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Improving the Performance of Water-based Drilling Fluids Using Sulfonated Asphalt

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ABSTRACT

Water-based drilling fluids (WBDFs) are extensively utilized in the oil and gas industry due to their environmental friendliness and economic advantages. However, their performance can be limited under challenging downhole conditions owing to fluid invasion and filtrate loss, which negatively affect wellbore stability and formation productivity. This study evaluated the effectiveness of different concentrations of sulfonated asphalt as a filtration-control additive in WBDFs. The drilling fluid samples were tested under laboratory conditions at 25 °C and 100 psi using standardized American Petroleum Institute (API) methods to evaluate density, pH, rheological properties, filtration characteristics, and filter cake thickness. The results showed a minimal impact on the density, with the pH values remaining within the recommended alkaline range for WBDF stability. Rheological properties indicated an increase in the yield point (12.5–27.4 lb/100 ft^2) and apparent viscosity (19.3–24.8 mPa•s), while the plastic viscosity slightly decreased (13.0–11.1 mPa•s). API filtration was significantly reduced from 9 mL to 5.4 mL (~40%), accompanied by a decrease in the filter cake thickness, indicating the formation of a thinner and less permeable barrier. Overall, sulfonated asphalt is an effective additive for improving the filtration control while enhancing the rheological performance of WBDFs.

Keywords: drilling fluid, rheological properties, american petroleum institute filtration, fluid loss, filter cake

1. INTRODUCTION

In oil and gas drilling, drilling fluids are indispensable for efficient and safe operations, as they transport drill cuttings to the surface, preserve wellbore integrity, and maintain control over formation pressures [1,2]. The effectiveness of these fluids depends largely on their rheological and filtration properties, which directly influence drilling efficiency and operational safety [3,4]. Poor drilling fluid performance can lead to significant drilling problems, including wellbore instability, differential sticking, and formation damage [4].

During overbalanced drilling, pressure differences between the wellbore and formation cause filtrate and fine solids to invade the formation [5]. As a result, pore throats can become plugged, permeability may decrease, and overall formation performance can be adversely affected, a significant decline in well productivity. Therefore, drilling fluids should form a thin, low-permeability filter cake to control fluid loss and prevent solid intrusion into the formation [6].

Extensive research has been conducted to improve drilling fluid performance using various additives, including polymers, bridging materials, and more recently, nanoparticles [7–10]. Polymeric additives are widely used because of their ability to enhance rheological properties and reduce fluid loss [11]; however, they often suffer from thermal degradation and reduced effectiveness under high-temperature conditions. Similarly, nanoparticle-based additives have shown promising results in improving filtration control and wellbore stability owing to their small particle sizes and high surface areas [12,13]. Despite these advantages, their practical applications are limited by their high cost, complex preparation methods, and potential environmental concerns.

In comparison, asphalt-based additives offer a cost-effective and environmentally compatible alternative, with the ability to act as efficient pore-plugging agents and form low-permeability filter cakes [14,15]. However, despite their potential, there are still limited experimental data evaluating the performance of sulfonated asphalt in water-based drilling fluids (WBDFs) under standard operating conditions, particularly in terms of their combined effect on rheological behavior, filtration control, and filter cake characteristics.

Therefore, this study aimed to address this research gap by systematically evaluating the performance of different concentrations of sulfonated asphalt as an additive in WBDFs. The novelty of this work lies in the integration of comprehensive drilling-fluid performance evaluation with advanced microstructural characterization and optimization of sulfonated asphalt-based formulations. This study focused on quantifying the impact of sulfonated asphalt on key drilling fluid properties, including rheology, American Petroleum Institute (API) filtration, and filter cake thickness, while investigating its microstructural characteristics using

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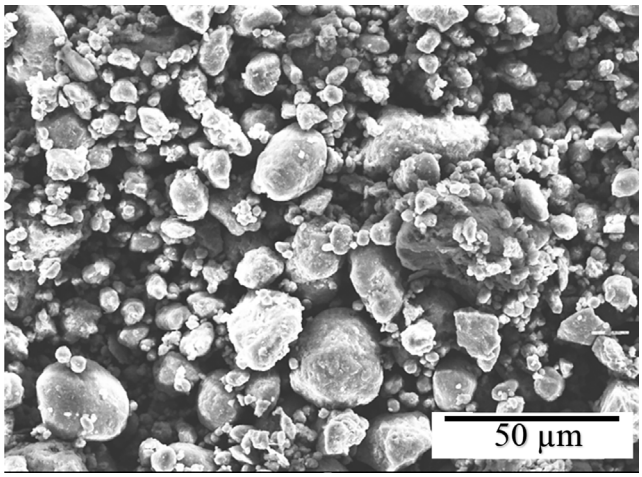


Figure 1. SEM image of the sulfonated asphalt particles

scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). The findings of this study contribute to a better understanding of the potential of sulfonated asphalt as a practical and efficient alternative to conventional additives in drilling fluid systems.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Materials. Sulfonated asphalt was used as a filtration-control and shale-stabilizing additive in the WBDF system, where it helps reduce HPHT fluid loss and improve wellbore stability.

Fresh water was used as the base fluid in the drilling fluid formulations. XC-polymer was used as a viscosifier to improve the rheological properties and suspension stability. Starch was added as a fluid-loss control additive. Lime was used as a pH-control agent to maintain the alkalinity of the drilling fluid system. Calcium carbonate ($CaCO_3$) with fine and medium particle sizes was used as the bridging and weighting material. A defoamer additive was used to minimize foam generation during mixing.

2.2. Sulfonated Asphalt Particle Characterization. SEM characterization was carried out using a JEOL JSM-5900LV microscope to evaluate the morphology and surface characteristics of the sulfonated asphalt additive. Figure 1 shows irregularly shaped particles with a heterogeneous structure that may aid pore plugging and filter cake formation.

Table 1. *Composition of the WBDF*

Name	Unit	Base drilling fluid
Water	mL	324.65
Defoamer	g	0.1
Lime	g	0.25
XC-polymer	g	1.5
Starch	g	3.5
$CaCO_3$ fine	g	4
$CaCO_3$ medium	g	4
Weighting material ($CaCO_3$)	g	85

The elemental composition of the sulfonated asphalt was determined using EDX (Oxford Instruments, Oxford, United Kingdom) attached to the scanning electron microscope. The EDX spectrum in Figure 2 confirms the presence of carbon (C), oxygen (O), sodium (Na), and sulfur (S), which are the principal elements in sulfonated asphalt. C was identified as the dominant element, followed by O, Na, and S, which is consistent with the chemical composition of sulfonated asphalt additives used in drilling fluid systems [16].

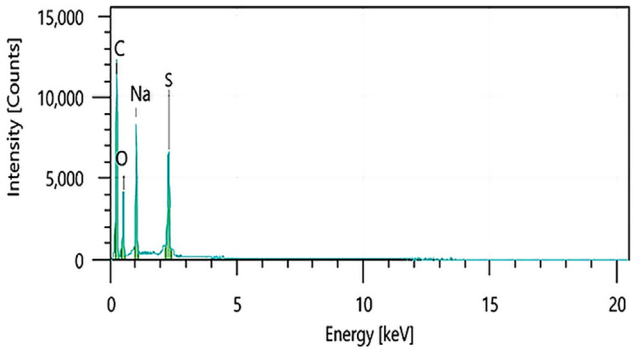
2.3. Drilling Fluid Composition and Preparation. The WBDF used in this investigation was prepared according to the formulation detailed in Table 1. The selected formulation was designed to provide a stable rheological performance and effective filtration control during drilling operations.

Mud 1 represents the base WBDF without sulfonated asphalt, whereas Mud 2, Mud 3, and Mud 4 were prepared by adding 1, 2, and 3 g of sulfonated asphalt, respectively, to the base drilling fluid formulation.

2.4. Experimental Methods.

2.4.1. Test setup. An experimental setup was designed to evaluate the physical, rheological, and filtration properties of WBDF under controlled laboratory conditions. All tests were conducted at ambient temperature (approximately 25 °C) to ensure consistency and repeatability of the results.

All drilling fluid samples were prepared under controlled conditions using a laboratory-scale mixer. Each additive, listed in Table 1, was added and mixed at a moderate shear rate for 15 min to ensure proper hydration and uniform dispersion. Sulfonated asphalt was then gradually added at concentrations of 1, 2, and



Element	Mass Percentage (%)	Atomic Percentage (at%)
C	56.1	67.5
O	23.6	21.3
Na	11.5	7.2
S	8.8	4.0
Total	100	100

Figure 2. EDX spectrum and elemental composition of sulfonated asphalt

3 g under continuous mixing, followed by an additional 10 min at a higher shear rate to ensure full dispersion. The samples were allowed to rest for 5 min to remove entrained air before testing [15]. All measurements were performed immediately after preparation to maintain consistency.

The experimental setup consisted of four main laboratory techniques used to evaluate drilling fluid performance: density measurement, pH measurement, rheological characterization using a rotational viscometer, and API filtration testing using a filter press. Drilling fluid density was measured with a mud balance, followed by pH determination using a digital pH meter. Rheological characterization was carried out using a rotational viscometer, whereas filtration properties were assessed using an API filter press.

All equipment was arranged in a controlled laboratory environment to minimize external variations. Each test was conducted using freshly prepared samples to avoid contamination or changes in fluid properties over time. The setup ensured that all measurements were performed under consistent conditions, allowing for a reliable comparison of the results. Each measurement was performed at least twice and the reported values represent the average, with only minimal variation observed between readings. A schematic representation of the experimental setup is provided in Figure 3.

2.4.2. Instrumentation. A range of calibrated laboratory instruments was employed to characterize the drilling fluid properties, with each instrument used to assess a particular parameter of the fluid system. Calibration was performed prior to testing to ensure measurement accuracy and consistency.

The density of the drilling fluid was measured using a Baroid mud balance, which provided direct readings of pounds per gallon (ppg), pounds per cubic foot (pcf), specific gravity, and the pressure gradient. The instrument operates using a fixed-volume cup and a balance arm with a sliding rider. Calibration was performed using freshwater with a known density of 8.33 ppg. The sample was then placed in a cup, and the rider was adjusted until the beam was level, allowing the density to be read directly from the scale.

A digital pH meter was used to measure the pH of the drilling fluid, providing an indication of the system's chemical stability. The instrument was calibrated prior to measurement using standard buffer solutions and the probe was immersed in the sample to obtain accurate pH readings under ambient laboratory conditions.

The drilling fluid samples were subjected to controlled rotational speeds ranging from 3 to 600 RPM. Dial readings were recorded at standard speeds (600, 300, 200, 100, 6, and 3 RPM), enabling the calculation of the apparent viscosity (AV), plastic viscosity (PV), and yield point (YP).

The filtration properties were evaluated using a standard API filter press. The test was conducted at a constant pressure of 100 psi for a duration of 30 min at approximately 25 °C. The system consisted of a pressurized cell equipped with filter paper, where fluid was forced through the medium and solids accumulated to form a filter cake. The filtrate volume was collected using a graduated cylinder and recorded at specific time intervals, including 30 s and 1, 2, 3, 4, and 5 min, followed by measurements at 10, 20, 25, and 30 min to monitor the cumulative fluid loss over time.

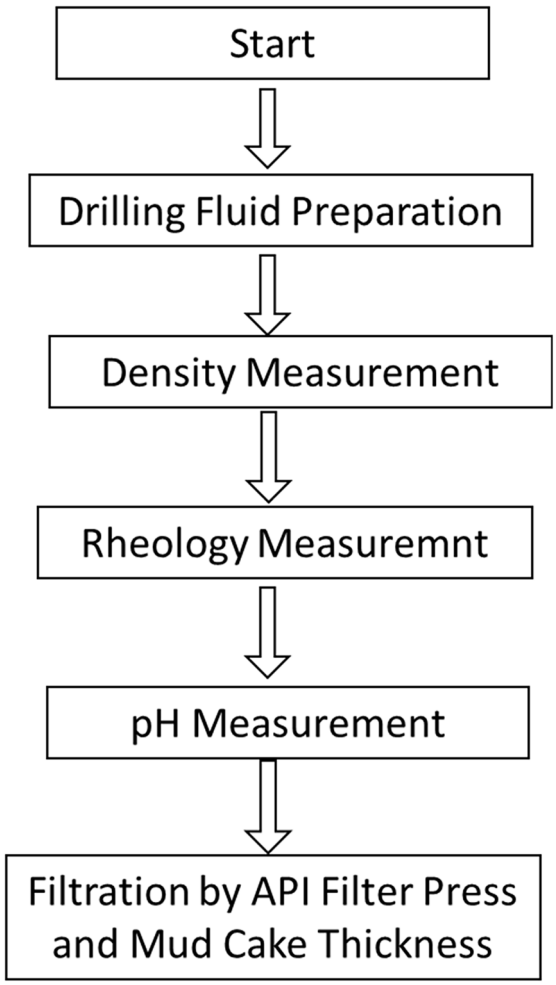


Figure 3. Experimental workflow illustrating the sequence of drilling fluid preparation and characterization procedures, including density, pH, rheological, and API filtration measurements

At the end of the test, the filter cake formed on the filter paper was carefully removed and its thickness was measured using a ruler with a resolution of 1/32 in. The filter paper containing the mud cake was weighed using a digital balance to determine the total mass.

To enhance clarity and reproducibility, representative images of the instruments used in this study are shown in Figure 4, including the mud balance, digital pH meter, rotational viscometer, and API filter press. These instruments constitute the core measurement system for evaluating the drilling fluid performance and ensuring standardized testing conditions.

3. RESULTS AND DISCUSSION

3.1. Density and pH. The measured density and pH values of the drilling fluid samples are listed in Table 2. The results indicate that the addition of sulfonated asphalt has a limited influence on the chemical stability of the system, as all pH values remained within the alkaline range (11.9–12.6), which is typical for WBDFs. Maintaining alkaline pH is important for preserving clay inhibition, minimizing corrosion, and maintaining drilling fluid stability during drilling operations.

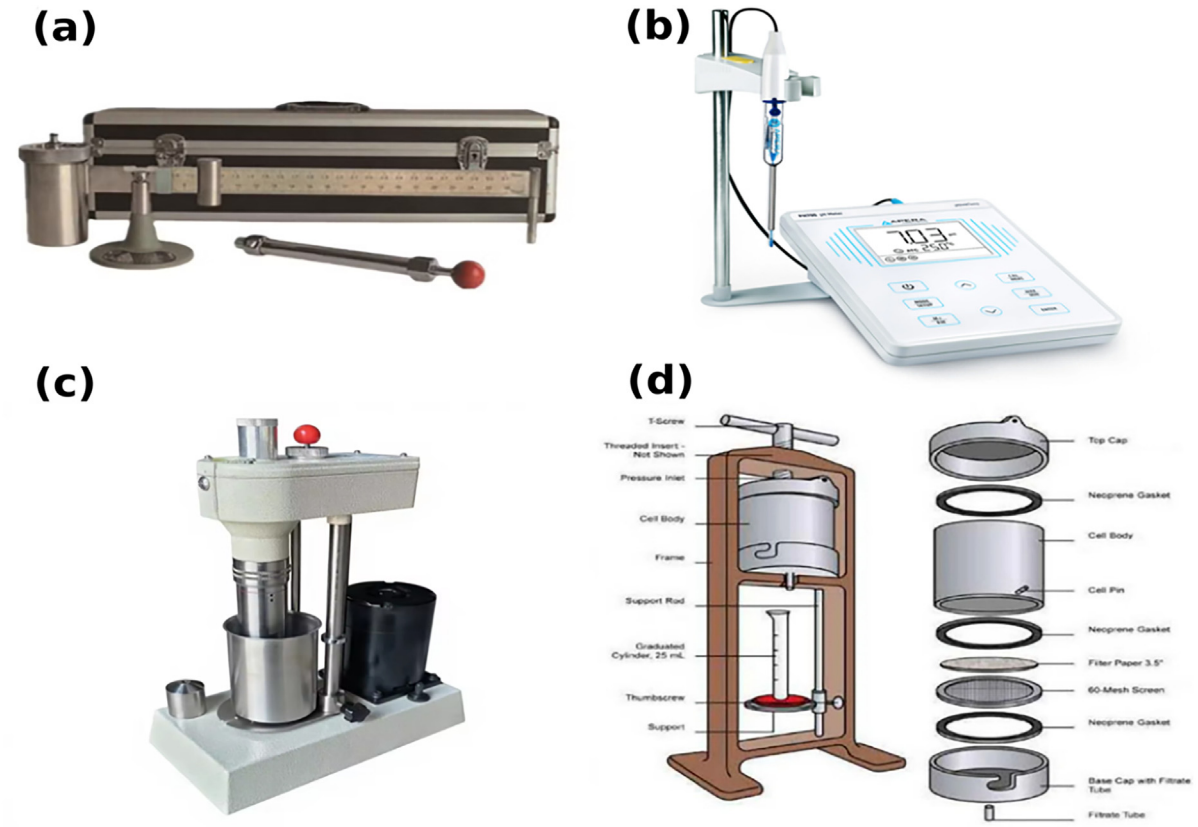


Figure 4. Laboratory instruments used for drilling fluid characterization: (a) mud balance, (b) pH meter, (c) rotational viscometer, and (d) API filter press

Table 2. *Density and pH values of drilling fluid samples*

Sample	Density (ppg)	pH
Mud 1 (base)	10	12.6
Mud 2	10.1	12.0
Mud 3	9.9	12.3
Mud 4	9.9	11.9

Table 3. *Rheological parameters (PV, YP, and AV) of the drilling samples*

Sample	PV (mPa · s)	YP (lb/100 ft²)	AV (mPa · s)
Mud 1 (Base)	13.0	12.5	19.3
Mud 2	14.2	15.5	21.9
Mud 3	12.4	18.9	21.9
Mud 4	11.1	27.4	24.8

A slight increase in density was observed at low additive concentrations (Mud 2), followed by a gradual decrease at higher concentrations. The reduction in density at elevated concentrations (Mud 3 and Mud 4) is possibly associated with incomplete dispersion and air entrainment during mixing. This behavior suggests that excessive additive loading may alter the fluid structure, leading to an apparent reduction in bulk density. Such effects have been reported for drilling fluids containing fine particulate additives, in which poor dispersion and particle agglomeration can increase the porosity and permeability of the filter cake [16].

The pH values remained within the recommended alkaline range (11.9–12.6) for stable WBDF operation, indicating that the addition of sulfonated asphalt did not significantly affect the chemical stability of the drilling fluid system. These results confirm that sulfonated asphalt does not significantly disrupt the chemical environment of the drilling fluid, although its dispersion behavior at higher concentrations should be carefully controlled.

3.2. Rheological Properties of Drilling Fluids. The rheological properties of the tested drilling fluids were evaluated using a rotational viscometer. Measurements were recorded at standard rotational speeds, the PV, AV, and YP were determined using the standard equations.

$$PV = \theta_{600} - \theta_{300} \quad (1)$$

$$AV = \frac{\theta_{600}}{2} \quad (2)$$

$$YP = \theta_{300} - PV \quad (3)$$

The rheological parameters (PV, YP, and AV) are summarized in Table 3 and Figure 5. An increasing sulfonated asphalt concentration produced a clear trend, indicating a strong effect on the drilling fluid's internal structure.

The YP showed a substantial increase, rising from 12.5 lb/100 ft² in the base fluid to 27.4 lb/100 ft² in Mud 4. This enhancement suggests improved interparticle interactions and stronger gel structure formation [17], which are critical for effective cutting suspension and transport. Similarly, the AV increased, indicating an improved carrying capacity of the fluid system [18,19]. This behavior is advantageous for enhancing the transport efficiency

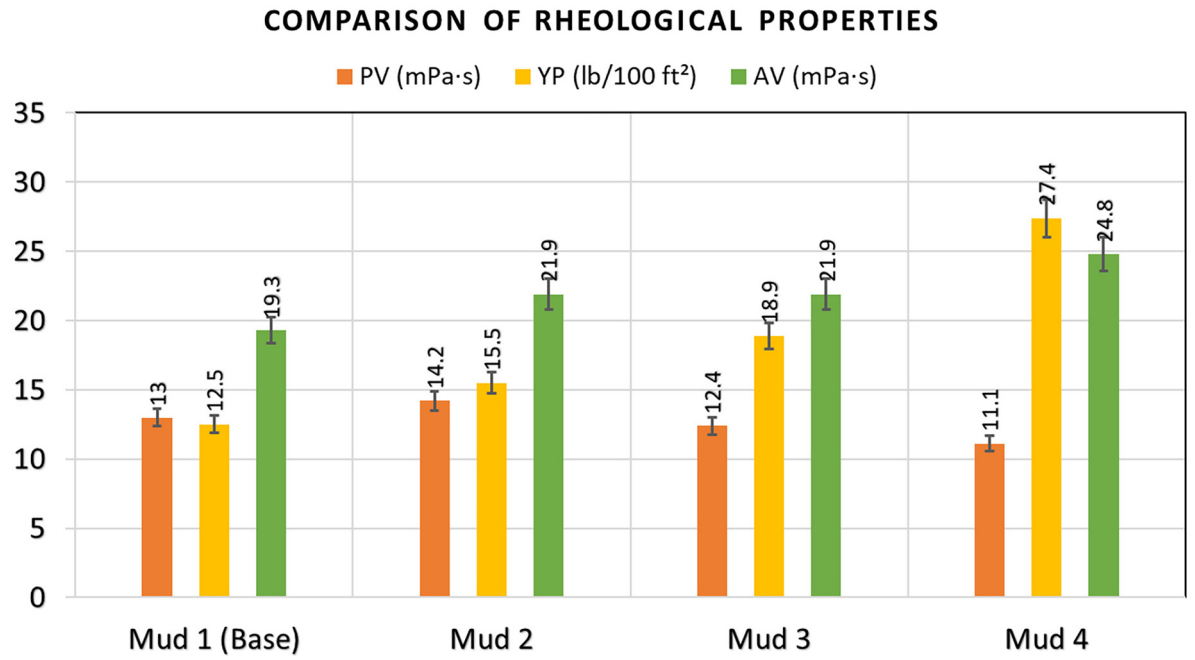


Figure 5. Comparison of the rheological parameters (PV, YP, and AV) of the tested drilling samples

of cuttings and preventing solid settling in the annulus during drilling operations.

In contrast, the PV exhibited a slightly decreasing trend at higher concentrations. This behavior may be attributed to changes in the particle alignment and reduced frictional resistance between solid particles under shear conditions. The decrease in the PV may also indicate improved particle distribution and reduced solid–solid interactions within the fluid system.

From a practical perspective, increases in YP and AV are beneficial for hole cleaning and wellbore stability. However, the significantly high YP observed at the highest concentration may lead to increased pump pressure requirements and energy consumption during drilling[20]. Therefore, although sulfonated asphalt improves the rheological performance, an optimal concentration must be selected to balance the performance and operational efficiency. The observed improvements in the YP and AV are consistent with previous studies on asphalt-based drilling fluid additives, which reported enhanced gel strength, improved suspension characteristics, and better hole-cleaning performance in WBDF systems[21]. However, slight variations in the PV behavior compared with previous investigations may be attributed to differences in the additive concentration, base fluid composition, and testing conditions[22].

3.3. API Filtration. The API filtration results and filter cake thicknesses are shown in Figures 6 and 7. A consistent reduction in fluid loss was observed with increasing sulfonated asphalt concentration, decreasing from 9.0 mL in the base fluid to 5.4 mL in Mud 4, corresponding to a total reduction of approximately 40%, as listed in Table 4.

The enhanced filtration performance can be attributed to the effective pore-plugging action of sulfonated asphalt particles. These particles are believed to deposit on the filter medium and penetrate pore spaces, creating a low-permeability barrier that

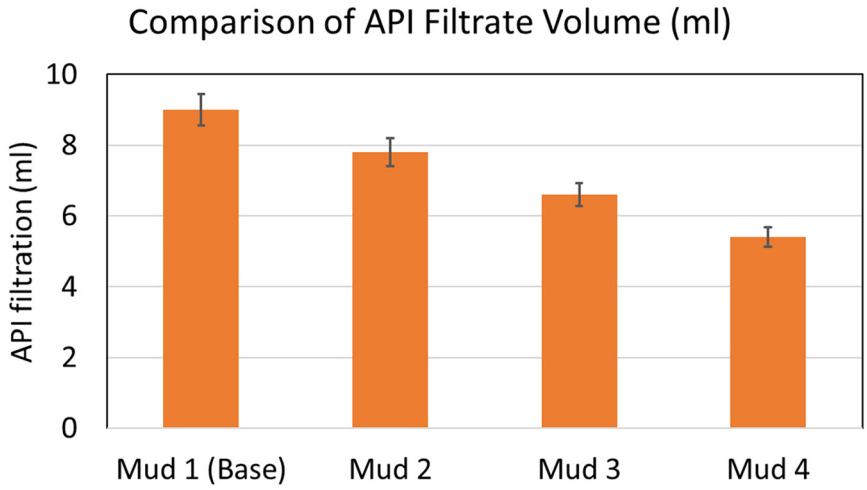


Figure 6. API filtration values of the tested drilling fluid samples

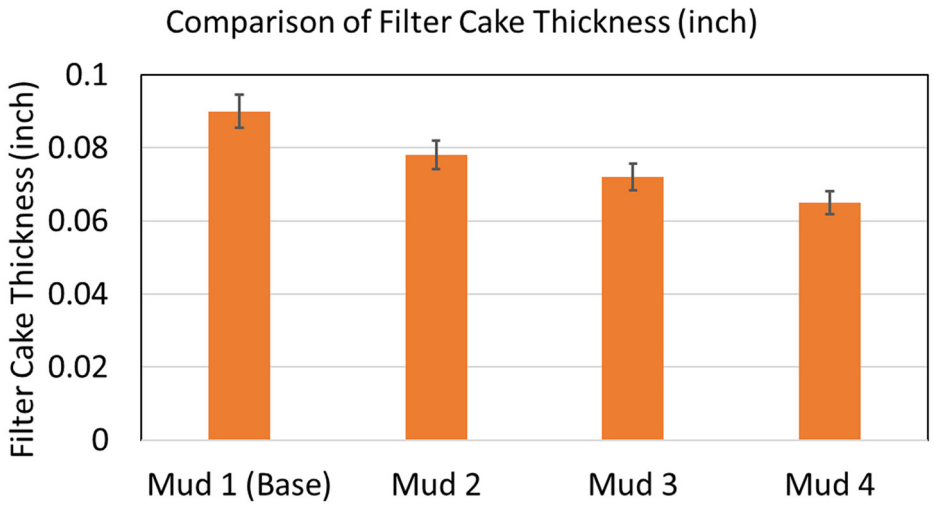


Figure 7. Filter cake thicknesses of the tested drilling fluid samples

Table 4. *Percentage decrease in API filtration for the tested drilling samples*

Sample	API Filtration Reduction (%)
Mud 2	13.3
Mud 3	26.7
Mud 4	40.0

minimizes filtrate invasion. Moreover, their fine particle size distribution and deformability improve their sealing efficiency under differential pressure, promoting the formation of a dense barrier. This interpretation is consistent with the observed reduction in filter cake thickness, which reflects the development of a thinner and more compact filter cake.

The reduction in the filter cake thickness from 0.09 to 0.065 in suggests improved packing efficiency and reduced permeability, which are desirable characteristics for minimizing formation damage[23]. A thinner, denser filter cake enhances wellbore stability and reduces differential sticking risks. Reduced filtrate invasion is also beneficial for minimizing formation damage and preserving formation permeability during drilling. These results demonstrate that sulfonated asphalt is highly effective as a filtration-control additive, particularly at higher concentrations, although the associated rheological changes must be considered. The reduction in API filtration observed in this study agrees with previous studies that reported that sulfonated asphalt improves filtration control through pore plugging and the formation of low-permeability filter cakes in WBDF systems[17]. Differences in the magnitude of filtration reduction reported in the literature may be associated with variations in the particle size distribution, drilling fluid formulation, and operating conditions.

4. CONCLUSIONS

This study demonstrated that sulfonated asphalt effectively improved the performance of WBDFs under standard laboratory conditions (25 °C and 100 psi). The API filtration was reduced from 9.0 to 5.4 mL (approximately 40%), while the YP increased from 12.5 to 27.4 lb/100 ft^{2}and the AV from 19.3 to 24.8 mPa · s, indicating an enhanced carrying capacity. The density and pH remained within the recommended operating ranges for stable WBDF systems, confirming their chemical and rheological stability. These findings highlight the potential of sulfonated asphalt as a practical and cost-effective additive for filtration control while maintaining acceptable rheological properties. However, this study was limited to standard conditions, and the performance under HPHT conditions was not evaluated. Future studies should focus on investigating the behavior of sulfonated asphalt under HPHT conditions and optimizing its concentration for field-scale applications.

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