Study on Attapulgite as Drilling Fluid Clay Additive in Persian Gulf Seawater

M. A. Choupani, S. S. Tabatabaee Moradi*, S. A. Tabatabaei Nejad

Faculty of Petroleum and Natural Gas Engineering, Sahand University of Technology, Tabriz, Iran

1. INTRODUCTION

Success in the drilling of oil and gas wells significantly depends on the drilling fluid performance. Drilling fluids are used in the well construction process for various purposes, including but not limited to cutting transport, bit cooling and lubrication, formation damage reduction, control of formation fluid pressure, transmission of formation information and providing wellbore stability [1-4].

There are three main types of drilling fluids: water based mud (WBM), Oil based mud (OBM) and pneumatic fluids. Due to the lower cost, better environmental compatibility and easy preparation procedures, water based muds are the most commonly used drilling fluid in the industry. In practice, various compositions of WBMs have been developed based on

*Corresponding Author Email: s.sh.tabatabae@gmail.com (S. S. Tabatabaee Moradi)
environmental considerations, geological and technical conditions of the well being drilled.

In the simplest form, a water based fluid is prepared by hydration of bentonite in water. Water as the basis is usually provided from local sources, like rivers, lakes, etc. to exclude additional cost of transportation. In the case of offshore drilling, seawater is preferred for preparation of WBMs. Bentonite, formed by weathering of volcanic ash, is a clay mineral of smectite group, mostly composed of montmorillonite mineral ((Al,Mg)₂(OH)₂(Si,Al)₄O₁₀(Ca), on H₂O). It is accepted as a common drilling fluid additive with a good hydration ability to decrease mud filtration volume, increase cutting transport ability and enhance rheological properties [5-9].

Attraction of positive ions by the negatively charged layers of bentonite attributes to the clay swelling, which in turn leads to the enhancement of drilling fluid rheological properties. However, in saline environment where seawater is preferred, high concentration of metal cations, such as Ca²⁺, Mg²⁺, Na⁺ etc. are present, which create an electrostatic charge imbalance in the layers of bentonite. This hinders the effective hydration and swelling of bentonite particles and even may lead to their flocculation and settling [10-12].

Researchers studied the behavior of bentonite WBM in the saline environments. Kelessidis et al. [13] investigated rheological behavior of Wyoming bentonite suspensions in different electrolyte concentration. Authors showed that salt addition to bentonite suspensions leads to decrease of parameters in the Herschel–Bulkley model i.e. yield stress, flow consistency index and flow behavior index.

Duman and Tunc [14] investigated the electro-kinetic and rheological properties of sodium bentonite in different electrolyte solutions. Based on experimental results, authors showed viscosity decrease with increase in salt concentration and concluded that divalent and trivalent cations significantly affect the properties of bentonite suspension.

Abu-Jdayil [15] studied the rheological properties of bentonites with different sodium to calcium ratios. It was found that salt addition decreased the viscosity and yield stress of bentonite suspensions and changed it’s rheological behavior from shear-thinning to Newtonian and shear-thickening.

Ren et al. [16] used a modified thixotropic loop to study the effect of salinity on rheological properties of bentonite suspensions. They reported that in saline environments, formation of gel structure between clay particles is hindered.

To reduce the adverse effect of seawater salinity on the performance of bentonite, one may suggest the use of desalination facilities to remove ions, especially divalent cations, from seawater. However, this process is costly, time consuming and not feasible due to the restricted capacity of desalination equipment [11].

To overcome this issue, researchers suggested use of salt-tolerant polymers, water-insoluble fiber materials, salt-tolerant clay minerals and pre-hydrated bentonite [11, 17]. Attapulgite and sepiolite are two type of non-swelling salt-tolerant clays. Sepiolite (Si₃₂Mg₆O₁₂.nH₂O) is a fibrous mineral of magnesium silicate group with acceptable rheological properties at high temperature and saline environments [18, 19]. Attapulgite or Polygorskite (Si₄O₁₀(Mg,Al,Fe)₃(OH)₇(OH)₄·4H₂O) is a needle like crystalline hydrated magnesium aluminum silicate with good rheological properties in saline environments [20]. Pre-hydrated bentonite, which is suggested as drilling fluid additive for saline environments, is prepared by hydration of the bentonite in fresh water for a specific time and then mixing the prepared suspension with salt water.

In this work, suspensions of bentonite, pre-hydrated bentonite and attapulgite in the synthetic Persian Gulf seawater were prepared and their rheological and filtration properties were investigated to check the feasibility of Persian Gulf seawater application as the basis of drilling fluids.

2. MATERIALS AND METHODS

Different drilling fluid compositions were prepared based on standard API procedures and tested for density, pH, rheological and filtration properties [21]. Fluids were developed based on fresh water (FW) and synthetic Persian Gulf seawater (SSW). SSW was prepared to be used instead of real seawater to exclude the effect of different compositions in samples on the experimental results. To prepare synthetic water, the result of Ion Chromatography analysis of seawater samples was used to calculate the type and mass of each salt, which should be dissolved in the fresh water. Table 1 present the amount of each salt in 1 liter of fresh water.

Additives, i.e. bentonite, attapulgite and soda ash, were provided by local producers. Soda ash was used to adjust the fluid pH. For preparation of bentonite and

| Table 1. Amount of salts required for preparation of SSW |
|-----------------------------------------------|
| **Salts**                | **Salt mass per liter of fresh water, g/L** |
| NaCl                      | 28                                           |
| KCl                        | 0.8                                          |
| MgCl₂·2H₂O               | 13.75                                        |
| CaCl₂·6H₂O               | 1.82                                         |
| Na₂SO₄                    | 4.99                                         |
| NaHCO₃                   | 0.1                                          |
attapulgite suspensions, additives were weighted based on chosen concentration and then mixed with water (fresh or seawater) for 20 minutes at 2000 rpm of the mixer (Figure 1). Pre-hydrated bentonite suspension was prepared by pre-mixing of 87.5 mL of fresh water and chosen amount of bentonite for 15 minutes at 2000 rpm. The mixture was left in the laboratory for 24 hours to achieve full bentonite hydration. The bentonite suspension in fresh water was then added to 262.5 mL of SSW.

Compositions of the developed drilling fluids are presented in Table 2.

As presented in Table 2, suspensions of 10% by the weight of bentonite and attapulgite were so viscous that could not be used in the tests. Also suspensions of 8% and 10% pre-hydrated bentonite could not be used in the experiments due to high viscosity of pre-mixed FW and bentonite. Settling of bentonite was observed, preparing 6%, 8% and 10% suspensions of bentonite in SSW, which hindered their use in experimental study (Figure 2).

2. 1. Filtration Measurement

Filtration properties, i.e. filtration volume and filter cake thickness, are of great importance in a successful drilling operation. Filtration of drilling fluid into the permeable subsurface formations reduce formation permeability and may lead to misinterpretation of well logging and well testing measurements. Presence of the filter cake, which forms on the borehole wall, helps to decrease filtration volume and promotes borehole stability. Filter cake should be thin and have low permeability. Thicker cakes with high permeability reduce diameter of the hole and leads to higher possibility of stuck pipes, increased torque and drag and poor primary cementing job [22-24].

Therefore, the goal in drilling fluid design is to reduce filtration volume and decrease mud cake permeability and thickness. In this work, to measure filtration properties, i.e. filtration volume and filter cake thickness, filter press was used (Figure 3).

| Sample | Name                  | FW, mL | SSW, mL | Soda ash, g | Bentonite, g | Attapulgite, g | Density, pcf | pH   | Comments                          |
|--------|-----------------------|--------|---------|-------------|--------------|----------------|--------------|------|-----------------------------------|
| 1      | 6% Ben. FW            | 350    | -       | 0.5         | 21           | -              | 63           | 10.6 |                                   |
| 2      | 8% Ben. FW            | 350    | -       | 0.5         | 28           | -              | 65           | 10.65|                                   |
| 3      | 10% Ben. FW           | 350    | -       | 0.5         | 35           | -              | -            | 10.7 | High viscosity, could not be tested |
| 4      | 6% Att. FW            | 350    | -       | 0.5         | -            | 21             | 64           | 10.57|                                   |
| 5      | 8% Att. FW            | 350    | -       | 0.5         | -            | 28             | 67           | 10.68|                                   |
| 6      | 10% Att. FW           | 350    | -       | 0.5         | -            | 35             | -            | 10.7 | High viscosity, could not be tested |
| 7      | 6% Ben. SSW           | -      | 350     | 0.5         | 21           | -              | -            | -    | Settling of bentonite             |
| 8      | 8% Ben. SSW           | -      | 350     | 0.5         | 28           | -              | -            | -    | Settling of bentonite             |
| 9      | 10% Ben. SSW          | -      | 350     | 0.5         | 35           | -              | -            | -    | Settling of bentonite             |
| 10     | 6% Att. SSW           | -      | 350     | 0.5         | -            | 21             | 77           | 9.35 |                                   |
| 11     | 8% Att. SSW           | -      | 350     | 0.5         | -            | 28             | 80           | 9.3  |                                   |
| 12     | 10% Att. SSW          | -      | 350     | 0.5         | -            | 35             | 83           | 9.27 |                                   |
| 13     | 6% Ben. Pre H.        | 87.5   | 262.5   | 0.5         | 21           | -              | 73           | 10.2 | High viscosity of pre-mixture     |
| 14     | 8% Ben. Pre H.        | 87.5   | 262.5   | 0.5         | 28           | -              | -            | -    | High viscosity of pre-mixture     |
| 15     | 10% Ben. Pre H.       | 87.5   | 262.5   | 0.5         | 35           | -              | -            | -    | High viscosity of pre-mixture     |
Filtration measurements involves placing the fluid in filter press cup and applying a 100 psi pressure on the fluid. The volume of filtered fluid through a filter paper is reported as the filtration volume (cm$^3$/30 min). Also, thickness of the cake, formed on the filter paper is reported.

2. 2. Rheological Measurements

Many drilling parameters such as Rate of Penetration (ROP), rock cutting transport to the surface, mud hydraulics, filter cake formation, filtration volume etc. are significantly dependent on the fluid rheological properties [25, 26].

In this work, rheological properties were measured using a Fann viscometer at different rotational speeds. To fit the exact rheological model to measured data, below steps were followed [27]:

1. Dial readings of the viscometer at 3, 6, 100, 200, 300 and 600 rpm for each fluids were recorded.
2. Rotational speed and dial reading at each speed were converted to shear stress and shear rate using following formulas:

$$\tau = 1.067 \theta_N$$  \hspace{1cm} (1)

$$\gamma = 1.703 N$$  \hspace{1cm} (2)

where $\tau$ is shear stress ($\frac{lb}{100ft^2}$), $\gamma$ is shear rate ($\frac{1}{s}$), $N$ is rotational speed (rpm) and $\theta_N$ is dial reading at rotational speed of $N$.

3. Recorded values of $N$ and $\theta_N$ were used to calculate the parameters of Newtonian, Bingham Plastic and Herschel-Bulkley models. For Newtonian model, shear stress is related to the shear rate as:

$$\tau = \mu \gamma$$  \hspace{1cm} (3)

where

$$\mu = \frac{300}{\pi} \theta_N$$  \hspace{1cm} (4)

In Equations (3) and (4), $\mu$ is the fluid viscosity.

For Bingham Plastic model, the relation between shear stress and shear rate is described as:

$$\tau = \tau_y + \mu_p \gamma$$  \hspace{1cm} (5)

where

$$\mu_p = \theta_{600} - \theta_{300}$$  \hspace{1cm} (6)

$$\tau_y = \theta_{300} - \mu_p$$  \hspace{1cm} (7)

$\mu_p$ is plastic viscosity (cp) and $\tau_y$ is yield stress ($\frac{lb}{100ft^2}$).

Herschel-Bulkley model relates shear stress and shear rate as:

$$\tau = \tau_y + k \gamma^n$$  \hspace{1cm} (8)

where

$$\tau_y = 2 \theta_3 - \theta_6$$  \hspace{1cm} (9)

$$n = 3.32 \log\left(\frac{R_{00p}}{R_{100}}\right)$$  \hspace{1cm} (10)

$$k = 510 \frac{\theta_{600}}{511^n}$$  \hspace{1cm} (11)
In Equations (8-11), \( n \) is flow behavior index (dimensionless) and \( k \) is consistency index (cp).

4. Knowing parameters of each model, shear stress values at different shear rates are calculated using models.

5. Measured values of shear stress and shear rate (step 2) are plotted against calculated shear stress and shear rate (step 4).

6. Error of each rheological model at each shear rate point is calculated. The model with least average absolute error is selected as the best fitted rheological model to describe the behavior of drilling fluids.

Gel strength of drilling fluid determines its ability to suspend cuttings and solid additives when fluid circulation is stopped in the annular space. The magnitude of yield stress and gel strength depend on attractive forces between particles in the fluid. Gel strength is measured under static condition, while dynamic condition is applied for yield stress measurement. To measure gel strength, fluid was kept static for 10 seconds and 10 minutes and then the viscometer was started at the rate of 3 RPM. The maximum dial indicator deflections were reported as the initial gel strength and 10 minutes’ gel strength respectively \[21, 28\]. It should be noted that all experiments were conducted at laboratory temperature (23 °C).

3. RESULTS AND DISCUSSION

Results of filtration and rheological experiments are explained and discussed in this section.

3.1. Results of Filtration Measurements

According to Table 3, increase in additive concentration, i.e. solid concentration, leads to less filtration volume and thicker mud cakes. It is also evident that filtration properties of attapulgite suspension in SSW is acceptable. However, comparing to attapulgite suspension in FW, filtration volume increased. This is due to the negative effect of ions in the SSW on the attapulgite performance. In the case of pre-hydrated bentonite, a thick cake and high filtration volume confirm the weak performance of the bentonite in saline environment, even in the pre-hydrated form. Therefore, this suspension was not tested for rheological properties.

3.2. Results of Rheological Measurements

3.2.1. Determination of Rheological Models

Results of rheological measurement were firstly used to determine the best fitted model. As an example, measured and calculated rheological properties for suspensions of 8% and 10% attapulgite in SSW are shown in Figures 4 and 5.

| No. | Name | Filtration volume, cm\(^3\)/30 min | Thickness of mud cake, mm |
|-----|------|---------------------------------|--------------------------|
| 1   | 6% Ben. FW | 27.5                           | 3.6                      |
| 2   | 8% Ben. FW | 22.5                           | 4.1                      |
| 3   | 6% Att. FW | 10                             | 2.8                      |
| 4   | 8% Att. FW | 8                              | 3.5                      |
| 5   | 6% Att. SSW | 17.5                          | 1.8                      |
| 6   | 8% Att. SSW | 14.5                          | 1.9                      |
| 7   | 10% Att. SSW | 13                            | 2.7                      |
| 8   | 6% Ben. Pre H. | 86                            | 7.1                      |

Figure 4. Determination of rheological model for 8% attapulgite suspension in SSW

Figure 5. Determination of rheological model for 10% attapulgite suspension in SSW
Figures 4 and 5 represent real viscometer data versus rheological models. It’s obvious that Herschel-Bulkley model gives better fit to data than others. Procedure of fitting rheological model to measured data was repeated for all drilling fluids and average absolute error for each rheological model was calculated. Details are presented in Table 4.

As it can be seen from the Table 4, for all bentonite and attapulgite suspensions, Herschel-Bulkley model fits the rheological data with a better accuracy.

### 3. 2. 2. Rheological Properties of Suspensions in FW

Rheological parameters \( (n, k \text{ and } \tau_y \text{ and gel strength}) \) of the bentonite and attapulgite suspensions in FW are presented in Figures 6 and 7. As it can be seen from these figures that flow behavior index \( (n) \) has a value less than 1 for all suspensions in fresh water. The index \( (n) \) shows the degree of non-Newtonian rheological behavior. For \( n \) values less than 1, a shear-thinning behavior happened, i.e. showing decrease of effective viscosity with shear rate increase, as is expected [29, 30].

Also it is evident that an increase in clay (bentonite and attapulgite) concentration results in higher \( k \), yield stress and gel strength values. This is due to the fact that at higher clay concentration a stronger three dimensional network and gel structure is formed between clay particles and water molecules [31].

However, despite of consistency index, yield stress and gel strength, an increase in clay concentration resulted in a slight decrease in \( n \) value. Experimental studies in the literature show that a lower \( n \) value in turbulent fluid flow contributes to a less pressure drop of drilling fluid in the circulation path [32, 33].

### 3. 2. 3. Rheological Properties of Suspensions in SSW

Bentonite particle settled down in the SSW and pre-hydrated bentonite suspension showed weak filtration properties. Therefore, only rheological properties of attapulgite suspensions in SSW were investigated. Rheological curves of 6%, 8% and 10% attapulgite in SSW are shown in Figure 8. As data implies, increase in attapulgite concentration reduces the adverse effect of salt on the rheological properties of the suspensions.

In Figure 9, consistency index and flow behavior index for attapulgite suspension in FW and SSW are compared.

| No. | Name     | Average absolute error in rheological model, % |
|-----|----------|-----------------------------------------------|
|     | Newtonian| Bingham Plastic | Herschel-Bulkley |
| 1   | 6% Ben. FW | 57.8          | 11.8          | 2.7       |
| 2   | 8% Ben. FW | 58            | 7.3           | 3.1       |
| 3   | 6% Att. FW | 58.7          | 10.3          | 1.6       |
| 4   | 8% Att. FW | 59.8          | 12.1          | 2.6       |
| 5   | 6% Att. SSW | 53.8          | 17.7          | 5         |
| 6   | 8% Att. SSW | 56.8          | 16.3          | 3.5       |
| 7   | 10% Att. SSW | 57.3          | 15.8          | 2.6       |
Figure 9 shows that values of $n$ and $k$ decrease in SSW. Salt prevents water penetration into the attapulgite, which leads to a weaker three-dimensional structure, and further decrease of consistency.

4. CONCLUSION

Performance of drilling fluids depend on the combination of fluid flow parameters, fluid filtration characteristics, well geometry, operational conditions etc. In this work, rheological and filtration properties of bentonite, pre-hydrated bentonite and attapulgite suspensions in FW and SSW were investigated.

Results of filtration measurements showed that because of salt negative effect on attapulgite performance, filtration volume of suspensions in SSW increased comparing to attapulgite suspensions in FW. In the case of pre-hydrated bentonite, a thick cake and high filtration volume were observed, which confirms the weak performance of the bentonite in saline environment, even in the pre-hydrated form.

Fitness of Newtonian, Bingham Plastic and Herschel-Bulkley models to the measured rheological data were examined. Results showed that Herschel-Bulkley model can be used for prediction of rheological properties with a good accuracy. This is the case for suspensions in both FW and SSW.

All suspension had a flow behavior index less than 1, showing their shear thinning character. A slight decrease of $n$ value is observed by increase in clay concentration. However, a lower $n$ value is desirable for turbulent fluid flow, as it contributes to a less fluid pressure drop.

By increasing bentonite and attapulgite concentrations, higher $k$, yield stress and gel strength values were reported. At higher clay concentration a stronger three-dimensional network of clay particles in aqueous environment and consequently a stronger gel structure are formed.

Based on experimental results, performance of the attapulgite suspensions in the SSW confirmed its application in saline environments. The SSW, in this study, was prepared in the laboratory based on the Persian Gulf sea water. Results show that developed composition can be adjusted further and be used in drilling of offshore wells in Persian Gulf.

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چکیده

سیالات حفاری جز شرایط عملکرد مناسب ساختمان‌های هستند. سیالات پایه آب به دلیل توانایی بهره‌وری با محیط زیست، هرینه کمتر و آماده ساده سازی آنها بر طور رایج استفاده می‌شوند. در حفاری‌های فراخال، آب دریا می‌تواند به عنوان پایه سیالات باشد و این امر از نظر تغذیه‌ای بهتر و محدودیت‌های کمتری دارد. با این حال، سیالات حفاری به دلیل کاهش قابل قبولی در شرایط کار در آب و آماده سازی آب رسانده شدند. در حفاری‌های فراخال، آب دریا به عنوان پایه سیالات می‌تواند به عنوان سوخت بهتری در مقایسه با محیطی باشد. همچنین، استفاده از بتن‌های خودرویی و ژل‌های تولید شده در محیط‌های ایران آماده شد. مخلوط‌های بتن‌های خودرویی و ژل‌های شکل‌برداری‌شده در آب شور شده در سیالات از دو نوع:بتن‌های خودرویی و ژل‌های شکل‌برداری شده به طور مناسب استفاده می‌شوند. در بررسی مدل‌های این سیالات، مقادیری از ژل‌های شکل‌برداری‌شده آزمایش شدند. نتایج آزمایش‌ها نشان داد که مدل‌های این سیالات می‌تواند با دقت به عنوان پایه سیالات حفاری در محیط‌های ایران استفاده شود.

م.آ. چوانی و ت.ن. شاه نوری