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Research Article

The Rheology and Performance of Geothermal Spring Water-Based Drilling Fluids

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In this study, the rheological properties and performances of mud prepared with geothermal spring water to be used by geothermal drilling operators were examined at ambient and elevated temperatures. In this context, mud samples were prepared in the compositions detailed in the API specification by using five different geothermal spring water types and a distilled water type. Afterwards, density, apparent viscosity, plastic viscosity, yield point, gel strength, fluid loss, pH, and filter cake thickness of these samples were measured. The drilling muds were analyzed by means of rheological tests in accordance with the standards of the American Petroleum Institute (API). The experimental results have revealed that the mud prepared with geothermal water have lower viscosity and yield point compared to those prepared with freshwater at elevated temperatures. The stability of the muds decreases, especially at temperatures higher than 250°F, and they start to become flocculated. It was concluded that geothermal water-based muds have higher API fluid loss and cake thickness than the freshwater-based one. Therefore, it could be interpreted that the muds prepared with geothermal spring water will exhibit lower flow performance and lower ability of hole cleaning and rate of penetration compared to the freshwater muds. Hence, it is recommended that this kind of water should not be used to prepare drilling mud.

1. Introduction

Drilling fluids are an important circulation component for the drilling process [1]. The drilling fluids are basically divided into three categories according to their continuous phase: water-based muds, oil-based muds, and gas-based muds [2]. A typical water-based mud usually consists of suspension of clay particles in water. Some of the main functions of the muds are transporting of cuttings, lubricating of drill string, preventing an influx of formation fluids, controlling the hydrostatic pressure, and stabilizing the well [3, 4]. The drilling muds must have certain rheological and filtration properties in order to perform these functions [5]. It is relatively difficult to maintain these properties of the mud during geothermal drilling [6, 7]. As it is well-known, geothermal drillings are carried out under hot and naturally fractured and/or vugular formations where they cause a large amount of lost circulation and degradation [8]. The lost circulation

is one of the most complicated problems that have existed in drilling engineering and leads to the requirement for a large volume of drilling fluid [9]. Therefore, it is significant for the operators to provide water from the source closest to the well site, both economically and technically. Operators sometimes use a geothermal spring source which is close to the well site to prepare drilling mud. In geothermal systems, geothermal water ascends to the surface by reacting with the subsurface formations causing mineral dissolution, so the variety and concentration of dissolved constituents in the geothermal waters are higher than those of freshwaters. The geothermal water composition is characterized by the macroelements of the reservoir rock and the subsurface environment to which it is exposed most of the time. The most frequently observed ions with high concentrations are Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO_3^-, CO_3^{2-}, SO_4^{2-}, and CO_2. Other micropollutants are heavy metals such as mercury, copper, lead, silver, iron, zinc, arsenic, manganese, chromium,

beryllium, selenium, vanadium, cadmium, nickel, strontium, uranium, cobalt, gallium, and antimony. Some other elements of boron and silica could be present in geothermal waters as well [10]. Therefore, these waters are likely to affect the drilling fluid properties such as rheology, fluid loss, shale inhibition, and lubricity.

There are various studies in the literature regarding the change in rheological and filtration properties depending on temperature, pressure, various contaminants and some additives, or the chemistry of the clays used. Some of these studies examined the effect of various additives on rheological properties without changing the fluids used to prepare mud while others have studied the effect of different fluids on rheological properties by keeping the additives constant. For instance, Vipulanandan and Mohammed [11] used nanoclays, Jain et al. [12] used nanocomposites, Kang et al. [13] used nanoparticles, Cai et al. [14] used nanosilicates, Li et al. [15] used cellulose nanocrystals, Navarrete et al. [16] used guar gum, Yan et al. [17] used synthetic polymers, Mahto and Sharma [18] used tamarind gum, Ahmad et al. [19] used acrylamide-based copolymer, and Meng et al. [20] used carbon ash as an additive to examine the effects on drilling mud. As a result, they observed that these additives improved the rheological properties to be present in an effective drilling mud. Luo et al. [4] and Ofei et al. [21] have used ionic liquids as an additive for drilling muds, and they concluded that these liquids reduce fluid loss by improving the rheological properties of drilling muds even at elevated temperatures. Kelessidis et al. [22] and Abu-Jdayil [23] analyzed the rheological properties of drilling muds prepared with salty water. They have stated that viscosity and yield point decreased whereas the filtrate volume increased as the concentration of salt increased. Furthermore, they observed that mud samples present shear thickening behavior with an increase in salt content. Zhao et al. [24] studied the effect of Na, K, Mg, and Ca inorganic salt cations on the rheological properties of the polyacrylamide/xanthan gum solution for drilling mud and concluded that these cations affected rheological properties negatively and reduced the viscosity and cutting capacity significantly at high concentrations. Willson et al. [25], Choi et al. [26], and Mao et al. [27] examined the performance of drilling mud prepared by seawater.

In this study, the rheological and filtration characteristics of drilling muds prepared with geothermal spring water were examined, and their effects on drilling performance were revealed.

2. Materials and Methods

2.1. Materials. Four different geothermal spring water samples obtained from various geothermal areas (gs1, gs2, gs3, and gs4), distilled water (dw1), Na-bentonite being the most commonly used clay type in drilling mud, XCD (xantham gum) for modifying viscosity, and CMC (carboxymethyl cellulose) for controlling fluid loss were used to prepare the mud samples. The chemical properties of geothermal spring water and distilled water are given in Table 1.

TABLE 1: Chemical properties of geothermal spring water samples and distilled water sample.

Chemical parameters	Samples				
	gs1	gs2	gs3	gs4	dwl
pH	7.41	7.72	8.33	7.64	8.10
Specific conductivity (μS/cm)	6714	3015.5	2028	1805	10.49
K^+ (mg/L)	98.8	26	33.2	34	—
Na^+ (mg/L)	1215	256	423	363	1.42
NH_4 (mg/L)	<0.1	1.28	1.92	1.82	—
Ca^{2+} (mg/L)	97	287	22.4	28.8	0
Mg^{2+} (mg/L)	17.5	34.3	0.72	8.64	0
$As_{(T)}$ (mg/L)	—	<0.05	—	—	0
$B_{(T)}$ (mg/L)	5.6	0.2	15.1	12.3	0
Li^+ (mg/L)	1.5	—	1.05	0.98	—
SiO_2 (mg/L)	81	56	203	187	—
CO_2 (mg/L)	0.5	7.47	—	—	—
HCO_3^- (mg/L)	7.6	245	580	626	—
CO_3^{2-} (mg/L)	<10	<10	90	0.0	—
SO_4^{2-} (mg/L)	432	839	139	141	1
Cl^- (mg/L)	1670	325	216	196	0.34
F^- (mg/L)	—	<0.1	—	—	—
NO_2^- (mg/L)	—	<0.1	<0.05	<0.05	0
NO_3^- (mg/L)	—	12.4	4.1	3.7	—
Salinity (ppt)	—	—	1.0	0.9	—
TDS (mg/L)	—	—	1504	1390	—
$Fe_{(T)}$ (mg/L)	—	—	0.46	0.475	0

The crystallographic properties of the sample used in this study were determined using a Rigaku Miniflex II X-ray diffractometer equipped with Cu α radiation in the 2θ range of 3–90° with a 0.01 step size and 0.5 deg/min, and the patterns were evaluated using a PDXL software program for mineral identification. The pattern given in Figure 1 shows that the bentonite sample was composed of sodium-rich montmorillonite (NaM) mineral together with quartz, clipoptilolite, albite, and illite which were identified as impurities.

The elemental analysis of bentonite sample was performed by X-ray fluorescence (XRF) using a Thermo ARL X-ray spectrometer. From the obtained results, it is found that the Na-bentonite sample is composed mainly of SiO_2 (61.59 wt%), Al_2O_3 (15.88 wt%), and Fe_2O_3 (5.62 wt%), in addition to Na_2O (2.71 wt%), MgO (2.21 wt%), CaO (1.53 wt%), K_2O (1.07 wt%), TiO_2 (0.92 wt%), and L.O.I. (7.82 wt%) trace elements in the bentonite which are P_2O_5, MnO, SrO, NiO, CuO, ZnO, and ZrO_2. These results showed that the Al_2O_3/SiO_2 ratio was about 1/3 to 1/4 as expected for montmorillonite which is the main component of bentonite used in the study.

2.2. Preparation of Drilling Mud Samples. The mud samples were prepared in the compositions detailed in the American Petroleum Institute (API) specification [28]. As shown in Figure 2, 500 mL of geothermal spring water was stirred with 32.14 g of bentonite for 20 minutes to maintain the clay-
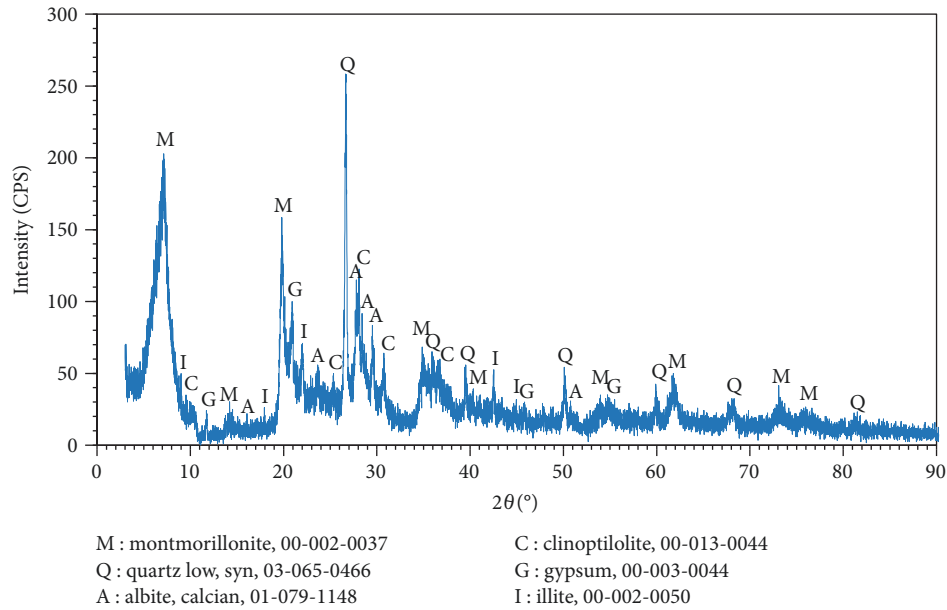
FIGURE 1: X-ray diffraction (XRD) of Na-bentonite.

M : montmorillonite, 00-002-0037
Q : quartz low, syn, 03-065-0466
A : albite, calcian, 01-079-1148

C : clinoptilolite, 00-013-0044
G : gypsum, 00-003-0044
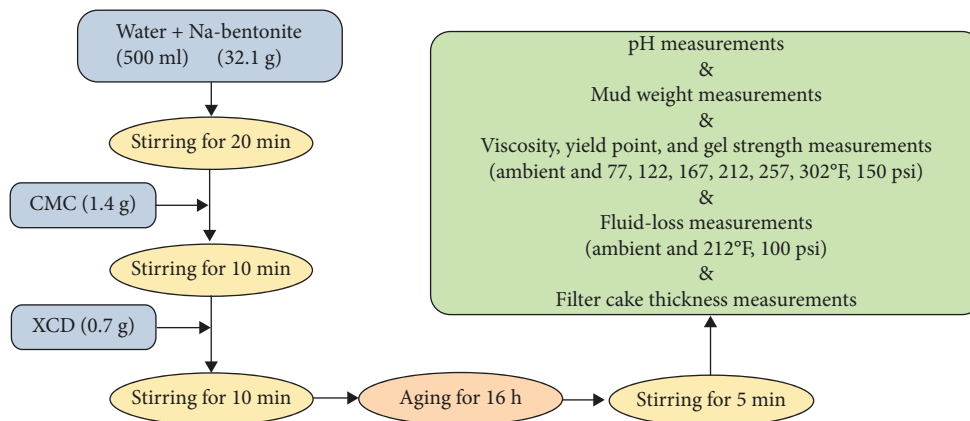I : illite, 00-002-0050

FIGURE 2: Flowchart of the experimental procedure.

water ratio according to API standards. Then, 1.4 g of CMC and 0.7 g of XCD were added to the solution, respectively. Finally, the solution was stirred for 10 minutes to form a homogeneous mixture. A Hamilton-Beach multiple mixer (model 9B) was used for mixing.

The above process was repeated for each geothermal spring water, and a total of four different mud samples were prepared. These samples were labeled as S1, S2, S3, and S4. Moreover, a sample was prepared with 500 mL of distilled water as base fluid in order to examine the effects of the water on the mud by following the steps. This sample was also labeled as D1. Prepared samples were remained in static condition at room temperature for 16 hours as specified in the API standard for bentonite clay. The five mud samples labeled S1, S2, S3, S4, and D1 were subjected to rheological and filtration tests. These tests were mud weight, viscosity, gel strength, fluid loss, and mud cake thickness measurements, respectively.

2.3. Determination of Rheological Properties. In the experimental study, API Standard Procedures were used in order to determine rheological properties [29].

The weight of the considered mud samples was determined by using the conventional OFITE (model 900) mud balance at ambient temperature, while the rheological properties (viscosity, yield point, and gel strength) were measured at both ambient and elevated temperatures by means of a Fann model 35 viscometer and Fann model 50 SL rheometer, respectively. Since the temperatures of geothermal resources ranged between 30°C (86°F) ± 150°C (302°F) [30], viscometer shear stress dial readings were obtained under 77, 122, 167, 212, 257, and 302 (°F) temperatures and 150 psi pressure every five seconds for each standard shear rate (3, 6, 100, 200, 300, and 600 rpm).

The Bingham plastic, power-low, and Herschel-Bulkley models are the fundamental models to describe the behavior of drilling mud [2]. Moreover, Vipulanandan [31] and

hyperbolic models [32, 33] have been used for the same purpose recently. However, drilling fluid is generally considered to be classified as Bingham plastic in the drilling industry and the rheological properties of drilling mud are determined based on this model [20, 34].

According to the Bingham plastic model, the apparent viscosity, plastic viscosity, and yield point were calculated using the following equations from 600 and 300 rpm reading:

$$\text{Apparent viscosity (AV)} = \frac{\theta_{600}}{2\,(\text{mPas})}, \tag{1}$$

$$\text{Plastic viscosity}\left(\mu_p\right) = \theta_{600} - \theta_{300}\,(\text{mPas}), \tag{2}$$

$$\text{Yield point}\left(y_p\right) = 0.5\left(\theta_{300} - \mu_p\right)\,(\text{Pa}). \tag{3}$$

The gel strength of muds was measured with the rotating viscometer. After that, the mud samples were immobilized for 10 seconds and 10 minutes. The maximum deflection value seen at 3 rpm was found as 10-second gel and 10-minute gel, respectively.

Fluid-loss measurements were conducted both at ambient and 212°F temperature conditions. The measurements at ambient temperature were performed using a LPLT (low pressure-low temperature) filter press, and the measurements at 212°F were made using the Fann 500 mL filter press in a pressure of 100 psi.

After the fluid-loss measurements, the mud cake on the No. 50 filtrate paper was left to evaporate water at ambient temperature for 24 hours, then the thickness of the mud cake was measured with a Vernier-type caliper.

3. Results and Discussion

The shear stress values and their relationship with the mud samples prepared with S1-4 and D1 are given in Figure 3 under both ambient and elevated temperatures (77, 122, 167, 212, 257, and 302 (°F)).

Figures 3(a)–3(f) reveal that the relationship between the shear stress and the shear rate is not linear between 0 and 100 rpm, but linearly increases up to 600 rpm, so the behavior of these samples can be described by the two-parameter Bingham plastic model, which assumes a linear relationship between the shear stress and the shear rate. As a matter of fact, the Bingham plastic model does not accurately predict fluid flow behavior at low shear rates but is useful for continuous monitoring and treating of drilling fluids. Fluids that exhibit Bingham plastic behavior do not flow until the shear stress exceeds a critical value known as the yield point. Once the yield point is reached, changes in shear stress and shear rate are proportional. This constant of proportionality, or the slope of the curve, is termed plastic viscosity. Moreover, it has been highlighted that shear stress values decreased as temperature increased for all the samples due to the thermal degradation of the components of the mud samples. When the rheograms are compared, it is seen that the shear stress values of the D1 sample is higher than those of S1, S2, S3, and S4 samples in all terms and conditions. For all samples,

the shear stress values decreased at 257 and 302 (°F) temperatures and low shear rate (3-6 (rpm)). Normally, it is expected that the shear stress increases with the increase in the shear rate value. Nevertheless, bentonite muds can maintain their stability up to 250°F and show shear thickening behavior at temperatures higher than 250°F. Therefore, gelling and filtration problems will occur at temperatures higher than 250°F in the boreholes where these drilling muds are used. These problems will cause the drilling fluid to flow into formation and reduce the carrying capacity.

Table 2 shows AV, PV, and YP and the ratio of YP to PV of the drilling mud samples depending on the temperature.

As can be seen in Table 2, temperature affects the AV of geothermal and freshwater muds negatively. On the other hand, the AV of freshwater mud is greater than that of geothermal water muds at constant temperature. As AV shows the flowability of the drilling mud and affects the rate of penetration, it could be noted that the muds prepared with geothermal spring water will have lower flow performance.

From Table 2, it is seen that the PV of the muds prepared with geothermal spring water is lower than that of mud prepared with freshwater at all temperatures. This indicates that the spring water causes reduction in bentonite swelling ability compared to distilled water. This difference is the result of the different concentration of dissolved solid in the content of geothermal water and distilled water and leads to a difference in the viscosity of water that is used to prepare mud samples, in which the viscosity of water is one of the factors affecting plastic viscosity. The yield point of the all samples varies considerably with elevated temperature. Furthermore, similar to the viscosity, the highest yield point values are seen for the D1 sample at all temperatures. The low YP will cause drilling mud not to meet the task of suspending the cuttings and carrying capacity. In addition, the plastic viscosities of the samples generally decrease up to 167°F temperature. Although an increase is observed in a temperature range from 167°F to 212°F, it decreases consistently at the temperatures higher than 212°F. However, the plastic viscosity of the S2 sample decreases continuously at temperatures higher than 167°F. Although fluctuations are observed for the yield points of the samples up to 167°F, the yield points of all samples reduce distinctly at temperatures higher than 167°F. Interestingly, the yield point of the S2 sample reached a negative value at 257 and 302 (°F). This could be due to the wall slip phenomena. Wall slip is a common problem during rheology measurements of drilling fluids and is defined as a difference between the velocity of the walls of the measuring geometry and of the adjacent fluid layer [35]. The low shear rate [36] is one of the parameters in which "wall slip" is traditionally associated.

Shear thinning behavior is a desired property as it provides a reduction in the pumping pressure and an improvement in the rate of penetration when the viscosity is low in the pipes and where the drilling mud has a high shear rate. The YP/PV ratio is the measurement of the shear thinning as well [1, 37]. When the ratio gets higher, the shear thinning becomes greater [1, 2]. It is observed that the YP/PV ratio is the highest for the D1 sample in all conditions. Moreover, this ratio should be at least 0.375 Pa/mPas to
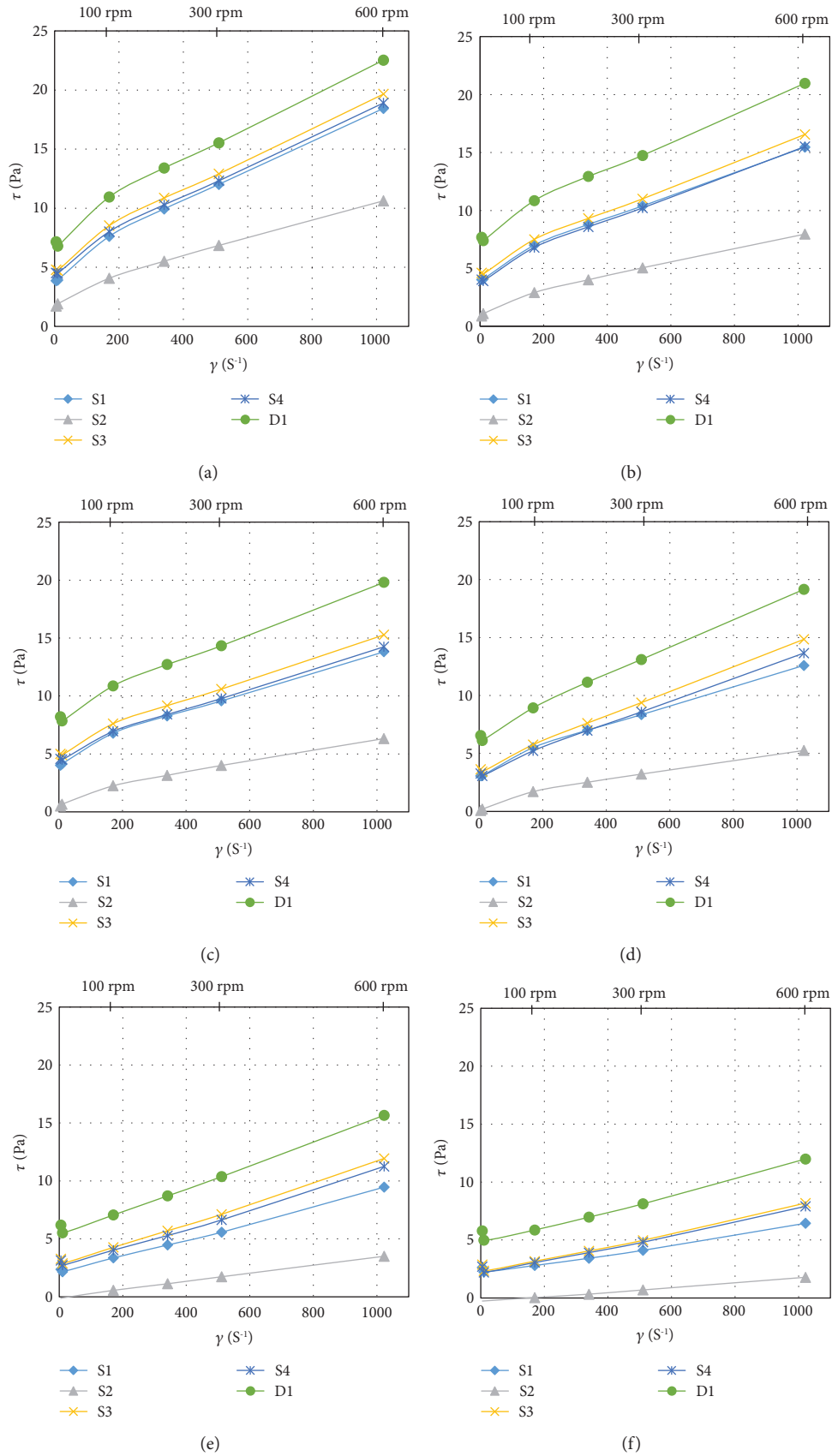
FIGURE 3: The rheograms of the $S1$, $S2$, $S3$, $S4$, and $D1$ samples at constant temperatures (a) 77°F, (b) 122°F, (c) 167°F, (d) 212°F, (e) 257°F, and (f) 302°F.

TABLE 2: Rheological properties of drilling mud samples.

Samples	S1	S2	S3	S4	D1
Apparent viscosity (AV) mPas at 150 psi					
Amb. con	17.305	11.180	19.700	18.900	22.895
77°F	19.265	11.095	20.535	19.747	23.535
122°F	16.154	8.315	17.298	16.209	21.910
167°F	14.422	6.604	15.948	14.874	20.675
212°F	13.153	5.490	15.506	14.267	20.008
257°F	9.881	3.648	12.465	11.748	16.354
302°F	6.735	1.867	8.551	8.260	12.526
Plastic viscosity (PV) mPas at 150 psi					
Amb. con.	9.590	6.920	10.650	10.650	10.650
77°F	13.404	7.887	14.097	13.748	14.602
122°F	10.602	4.489	11.609	11.073	13.004
167°F	8.847	4.838	9.763	9.312	11.411
212°F	8.870	4.253	11.401	10.588	12.625
257°F	8.129	3.690	10.068	9.640	11.060
302°F	4.877	2.282	6.707	6.464	8.079
Yield point (YP) Pa at 150 psi					
Amb. con.	7.884	4.353	9.249	8.431	12.514
77°F	5.985	3.279	6.578	6.130	9.129
122°F	5.673	4.248	5.813	5.247	9.100
167°F	5.697	1.804	6.320	5.683	9.467
212°F	4.376	1.264	4.194	3.758	7.543
257°F	1.789	-0.04	2.449	2.153	5.410
302°F	1.897	-0.41	1.884	1.835	4.543
YP/PV Pa/mPas at 150 psi					
Amb. con.	0.822	0.629	0.868	0.791	1.175
77°F	0.446	0.415	0.466	0.445	0.625
122°F	0.535	0.946	0.500	0.473	0.699
167°F	0.643	0.372	0.647	0.610	0.829
212°F	0.493	0.297	0.367	0.354	0.597
257°F	0.220	−0.01	0.243	0.223	0.489
302°F	0.388	−0.41	0.280	0.283	0.562

TABLE 3: The other rheological properties of the drilling mud samples.

	S1	S2	S3	S4	D1
Density (g/cm^3)	1.031	1.031	1.031	1.031	1.031
Filtration pH at 75°F	6.0	7.0	8.0	8.0	7.0
Filter cake thickness (mm)	0.13	0.15	0.12	0.15	0.11
Gel strength (lb/100 ft^2) 10 s/10 min	7.5/17	4/8	10/27	12/27	16/19
API fluid loss cc at 100 psi and amb. temperature					
30 s	0.5	0.8	0.5	0.3	0.8
1 min	0.8	1.2	1.0	0.5	1.2
3 min	2.1	2.5	1.6	1.5	1.7
5 min	2.6	3.5	2.4	2.3	2.4
7.5 min	3.4	4.4	3.3	3.0	3.2
10 min	4.2	5.3	3.9	3.7	3.7
15 min	5.4	6.6	5.1	4.8	4.8
20 min	6.4	7.7	6.0	5.7	5.1
25 min	7.2	8.7	7.0	6.4	6.5
30 min	8.0	9.7	7.6	7.1	7.05
High-temperature fluid loss. cc at 100 psi and 212°F					
30 s	2.4	1.0	3.0	3.0	3.3
1 min	2.6	1.8	3.2	3.2	4.3
3 min	3.2	2.8	3.8	4.2	5.8
5 min	3.8	3.8	4.8	5.6	6.7
7.5 min	4.9	5.4	5.8	6.6	7.6
10 min	5.6	6.4	6.7	7.2	8.4
15 min	7.2	8.6	8.4	8.8	9.9
20 min	8.8	10.2	10.0	10.4	11.4
25 min	10.3	12.0	11.2	12.0	12.8
30 min	11.4	13.8	13.6	14.0	13.0

achieve sufficient hole cleaning [4, 21]. The YP/PV ratio of the D1 sample is higher than 0.375 Pa/mPas at all temperatures. However, it is noted that the ratio of geothermal water-based mud samples is below this value at temperatures above 212°F. This indicates that freshwater bentonite muds exhibit more shear thinning behavior compared to geothermal water-based bentonite muds. As the ratio decreases depending on temperature, muds prepared using geothermal water will adversely affect the hole cleaning and penetration rate. Therefore, it will directly cause a considerable increase in the cost of drilling.

Density, gel strength, mud cake thickness, pH, and fluid loss tests were also performed. The results are shown in Table 3.

Mud density is one of the key parameters for successful drilling and affects the performance of drilling mud. The mud density measurements revealed that the density of each of the samples was 1.031 g/cm^3. It has been noted that the density of the samples taken from different locations would not change the drilling performance in drilling mud suspensions prepared with the same concentration of bentonite and water.

The gel strength is the shear stress measured at low shear rate after the mud was set quiescently for a period of time (10 seconds and 10 minutes in the standard API procedure). The minimum difference between the results of 10 sec and 10 min was measured in the D1 sample as 3.0 lb/100 ft^2. This indicates that the D1 sample has a higher cutting carrying capacity and thixotropic properties than the other mud samples. As a matter of fact, when circulation was over, suspended particles were prevented from collapsing into the bottom of the well. The problem of pipe sticking was also prevented due to gel strength. The initial gel strengths of the drilling muds should be high enough to prevent the cuttings in suspension from collapsing. Therefore, it is possible

that the muds prepared with geothermal spring water cause high-pressure changes during maneuvering and it is likely to crack the weak formations.

It is observed that the fluid loss of all samples increased in the course of time at ambient and elevated temperatures up to 302°F. When the API and the high-temperature fluid loss values at the end of 30 seconds and 30 minutes of each sample are examined, it is seen that the mud sample retained its stability and the lowest difference is the sample labeled as $D1$. As the increment in the filtration rate of the fluid increases, the filtrate volume flowing into the underground formation may cause contamination of the production zone and/or deterioration of well stability. In all these cases, more filtration control agents will be required, and the cost of fluid will be directly affected.

After the API fluid loss test, the best filter cake measured by caliper of the mud samples is obtained for the $D1$ sample with a value of 0.11 mm. This indicates that the mud prepared by using geothermal water causes a thicker filter cake on wellbore during drilling operations compared to the freshwater muds. When geothermal water is preferred to prepare mud by operators, it will be more likely to encounter problems such as stuck pipe, excessive torque, drag, high swab, and surge pressures compared to freshwater muds.

4. Conclusions

As a result of experiments conducted on five different mud samples in order to compare the drilling performance of the drilling muds prepared with geothermal spring water and freshwater, the following conclusions were found.

(i) Muds prepared with geothermal water have lower viscosities and yield points than those prepared with freshwater at elevated temperatures. The stability of the muds deteriorates, and the muds start to become flocculated especially at temperatures higher than 250°F. Moreover, since the viscosity and yield point of both types of muds are not high enough for drilling mud to perform its functions, this will lead to an increase in the amount of mud filtrate invasion and decrease the carrying capacity of drilling muds

(ii) The shear stress values at constant shear rate and shear thinning behavior of geothermal water-based muds are found to be lower than those of muds prepared with freshwater at both ambient and elevated temperatures. Therefore, these muds will exhibit lower flow performance, lower ability of hole cleaning, and lower rate of penetration compared to freshwater muds

(iii) Geothermal water muds lead to greater filtrate volume than that of freshwater muds at both ambient and elevated temperatures. In other words, it could be noted that there is an increase in the volume of filtrate flowing through the formation during drilling when geothermal water-based muds are used. It could also lead to contamination of the production zone and degradation of well stability. Therefore, it

will require a significant amount of fluid loss additive to control the filtration. As a result, this will directly affect the cost of the well

(iv) Muds prepared with geothermal water are found to have a greater cake thickness than are muds prepared with freshwater. Therefore, it may cause the drill string to stick to the wellbore and increase the possibility of other damages inside the well due to higher swab and surge pressures

Briefly, it could be noted that the muds prepared with geothermal spring water will cause lower drilling performance and high cost compared to muds prepared with freshwater. Therefore, it is recommended that geothermal spring water should not be used to prepare drilling mud in terms of effectiveness and cost of drilling.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

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