	2.995	0.06182	0.6542	0.9998
70	4.534	0.03503	0.7169	0.9996
90	8.033	0.01483	0.7977	0.9942

Discussion

The rheological parameters reflect the strength and nature of interparticle interactions among clay particles. The observed increase in yield stress with temperature may be attributed to enhanced face-to-face electrostatic repulsive interactions, which intensify as the temperature rises. In such a face-to-face interaction structure, the electrostatic repulsive potential primarily governs the separation distance between adjacent particles. As a result, the particles are drawn into a deep van der Waals potential well. Consequently, as the separation distance decreases, the repulsive potential increases, leading to a corresponding rise in yield stress [6]. Similarly, at higher concentrations, the reduced interparticle distance results in an increased yield stress.
At low shear rates, elevated temperatures increase yield stress due to stronger interparticle repulsive forces. However, at higher shear rates, the clay particle network becomes disrupted. It is hypothesized that at higher temperature, between bentonite particles adhesion occurs and with increasing the temperature the network structure breaks down. After reorganization, bentonite particles show less resistance to flow even at high shear rates. As a result, shear stress decreases with increasing temperature under high shear conditions.

Conclusion

1. The rheological behavior of sodium bentonite dispersions at concentrations of 8 and 12 grams is accurately described by the Herschel-Bulkley model across the entire range of shear rates and temperatures studied.
2. At low shear rates, shear stress increases significantly with temperature, whereas at high shear rates, the lowest temperature yields the highest shear stress.
3. Yield stress exhibits an increasing trend with rising temperature.
4. Higher bentonite concentrations result in increased shear stress and yield stress across all temperatures.

REFERENCES

(1) Amani, M.; Al-Jubouri, M. The Effect of High Pressures and High Temperatures on the Properties of Water Based Drilling Fluids. *Energy Science and Technology* **2012**, *4* (1), 27–33. https://doi.org/10.3968/j.est.1923847920120401.256.

(2) Du, M.; Liu, P.; Clode, P. L.; Liu, J.; Haq, B.; Leong, Y. K. Impact of Additives with Opposing Effects on the Rheological Properties of Bentonite Drilling Mud: Flow, Ageing, Microstructure and Preparation Method. *J Pet Sci Eng* **2020**, *192*. https://doi.org/10.1016/j.petrol.2020.107282.

(3) Alderman, N. J.; Research, C.; Gavignet, ; A; Forex, S.; Guillot, ; D; Schlumberger, D.; Maitland, G. C.; Research, S. C. *SPE High-Temperature, High-Pressure Rheology of Water-Based Muds*. http://onepetro.org/SPEATCE/proceedings-pdf/88SPE/88SPE/SPE-18035-MS/3466275/spe-18035-ms.pdf/1.

(4) Vryzas, Z.; Kelessidis, V. C.; Nalbantian, L.; Zaspalis, V.; Gerogiorgis, D. I.; Wubulikasimu, Y. Effect of Temperature on the Rheological Properties of Neat Aqueous

Wyoming Sodium Bentonite Dispersions. *Appl Clay Sci* **2017**, *136*, 26–36. https://doi.org/10.1016/j.clay.2016.11.007.
(5) Mohammed, A. S. Effect of Temperature on the Rheological Properties with Shear Stress Limit of Iron Oxide Nanoparticle Modified Bentonite Drilling Muds. *Egyptian Journal of Petroleum* **2017**, *26* (3), 791–802. https://doi.org/10.1016/j.ejpe.2016.10.018.
(6) Lin, Y.; Cheah, L. K. J.; Phan-Thien, N.; Khoo, B. C. Effect of Temperature on Rheological Behavior of Kaolinite and Bentonite Suspensions. *Colloids Surf A Physicochem Eng Asp* **2016**, *506*, 1–5. https://doi.org/10.1016/j.colsurfa.2016.06.012.