International Journal of Engineering

Journal Homepage: www.ije.ir

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

PAPER INFO

Paper history:
Received 8 November 2021
Received in revised form 20 December 2021
Accepted 23 December 2021

Keywords:
Clay Mineral
Drilling Fluid
Filtration
Herschel-bulkley Model

ABSTRACT

Drilling fluids are a vital part of every successful well construction operation. Water based fluids are used commonly due to better environmental compatibility, lower cost and easier preparation. In offshore drilling, seawater can be used as the basis of water based fluids. Salinity of seawater restricts application of some additives. For example, bentonite settles in saline environments. In this study, a synthetic water is prepared based on Persian Gulf seawater. Bentonite, pre-hydrated bentonite and attapulgite suspensions were developed based on fresh water and prepared synthetic water. Rheological and filtration properties of fluids were tested to check their performance in synthetic seawater. Results of filtration measurements showed a thick mud cake and high filtration volume in pre-hydrated bentonite fluids. In the case of attapulgite, filtration volume of suspensions in synthetic water increased comparing to suspensions in fresh water. However, filtration properties were acceptable. Study on rheological properties revealed that Herschel-Bulkley model can predict rheological properties with a good accuracy. This is the case for suspensions in both fresh and seawaters. Also it was seen that all suspension had a flow behavior index less than 1, showing their shear thinning character. By increasing clay concentrations, higher consistency index, 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 were formed. Overall, it can be concluded that attapulgite can be used in the saline environment of Persian Gulf seawater.

doi: *10.5829/ije.2022.35.06c.12*

NOMENCLATURE

N	rotational speed (rpm)	τ	shear stress ($\frac{lb_f}{100ft^2}$)
n	flow behavior index (dimensionless)	τ_y	yield stress ($\frac{lb_f}{100ft^2}$)
k	consistency index (cp)	γ	shear rate ($\frac{1}{s}$)
WBM	water based mud	θ_N	dial reading at rotational speed of N
OBM	Oil based mud	μ	fluid viscosity
FW	fresh water	μ_p	plastic viscosity (cp)
SSW	synthetic seawater		

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.tabatabaee@gmail.com* (S. S. Tabatabaee Moradi)

Please cite this article as: M. A. Choupani, S. S. Tabatabaee Moradi, S. A. Tabatabaei Nejad, Study on Attapulgite as Drilling Fluid Clay Additive in Persian Gulf Seawater, ***International Journal of Engineering, Transactions C: Aspects*** Vol. 35, No. 03, (2022) 587-595

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 ($(Al,Mg)_2(OH)_2(Si,Al)_4O_{10}(Ca)_x$ on H_2O). 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 Ca^{2+}, Mg^{2+}, 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 ($Si_{12}Mg_8O_{32}.nH_2O$) is a fibrous mineral of magnesium silicate group with acceptable rheological properties at high temperature and saline environments [18, 19]. Attapulgite or Palygorskite ($Si_8O_{20}(Mg,Al, Fe)_5(OH)_2(OH_2)_4.4H_2O)$) 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 perpetration of SSW

Salts	Salt mass per liter of fresh water, g/L
NaCl	28
KCl	0.8
$MgCl_2\,2H_2O$	13.75
$CaCl_2\,6H_2O$	1.82
Na_2SO_4	4.99
$NaHCO_3$	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).

Figure 1. High speed drilling fluid mixer

TABLE 2. Composition of drilling fluids based on fresh water and synthetic seawater

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	
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

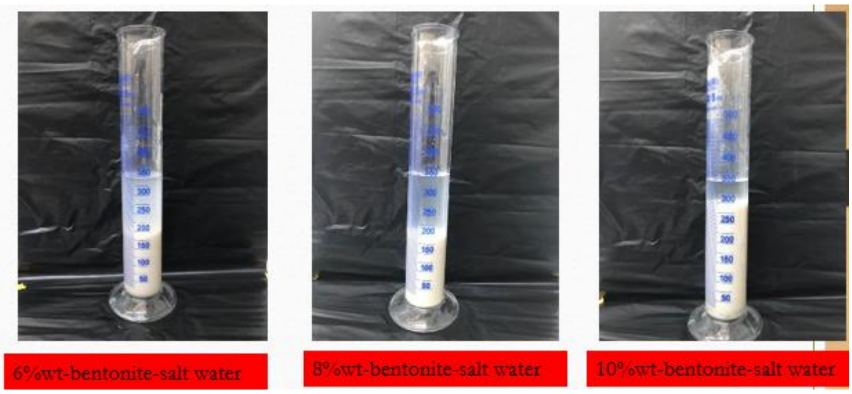

Figure 2. Settling of bentonite in SSW

Figure 3. Filter press

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:

$$\tau = 1.067\,\theta_N \quad (1)$$

$$\gamma = 1.703\,N \quad (2)$$

where τ is shear stress ($\frac{lb_f}{100ft^2}$), γ is shear rate ($\frac{1}{s}$), N is rotational speed (rpm) and θ_N is dial reading at rotational speed of N.

3. Recorded values of N and θ_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:

$$\tau = \mu\,\gamma \quad (3)$$

where

$$\mu = \frac{300}{N}\theta_N \quad (4)$$

In Equations (3) and (4), μ is the fluid viscosity.

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

$$\tau = \mu_p\,\gamma + \tau_y \quad (5)$$

where

$$\mu_p = \theta_{600} - \theta_{300} \quad (6)$$

$$\tau_y = \theta_{300} - \mu_p \quad (7)$$

μ_p is plastic viscosity (cp) and τ_y is yield stress ($\frac{lb_f}{100ft^2}$).

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

$$\tau = \tau_y + k\,\gamma^n \quad (8)$$

where

$$\tau_y = 2\theta_3 - \theta_6 \quad (9)$$

$$n = 3.32\log(\frac{R_{600}}{R_{300}}) \quad (10)$$

$$k = 510\,\frac{\theta_{600}}{511^n} \quad (11)$$

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 theological experiments are explained and discussed in this section.

3. 1. Results of Filtration Measurements

Results of filtration test on different drilling fluid compositions are shown in Table 3.

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

TABLE 3. Filtration properties of drilling fluid

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

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.

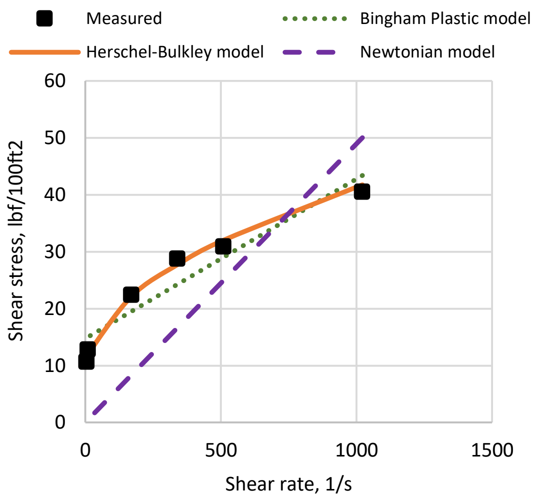

Figure 4. Determination of rheological model for 8% attapulgite suspension in SSW

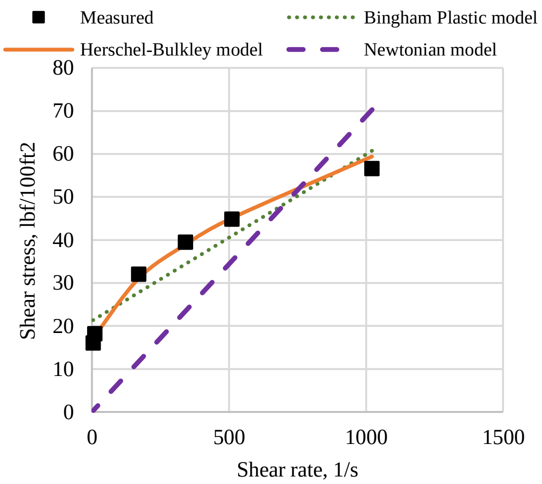

Figure 5. Determination of rheological model for 10% attapulgite suspension in SSW

Figures 4 and 5 represents real viscometer data versus rheological models. Its 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 and τ_y 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].

TABLE 4. Average absolute error in rheological models

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

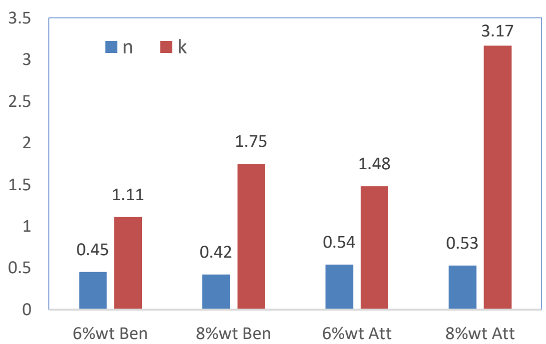

Figure 6. Comparison of rheological properties (n, k) for attapulgite and bentonite suspension in FW

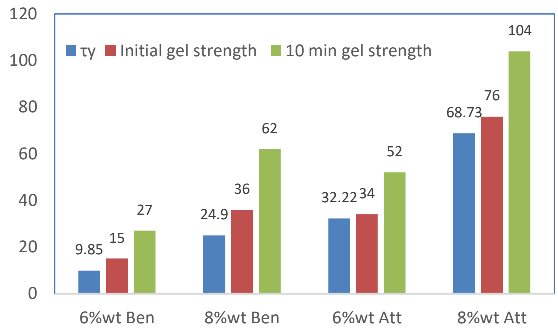

Figure 7. Comparison of rheological properties (τ_y and gel strength) for attapulgite and bentonite suspension in FW

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.

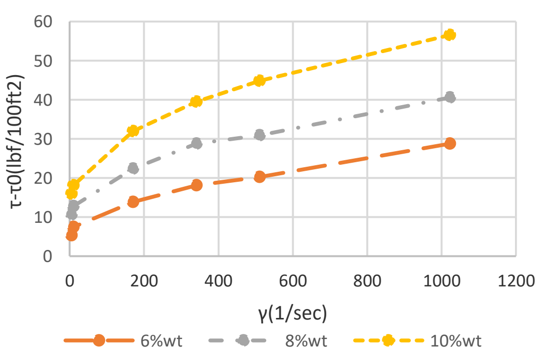

Figure 8. Rheological properties of the attapulgite suspensions in SSW

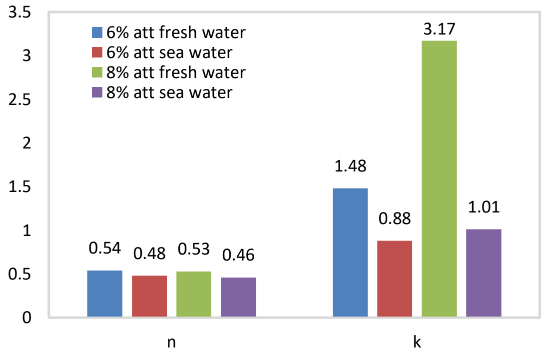

Figure 9 Rheological properties of attapulgite suspension in FW and SSW

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 environemnts. 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.

5. REFERENCES

1. Vipulanandan, C., Mohammed, A., "Effect of drilling mud bentonite contents on the fluid loss and filter cake formation on a field clay soil formation compared to the API fluid loss method and characterized using Vipulanandan models", ***Journal of Petroleum Science and Engineering,*** 189, (2020), 107029. doi: https://doi.org/10.1016/j.petrol.2020.107029
2. Dvoynikov, M.V., Nutskova, M.V., Blinov, P.A., "Developments Made in the Field of Drilling Fluids by Saint Petersburg Mining University", ***International Journal of Engineering, Transactions A: Basics***, 33, (2020), 702-711. doi: 10.5829/ije.2020.33.04a.22
3. Lijuan, P., Xiaoping, L., Wu, L., Fuhao, Z., Tongliang, W., Huang, W., Fuwei, W., "Study on Rheological Property Control Method of "Three High" Water Based Drilling Fluid", ***International Journal of Engineering, Transactions B: Applications***, 33, (2020), 1687-1695. doi: 10.5829/ije.2020.33.08b.28
4. Leusheva, E, Morenov, V., Tabatabaee Moradi, S.Sh., "Effect of Carbonate Additives on Dynamic Filtration Index of Drilling Mud", ***International Journal of Engineering, Transactions B: Applications***, 33, (2020), 934-939. doi: 10.5829/ije.2020.33.05b.26
5. Willson, S.M., Driscoll, P., Judzis, A, Black, A., Martin, W., Ehgartner, B., Hinkebein, T., "Drilling Salt Formations Offshore With Seawater Can Significantly Reduce Well Costs", ***SPE Drilling & Completion***, 19, (2004), 147–155. doi: https://doi.org/10.2118/87216-PA
6. Liu, J., Cheng, Y., Zhou, F., Amutenya Evelina, L.M., Long. W., Chen, S., He, L., Yi, X., Yang, X., "Evaluation method of thermal stability of bentonite for water-based drilling fluids", ***Journal of Petroleum Science and Engineering,*** (2021), 109239. doi: https://doi.org/10.1016/j.petrol.2021.109239
7. Temraz, M.G., Hassanien, I., "Mineralogy and rheological properties of some Egyptian bentonite for drilling fluids", ***Journal of Natural Gas Science and Engineering***, 31, (2016), 791-799. doi: http://dx.doi.org/10.1016/j.jngse.2016.03.072
8. Gautam, S., Guria, Ch., Rajak, D.K., Pathak, A.K., "Functionalization of fly ash for the substitution of bentonite in drilling fluid", ***Journal of Petroleum Science and Engineering,*** 166, (2018), 63-72. doi: https://doi.org/10.1016/j.petrol.2018.02.065
9. Karagüzel, C., Çetinel, T., Boylu, F., Çinku, K., Çelik, M.S., "Activation of (Na, Ca)-bentonites with soda and MgO and their utilization as drilling mud", ***Applied Clay Science,*** 48, (2010), 398-404. doi: 10.1016/j.clay.2010.01.013
10. Scheid, C.M., de Carvalho, R.V., de Oliveira, B.R., de Oliveira Borges, R.F., Calçada, L.A., "Evaluation of the dissolution kinetics of NaCl particles in aqueous drilling fluids viscosified with bentonite", ***Journal of Petroleum Science and Engineering,*** 174, (2019), 563-571. doi: https://doi.org/10.1016/j.petrol.2018.11.017
11. Zou, Z., Zhou, F., Wang, Q., Zhao, Q., Tian, Y., Liu, W., Chen, L., "Enhanced dispersive stability of bentonite suspension in

saline water-based mud", ***Colloids and Surfaces A,*** 579, (2019), 123589. doi: https://doi.org/10.1016/j.colsurfa.2019.123589

12. Li, M., Wu, Q., Han, J., Mei, Ch., Lei, T., Lee, S., Gwon, J., "Overcoming Salt Contamination of Bentonite Water-Based Drilling Fluids with Blended Dual-Functionalized Cellulose Nanocrystals", ***ACS Sustainable Chemistry & Engineering*** 8, (2008), 11569-11578. doi: https://dx.doi.org/10.1021/acssuschemeng.0c02774
13. Kelessidis, V.C., Tsamantaki, C., Dalamarinis, P., "Effect of pH and electrolyte on the rheology of aqueous Wyoming bentonite dispersions", ***Applied Clay Science,*** 38, (2007), 86-96. doi: 10.1016/j.clay.2007.01.011
14. Duman, O., Tunç, S., "Electrokinetic and rheological properties of Na-bentonite in some electrolyte solutions", ***Microporous and Mesoporous Materials,*** 117, (2009), 331-338. doi: 10.1016/j.micromeso.2008.07.007
15. Abu-Jdayil, B., "Rheology of sodium and calcium bentonite–water dispersions: Effect of electrolytes and aging time", ***International Journal of Mineral Processing***, 98, (2011), 208-213. doi: 10.1016/j.minpro.2011.01.001
16. Ren, J., Deshun, Y., Zhai, R., "Rheological behavior of bentonite-water suspension at various temperatures: Effect of solution salinity", ***Engineering Geology***, 295, (2021), 106435. doi: https://doi.org/10.1016/j.enggeo.2021.106435
17. Mirarab Razi, M., Mirarab Razi, F., "An Experimental Study of Influence of Salt Concentration, Mixing Time, and pH on the Rheological Properties of Pre-Hydrated Bentonite Slurries Treated by Polymers", ***Journal of Dispersion Science and Technology,*** 34, (2013), 764-770. doi: https://doi.org/10.1080/01932691.2012.695942
18. Altun, G., Ettehadi Osgouei, A., "Investigation and remediation of active-clay contaminated sepiolite drilling muds", ***Applied Clay Science***, 102, (2014), 238-245. doi: http://dx.doi.org/10.1016/j.clay.2014.10.002
19. Ettehadi, A., Ulker, C., Altun, G., "Nonlinear viscoelastic rheological behavior of bentonite and sepiolite drilling fluids under large amplitude oscillatory shear", ***Journal of Petroleum Science and Engineering***, 208, (2022), 109210, doi: https://doi.org/10.1016/j.petrol.2021.109210
20. Asghari, I., Esmaeilzadeh, F., "Manipulation of key parameters in RESS process for attapulgite particles utilizing in drilling mud and investigation on its rheological characteristics", ***Journal of Petroleum Science and Engineering***, 112, (2013), 359-369. doi: http://dx.doi.org/10.1016/j.petrol.2013.09.013
21. American Petroleum Institute Specifications 13I, "Recommended Practice Standard Procedure for Laboratory Testing of Drilling Fluids", (2009).
22. Rabbani, A., Salehi, S., "Dynamic modeling of the formation damage and mud cake deposition using filtration theories coupled with SEM image processing", ***Journal of Natural Gas Science and Engineering***, 42, (2017), 157-168. doi: http://dx.doi.org/10.1016/j.jngse.2017.02.047
23. Fattah, K.A., Lashin A., "Investigation of mud density and weighting materials effect on drilling fluid filter cake properties and formation damage", ***Journal of African Earth Sciences***, 117, (2016), 345-357. doi: http://dx.doi.org/10.1016/j.jafrearsci.2016.02.003
24. Tran, M.H., Abousleiman, Y.N., Vinh, X.N., "The Effects of Low-Permeability Mud cake on Time-Dependent Wellbore Failure Analyses", in IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, (2010). doi: https://doi.org/10.2118/135893-MS
25. Gudarzifar, H., Sabbaghi, S., Rezvani, A., Saboori, R., "Experimental investigation of rheological & filtration properties and thermal conductivity of water-based drilling fluid enhanced", ***Powder Technology***, 368, (2020), 323-341. doi: https://doi.org/10.1016/j.powtec.2020.04.049
26. Mohamed, A., Salehi, S., Ahmed, R., "Significance and complications of drilling fluid rheology in geothermal drilling: A review", ***Geothermics***, 93, (2021), 102066. doi: https://doi.org/10.1016/j.geothermics.2021.102066
27. Ochoa, M.V., "Analysis of drilling fluid rheology and tool joint effect to reduce errors in hydraulics calculations", PhD Dissertation, Texas A&M University, (2006).
28. Ramsey, M.S., "Practical Wellbore Hydraulics and Hole Cleaning", Gulf Professional Publishing, (2019). doi: https://doi.org/10.1016/B978-0-12-817088-5.00006-X.
29. Kamali, F., Saboori, R., Sabbaghi, S., "Fe_3O_4-CMC nanocomposite performance evaluation as rheology modifier and fluid loss control characteristic additives in water-based drilling fluid", ***Journal of Petroleum Science and Engineering***, 205, (2021), 108912. doi: https://doi.org/10.1016/j.petrol.2021.108912
30. Nabati, A., Bahrainian, S.S., Haji Dolu, E., "Improved Rheological Model of Oil-Based Drilling Fluid for Southwestern Iranian Oilfields", ***Journal of Petroleum Science and Technology***, 8, (2018), 53-71. doi: 10.22078/jpst.2017.2706.1459
31. Ouaer. H., Gareche, M., Rooki, R., "Rheological studies and optimization of Herschel–Bulkley parameters of an environmentally friendly drilling fluid using genetic algorithm", ***Rheologica Acta***, 57, (2018), 693-704. doi: https://doi.org/10.1007/s00397-018-1110-z
32. Kelessidis, V.C., Dalamarinis, P., Maglione, R., "Experimental study and predictions of pressure losses of fluids modeled as Herschel–Bulkley in concentric and eccentric annuli in laminar, transitional and turbulent flows", ***Journal of Petroleum Science and Engineering***, 77, (2011), 305-312. doi: https://doi.org/10.1016/j.petrol.2011.04.004
33. Kelessidis, V.C., Maglione, R., Tsamantaki, C., Aspirtakis, Y., "Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during drilling", ***Journal of Petroleum Science and Engineering***, 53, (2006), 203-224. doi: https://doi.org/10.1016/j.petrol.2006.06.004

Persian Abstract

چکیده

سیالات حفاری جز ضروری هر عملیات موفقیت آمیز ساخت چاه هستند. سیالات پایه آبی به دلیل تطابق بهتر با محیط زیست، هزینه کمتر و آماده سازی ساده تر به طور رایج استفاده می شوند. در حفاری فراساحلی، آب دریا می تواند به عنوان پایه سیالات پایه آبی استفاده شود. شوری آب دریا، کاربرد برخی از افزودنی ها را محدود می کند. به عنوان مثال، بنتونیت در محیط های شور ته نشین می شود. در این مطالعه، یک آب مصنوعی بر اساس آب دریای خلیج فارس آماده شد. مخلوط های بنتونیت، بنتونیت پیش هیدراته و آتاپولجیت در آب شیرین و آب مصنوعی ساخته شده، توسعه داده شدند. به منظور ارزیابی عملکرد این سیالات در آب مصنوعی، ویژگی های رئولوژیکی و فیلتراسیون آن ها آزمایش شدند. نتایج اندازه گیری فیلتراسیون نشان دهنده تشکیل کیک گل ضخیم و حجم بالای فیلتراسیون در سیال بنتونیت پیش هیدراته بود. در مورد اتاپولجیت، حجم فلتراسیون در آب مصنوعی در مقایسه با سیال اتاپولجیت در آب شیرین بیشتر بود. اما ویژگی های فیلتراسیون قابل قبول بودند. مطالعه ویژگی های رئولوژیکی نشان داد که مدل هرشل بالکلی می تواند با دقت خوبی جهت پیش بینی خواص رئولوژیکی سیالات به کار رود. این مورد درباره سیالات در آب دریا و آب شیرین صادق بود. همچنین مشاهده شد که شاخص رفتار سیال در همه سیالات کمتر از ۱ بود که نشان دهنده رفتار کاهش گرانروی با افزایش نرخ برش در سیالات می باشد. با افزایش غلظت رس، مقادیر بیشتری از شاخص یکپارچگی، تنش تسلیم و استحکام ژل گزارش شد. در غلظت های بالاتر رس، شبکه سه بعدی قوی تر و در نتیجه سختار ژل قوی تری در محیط های آبی تشکیل می شود. به طور کلی، می توان نتیجه گرفت که اتاپولجیت در محیط شور آب دریای خلیج فارس قابل استفاده است.