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ORIGINAL RESEARCH PAPER

Experimental Investigation on the Effect of Clay Minerals in the Drilling Fluid on Filter Cake Properties

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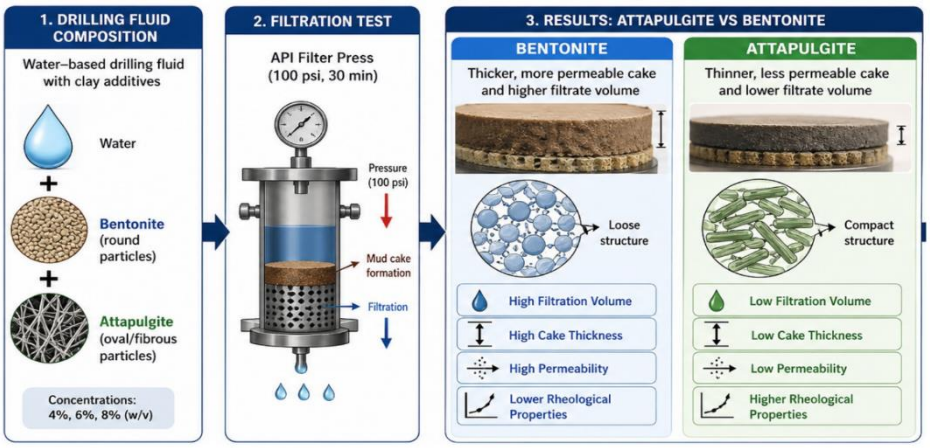
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A B S T R A C T

During the contact of drilling fluid with the formation rocks at the wellbore wall, base fluid is filtered through the rock, where solid components of the fluid are deposited on the rock surface to form a thin layer, called mud cake. Thin, low-permeability and low-porosity mud cakes are desirable to prevent further fluid filtration, provide wellbore stability and minimize stuck pipe possibility. In this study, water-based drilling fluids with the additive of two clay minerals, bentonite and attapulgite, are prepared and experimentally tested for filtration and rheological properties. Based on the results, it was found that drilling fluid with attapulgite additive had 56.2%, 16.1% and 55.8% lower filtration volume, cake thickness and cake permeability comparing to other fluids. Also, Drilling fluids with attapulgite have higher rheological characteristics compared to fluids with bentonite content. This can be due to the better dispersion characteristics of attapulgite. The better performance of the attapulgite is mainly related to its oval particle shape, where a more compact and less permeable cake can be built.



Nomenclature

BV	Bulk Volume	T_{mc}	Mud cake thickness
EDX	Energy Dispersive X-Ray	P_{mc}	Pressure across filter cake
PSD	Particle Size Distribution	**Greek Symbols**	
PV	Pore Volume	ρ_g	Additive density
SEM	Scanning Electron Microscope	ρ_f	Drilling fluid density
K_{mc}	Mud cake permeability	μ	Filtrate viscosity
q	Filtration rat		

1. Introduction

Drilling fluids, also known as drilling muds, are mainly used in the wellbore construction for drill bit cooling, drill string lubrication, transformation of hydraulic power to the bit, wellbore stability provision and prevention of fluid unwanted entrance into the wellbore [1-3].

In an idealized condition, during drilling operations, drilling fluids are constantly circulating in a closed loop, where a certain fluid volume is pumped from surface down to the hole and flows through drill pipes, bit nozzles and annulus back to the surface. Drilling fluids are usually composed of two main components: continuous and discontinuous phases. In water-based fluids, as the most commonly used drilling fluid in the industry, the continuous phase is water and the discontinuous phase is usually solid additives, which are used to

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modify the fluid properties. Among the solid additive, clay minerals, weighting agents and polymers are the mostly used ones. In the contact of drilling fluid with the surrounding rocks, fluid is filtered through the rock, where solid additives are deposited on the rock surface. This leads to gradual formation of a semi-solid layer on wellbore wall, defined as mud cake or filter cake [4]. Thin, low-permeability and low-porosity mud cakes are desirable to prevent further fluid filtration, provide wellbore stability, minimize stuck pipe possibility, and maintain the hole diameter [5-6]. Several factors affect the mud cake propertis, including drilling fluid composition and characteristics, the magnitude of differential pressure between the well and formation, well geometry and formation properties.

There are several experimental studies devoted to the evaluation of mud cake main properties, i.e. porosity, permeability and thickness. Kelessidis et al. (2007) studied the effect of lignite on the bentonite mud cake properties. Authors also developed a methodology for permeability determination of mud cakes. In the conclusions, authors stated that lignite addition at a concentration of 3% by the weight, leads to a significant reduction of mud cake permeability [7].

In the work of Rugang et al. (2014), an experimental study was conducted on the water-based drilling fluids to characterize the impact of fluid compostion on the mud cake properties. Based on the results, it was found that the mud cakes have heterogenous structures and the components in the drilling fluid have a significant impact on mud cake properties and structure [8].

Cook et al. (2016) developed different water-based and oil-based drilling fluids and experimentally characterized the properties of mud cakes. By conducting experimental tests, authors revealed the significant effect of mud cake compostion and properties on the effectiveness of wellbore strengthening technique [9].

Bageri et al. (2020) experimentally studied the effect of perlite as an additive to control drilling fluid filtration. Measuring the mud cake properties, it was found that the perlite addition to barite-based drilling fluids resulted in a thinner, less porous, and less permeable mud cake [6].

Falahati et al. (2020) developed different formulations of water-based drilling fluids and characterized mud cake properties, i.e. porosity, thickness and yield stress. Authors revealed the effects of concentration, size distribution and shape of fluid additives on the mud cake properties. Results showed that mud cakes composed of $CaCO_3$ additive were thicker and stronger than that of $BaSO_4$ [10].

Vipulanandan and Mohammed (2020) investigated the effect of bentonite content on the drilling fluid filtration properties using a standard filtration device. Authors measured filtration volume, mud cake porosity and thickness. Based on the results, less porous and thicker mud cakes were observed by increase in the bentonite content [11].

Clay minerals are the mostly used additive in water based drilling fluids, which are used to enhance the filtration and rheological properties of the fluid. There are different clay mineral groups, applicable in the drilling industry, however, as it can be seen, in most of the previous studies, mud cake properties were investigated for water-based compositions with bentonite as the clay minerals, while the effect of other clays such as attapulgite was not sufficiently covered. Attapulgite or palygorskite ($Si_8O_{20}(Mg, Al, Fe)_5(OH)_2(OH_2)_4.4H_2O$) is a hydrated magnesium aluminum silicate, which has been proved to have better performance, especially in saline and high-temperature environments [1, 12, 13].

Although bentonite has been extensively studied, the effect of attapulgite, especially on mud cake permeability, porosity, and thickness, remains insufficiently investigated [1, 12, 13, 14]. Therefore, this study aims to fill this gap by experimentally comparing bentonite and attapulgite in the drilling fluids and establishing a relationship between rheological and filtration properties. For this purpose, water-based fluids are developed using bentonite and attapulgite to investigate their effect on mud cake properties, i.e., porosity, permeability, and thickness. The novelty of the study lies in the application of attapulgite and bentonite-attapulgite mixture to study their effect on the mud cake properties.

2. Materials and Methods

Water-based drilling fluids with bentonite and attapulgite contents were prepared and tested. Figure 1 represents the schematics of the experimental tests on the additives, drilling fluids, filtrates, and mud cakes.

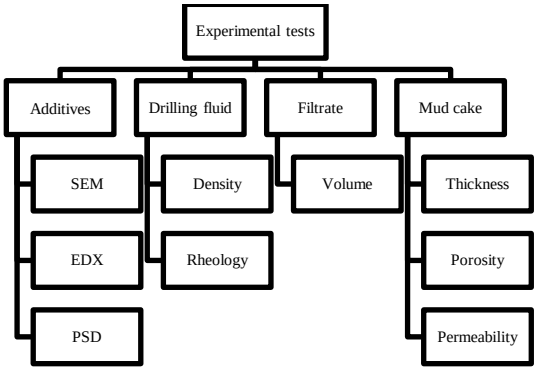


Figure 1. Experimental tests.

2.1. Drilling Fluid Composition and Preparation

Drilling fluids were prepared based on standard procedures, where required amounts of additives were mixed with fresh water for 20 minutes at a speed of 2000 revolutions per minute. TABLE 1 presents tested drilling fluid compositions.

Bentonite, composed of montmorillonite clay mineral ($(Al,Mg)_2(OH)_2(Si,Al)_4O_{10}(Ca)_x$ on H_2O) and attapulgite ($Si_8O_{20}(Mg,Al,Fe)_5(OH)_2(OH_2)_4.4H_2O$) [1, 12], were provided by local producers. SEM (Scanning Electron Microscope) images, EDX (Energy Dispersive X-Ray) and PSD (Particle Size Distribution) analysis were conducted for a more comprehensive characterization of additives.

Table 1. Developed drilling fluid compositions.

Fluid name	Composition			Density, g/cc
	Water, ml	Bentonite, g	Attapulgite, g	
4% Bentonite	350	14.3	0	1.05
6% Bentonite	350	21.3	0	1.08
8% Bentonite	350	28.3	0	1.12
4% Attapulgite	350	0	14.3	1.06
6% Attapulgite	350	0	21.3	1.1
8% Attapulgite	350	0	28.3	1.13

Figures 2 and 3 present the SEM images of bentonite and attapulgite. SEM images can provide a morphological basics for interpretation of particles shapes, which may affect the quality of the mud cake. Qualitative interpretation from SEM images may suggest that the bentonite particles are more spherical in shape, while attapulgite particles are more oval. Also, it can be seen from the figures that there is a distribution of particle sizes in each sample. PSD analysis can be more helpful in a quantitative description of additives.

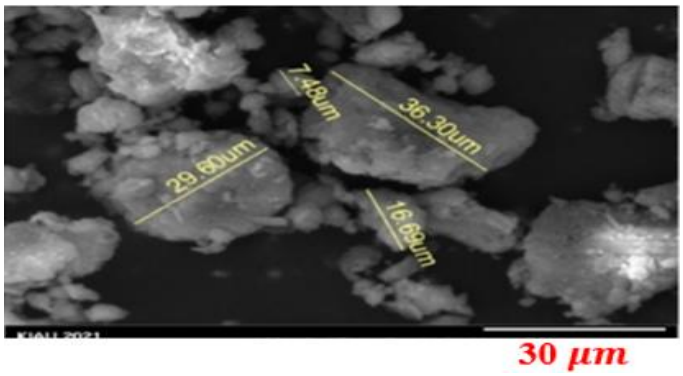


Figure 2. SEM images of bentonite particles.

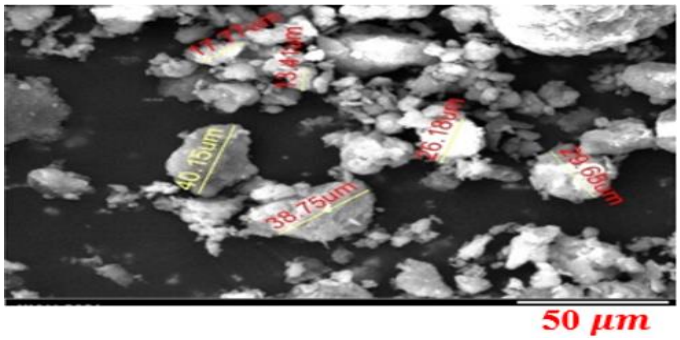


Figure 3. SEM images of attapulgite particles.

EDX with an applied energy of 30 kV was used to identify the elemental composition of the additives. The results of EDX analyses are shown in Figures 4 and 5. The existed elements in the EDX spectrum of bentonite and attapulgite

indicate the purity of the additives, and therefore, they can be used in drilling fluid compositions for further experiments.

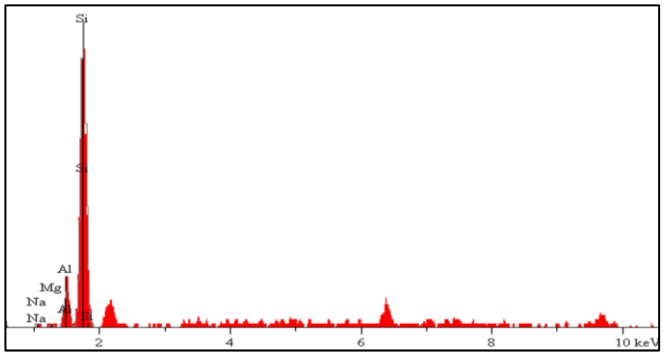


Figure 4. EDX spectrum of the bentonite.

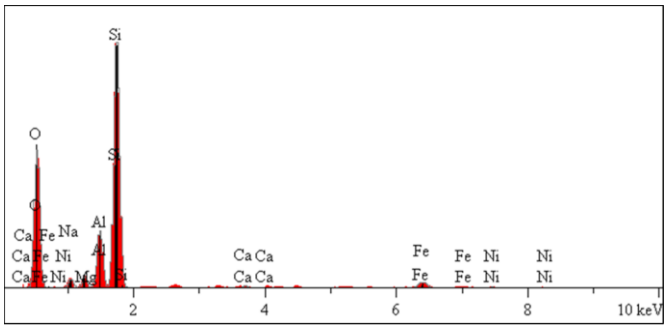


Figure 5. EDX spectrum of the attapulgite.

Diffraction method was used for PSD analysis of the additives. Figures 6 and 7 show the PSD of bentonite and attapulgite. The results of PSD analysis imply that the average size of attapulgite particles (6.137 µm) is larger than bentonite particles (5.062 µm). The size of additives are in direct relation with mud cake properties. For example, mud cakes, composed of larger particles are expected to have larger porosity values.

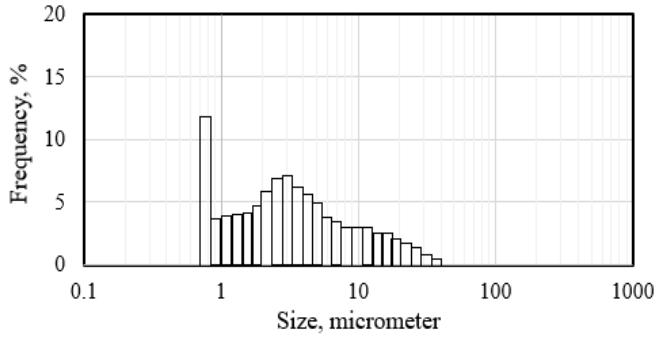


Figure 6. PSD analysis of bentonite.

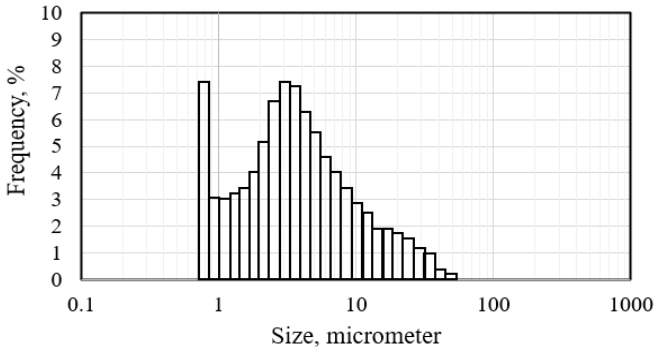


Figure 7. PSD analysis of Attapulgite.

2.2. Experiments

In this section, methodologies of different experiments are presented.

2.2.1. Filtration Test

In the filtration test, the drilling fluid is statically filtered in the filter press equipment under specific pressure and temperature and in a period of 30 minutes. The results of the experiment are reported as the volume of the passed liquid phase through a standard filter paper (filtrate volume, expressed in cm^3/30 min.) and the thickness of the mud cake that was left on the filter paper (Figure 8). After conducting the filtration tests and obtaining mud cakes, further tests were conducted to determine mud cake porosity and permeability. In this research, low-pressure, low-temperature filter press was used (Figure 9), i.e. the mud cakes were formed at room tempertaure and under 100 psi differential pressure.



Figure 8. Mud cake.



Figure 9. Filter press.

2.2.2. Mud Cake Thickness

To measure the mud cake thickness, cakes were obtained from the filtration cell. Then the excess drilling fluid on the mud cake surface was carefully wiped and the thickness was measured in millimeters. This procedure was repeated at several spots and the mud cake thickness was reported as the difference between average measured thicknesses and filter paper thickness.

2.2.3. Mud Cake Porosity

To calculate the mud cake porosity, the cake was obtained from filtration cell. After slow removal of excess drilling fluid from the cake surface, the wet filter paper and mud cake were weighted. The cake wet weight then was calculated by subtracting the wet weight of the filter paper. The cake then was placed for 24 hours at the temperature of 93˚C. The resultant dry cake was weighted. Knowing the wet and dry weights of the cake, additive density and drilling fluid density, the cake porosity can be determined as follows [15]:

$$\emptyset_{mc} = \frac{PV}{BV} \quad (1)$$

where *PV* is the cake pore volume and *BV* is the cake bulk volume. *PV* and *BV* were calculated using following equations:

$$BV = \frac{dry\ weight\ of\ cake}{\rho_g} \quad (2)$$

$$PV = \frac{wet\ weight\ of\ cake - dry\ weight\ of\ cake}{\rho_f} \quad (3)$$

In the above equations, ρ_g is additive density and ρ_f is drilling fluid density.

2.2.4. Mud Cake Permeability

Cake permeability was determined using the approach, suggested by Dewan and Chenevert, where permeability is related to the pressure difference across the mud cake [15, 16]:

$$K_{mc} = 14700 \frac{qT_{mc}\mu}{P_{mc}} \quad (4)$$

In the above equation, K_{mc} is mud cake permeability, q is filtration rate, T_{mc} is mud cake thickness, μ is filtrate viscosity and P_{mc} is pressure across filter cake. Filtration rate (q) can be determined by calculating the slope of straight section in the filtration volume-time curve. For example, for 6 %wt. bentonite, the slope of straight section (q) equals to 0.012 cc/sec (Figure 10).

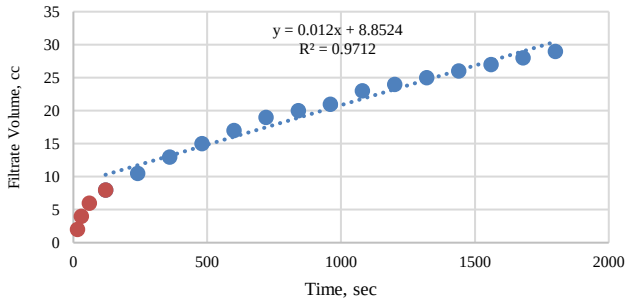


Figure 10. Filtration rate from filtrate volume-time curve.

2.2.5. Rheological Measurements

Drilling fluid rheology indicates how the mud flows under the force exerted by the mud pumps. The viscosity is considered as the most important rheological property of fluids, refering to the resistance of a fluid against the flow. In drilling fluids, various concepts related to the viscosity are discussed. One of the key concepts associated with viscosity in drilling fluids is plastic viscosity, which represents the resistance of the mud to flow caused by friction between the layers of mud. The yield point defines the minimum shear stress required to initiate the flow. This parameter is related to the fluid's ability to retain suspended solid particles and prevent their sedimentation when circulation stops. Fluids with higher yield point have a stronger gel-like structure. While the yield point is a rheological measurmnet in dynamic conditions, gel strength, shows the fluid's ability to maintain its gel-like structure after a period of rest at static conditions. This feature is crucial for preventing cuttings slippage and particle deposition in the bottomhole [17-19].

In this study, the FANN 35a rotary viscometer (Figure 11) was used to measure the rheological parameters of the drilling fluid at laboratory conditions. The device creates a uniform shear field and examines the flow behavior of the mud under controlled conditions. For rheological measurements, the needle deflection of viscometer indicator at each rotational speed was measured and following equations were used to calculate different rheological properties [20]:

$$\gamma = 1.703 \times V \quad (5)$$

$$\tau = 1.067 \times R \quad (6)$$

$$\mu_P = \theta_{600} - \theta_{300} \quad (7)$$

$$\tau_Y = \theta_{300} - \mu_P \quad (8)$$

where V is viscometer rotational speed, R is the value of needle deflection, γ is shear rate, τ is shear stress, μ_P is plastic viscosity, τ_Y is yield pint, θ_{600} and θ_{300} are the viscometer deflections at 600 and 300 rpm rotational speeds respectively.

For gel strength calculation, the fluid was remained constatnt for 10 seconds and 10 minutes. After being in static conditions, the readings of viscometer at 3 RPM and 6 RPM rotational speeds were reported as initial and 10 minutes gel strength of the drilling fluid [20].



Figure 11. FANN 35a rotary viscometer.

3. Results and Discussion

In this section, results of experimental analysis on fluid rheology, filtration volume, mud cake thickness, porosity and permeability are presented. Figure 12 shows the filtration volume of different drilling fluids.

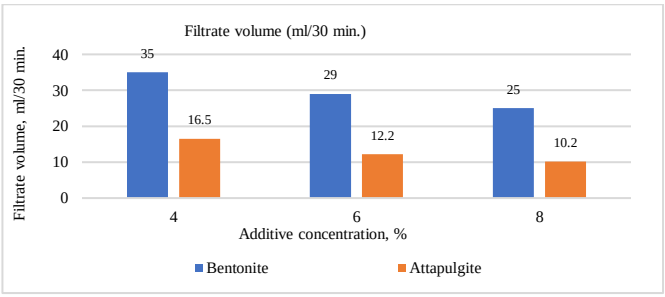


Figure 12. Filtrate volume from the filtration tests.

The results show that by the increase in clay concentration (bentonite, attapulgite and their mixture), the filtration volume decreases. In fact, increase in solid concentration in the fluid prevents fluid movement through the filter paper, resultig in less filtration volume.

Also, it is evident from the Figure 12 that less filtrate volume is observed in the fluids containing attapulgite. The reason for this trend can be the oval shape of the attapulgite particles, where a stronger bridge-like structure is created to prevent the fluid flow through mud cake.

Thicknesses of obtained mud cakes are presented in Figure 13. Results show that the increase in the clay concentration led to an increase in the mud cake thickness, which seems consistent with expected behavior considering the presence of more solids in the composition. In addition, drilling fluids containing attapulgite proved to be thinner than other fluids. This could be due to the oval shape of the attapulgite particles, which forms a more compact structure of the mud cake.

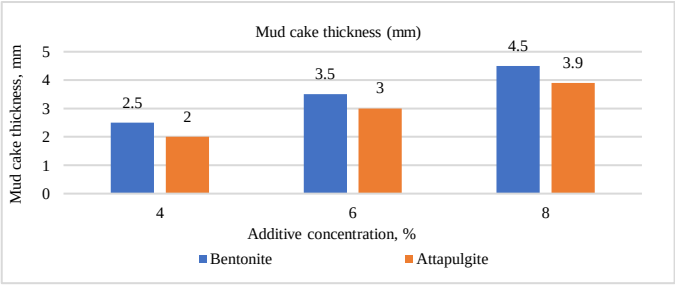


Figure 13. Mud cake thickness from filtration tests.

From Figure 14, it can be concluded that the porosity variation for different compositions is not significant. However, mud cakes of attapulgite drilling fluids have higher porosities due to the larger size of attapulgite particles compared to bentonite particles.

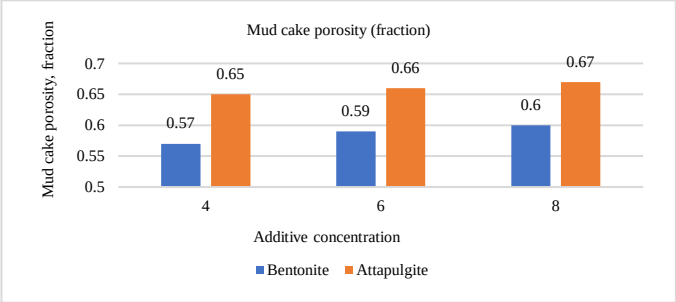


Figure 14. Mud cake porosity.

Figure 15 shows that the mud cakes of attapulgite drilling fluids have lower permeabilities than other cakes. This result is in agreement with the filtration volume results, presented in Figure 12. Lower permeability is directly related to the shape of particles where oval-shaped particles of the attapulgite can be more efficient in permeability reduction, compared to the spherical particles of the bentonite.

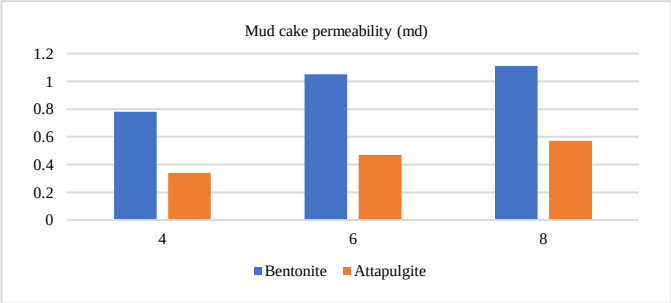


Figure 15. Mud cake permeability.

Results of the Figures 12-15 showed that in average, attapulgite fluids showed 56.2%, 16.1% and 55.8% lower filtration volume, cake thickness and cake permeability respectively. This results can be attributed to the oval shape of the attapulgite particles, where more comapct cake structure is formed under the pressure.

The results of rheological measurements on the drilling fluids are shown in Figures 16, 17.

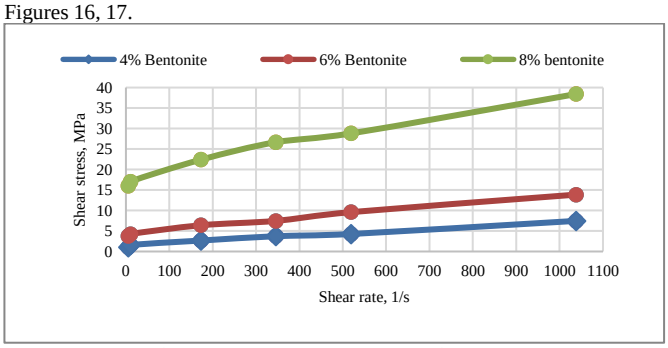


Figure 16. Results of rheological measurment on drilling fluid with bentonite.

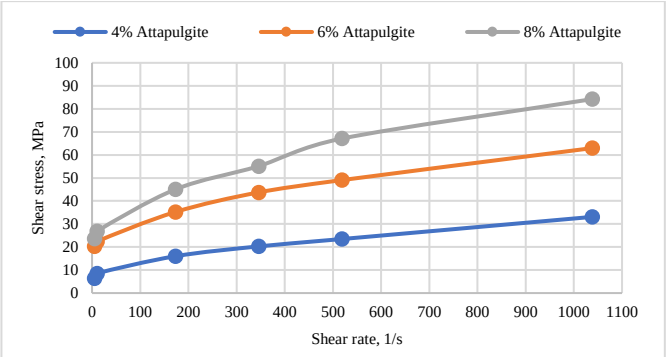


Figure 17. Results of rheological measurment on drilling fluid with attapulgite.

Also, the plastic viscosity, yield point and the gel strengths of the developed drilling fluids were detemined (Table 2). As the results imply, drilling fluids with attapulgite have higher rheological characteristics compared to fluids with bentonite content. This indicates the better dispersion characteristics of attapulgite. Higher yield point and gel strength can improve cuttings suspension and wellbore cleaning efficiency.

Table 2. Rheological properties of drilling fluids.

NO.	Clay Concentration	PV	YP	Initial Gel Strength ($lb_f/100ft^2$)	10 Min Gel Strength ($lb_f/100ft^2$)
1	4% Attapulgite	9	13	40	53
2	6% Attapulgite	13	33	80	90
3	8% Attapulgite	15	36	86	108
4	4% Bentonite	3	1	8	12
5	6% Bentonite	4	5	17	20
6	8% Bentonite	9	18	50	55

For furthur investigation, the relationship between drilling fluid rheological properties and filtration of fluids was investigated. Figure 18 shows the fluid plastic viscosity versus filtrate volume. The results shows that there is an inverse relationship between fluid plastic viscosity and filtration volume, showing a linear relationship for fluids with attapulgite content. This result seems reasonable as fluids with higher viscosities show higher resistance against flow to into the formation.

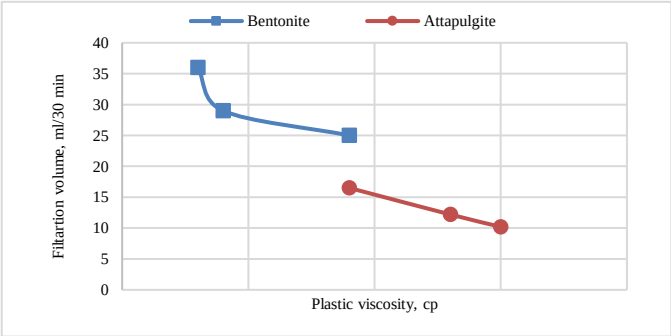


Figure 18. Filtrate volume versus plastic viscosity.

4. Conclusions

Based on the results of the experimental tests on the effect of bentonite and attapulgite on the drilling fluid filtration and rheological properties, following conclusions can be made:

- Attapulgite provided better filtration properties for the drilling fluid than bentonite, where a lower filtration volume, cake permeability and cake thickness were reported. In average, attapulgite fluids showed 56.2%, 16.1% and 55.8% lower filtration volume, cake thickness and cake permeability respectively.
- Drilling fluids with attapulgite have higher rheological characteristics compared to fluids with bentonite content. This can be due to the better dispersion characteristics of attapulgite.
- The improved performance of attapulgite additive is most likely due to the fibrous morphology, which enhances particle interlocking and reduces pore connectivity within the filter cake.

Credit Authorship Contribution Statement

Mehdi Mazloom: Investigation and perform calculations, Seyyed Shahab Tabatabaee Moradi: Supervision, Project administration, and Manuscript writing and editing results.

Conflicts of Interest

The authors declare that they do not have any personal or financial conflicts of interest.

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