New Versatile Additive to Improve Fluid Loss Control in Water-Based Mud for Harsh Drilling Conditions

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Keywords

Water-based mud, fluid loss control, geothermal drilling, synthetic polymer

ABSTRACT

Excessive mud losses can cause several problems to the drilling operations, such as formation damage, well instability, and differential sticking, which complicate drilling operations and increase the nonproductive time. Several additives have been introduced to improve fluid loss control in water-based muds (WBMs) and mitigate fluid invasion problems. However, these products are still limited by temperature and/or salinity. This paper introduces a new polymeric additive to improve fluid loss control of WBM systems in a wide range of temperatures and salinity without significantly impacting mud rheology.

The new product was evaluated in different mud systems, including freshwater, saturated brine (up to 330,000 ppm), and weighted mud (13 ppg). The effect of the new product on the mud's rheological properties was investigated. Fluid loss experiments were conducted at low-temperature and high-temperature conditions to evaluate the new product's filtration performance. A thermal stability study was also performed by hot rolling the mud samples for 16 hrs at various temperatures (up to 450°F). The new additives' performance was compared with other incumbent products used in the industry regarding required dosage, thermal stability, rheological properties, and filtration performance.

This study showed that the new product significantly reduced fluid loss and was stable at high temperatures (up to 450°F). From filtration experiments, lower dosages of the new products significantly reduced filtrate volumes, while higher concentrations of conventional additives were required to achieve comparable performance. The developed product showed a minor impact on the rheological properties of the WBM. Moreover, less than a 2-mL increase in the fluid loss was observed after aging the drilling mud system at up to 450°F for 16 hrs, indicating its high thermal resistance. This versatile additive can improve the efficiency of geothermal drilling under harsh conditions of temperature and salinity and with various mud systems.

1. Introduction

Drilling in geothermal formations contributes significantly to the success and feasibility of geothermal projects. 40-60% of this cost is spent on drilling operations (Bavadiya et al., 2019). The increased drilling cost is attributed to many factors, such as high temperature, depth, hard and abrasive formations, and extended drilling time due to other drilling problems (Chemwotei, 2011; Finger and Blankenship, 2010; Kruszewski and Wittig, 2018). The high downhole temperature is one of the root causes of drilling issues. These issues include mud degradation, casing and cement sheath damage resulting from thermal stresses, and failure of drilling tools (Shadravan and Amani, 2012; Wu et al., 2020). All these challenges create a high potential for technological advancements to improve drilling efficiency and minimize cost.

Drilling muds are a key factor in the success and total cost of drilling operations (Chemwotei, 2011). Drilling fluids balance the formation pressure, transport the drilled cuttings, cool and lubricate the drill bit and downhole tools, and improve wellbore stability (Caenn et al., 2011). On the other hand, inappropriate design of drilling mud can lead to severe drilling problems. For instance, mud losses trigger several issues in the drilling operations, such as formation damage, well instability, well control issues, and differential sticking (Mohamed et al., 2020; Monteiro et al., 2005; Vivas et al., 2020). Consequently, more time and effort are required to resume drilling operations.

Water and bentonite clay was the primary drilling fluid used in the early stages of geothermal development (Erge et al., 2020). This mud was used to drill the first geothermal well in The Imperial Valley in California. Clay flocculation at high temperatures (above 250°F) causes undesired changes in rheological properties. Treating the drilling mud with lignosulfonate was then introduced; however, the treatment was unsuccessful (Zilch et al., 1991). According to field practices, drilling a producing formation with clay-based fluid was unfavorable. Mud invasion induces damage and reduces formation permeability, greatly affecting energy extraction (Finger and Blankenship, 2010; Kruszewski and Wittig, 2018). Therefore, more efforts were put toward replacing bentonite-based fluids.

Sepiolite clay was also introduced due to its rheological performance and thermal stability. However, sepiolite showed poor filtration control, and excessive mud losses resulted. Treatment plans were performed on sepiolite by adding some polymers and low bentonite concentrations to improve the filtration properties (Altun et al., 2010; Finger and Blankenship, 2010). For instance, Perricone and Lucas (1981) introduced a low molecular weight copolymer to treat bentonite muds. Better thermal stability and rheological properties were achieved. Another generation of drilling fluids used in geothermal drilling is polymer-based mud. Polymeric products are added to increase the mud viscosity and provide filtration control. A mixture of polymers and bentonite was also used in geothermal drilling to improve bentonite-based mud and reduce the cost of polymer-based mud (Chemwotei, 2011). Viscous polymer pills are also used in geothermal drilling to clean the wellbore and minimize mud losses (Thorhallsson, 2011; Tuttle, 2005).

Natural and synthetic polymers have been extensively used in geothermal drilling. Natural polymers are known for their high tolerance to salinity but low thermal resistance. Moreover, brine produced from geothermal formations has also been tested and used to formulate drilling mud for geothermal wells to save the cost of freshwater used in drilling mud preparation and produced water disposal (Avci and Mert, 2019). Formation brine can be very saline to an extent that hinders the polymer's performance. Brine salinity and temperature are significant factors when selecting mud additives as they may cause chemical or thermal degradation to the polymeric additives. The polymer industry introduced many advancements in the area of synthetic polymers, especially acrylamide-based products. These products are used for various drilling and cementing applications such as viscosifying drilling muds, fluid loss control, shale and scale inhibition, dispersant, and lost circulation remedy. Unique and innovative synthesis processes have been introduced to expand their applications and overcome their technical limitations and the shortage might be faced with natural polymers. Despite the continuous developments in polymer science, natural and synthetic polymers are still limited by temperature, salinity, and cost (Ma et al., 2019).

Therefore, this paper introduces a new polymeric additive to improve fluid loss control of WBM systems in a wide range of temperatures and salinity without significantly impacting their rheological properties. The new product is an acrylamide-based synthetic polymer with a unique chemistry that provides high resistance to salts and temperature to drill geothermal wells efficiently. The new synthetic polymer was evaluated thoroughly by measuring fluid loss and rheological properties under various testing conditions. Its performance was also compared with other natural cellulosic polymers used in geothermal drilling, such as polyanionic cellulose (PAC) and carboxymethyl cellulose (CMC).

2. Material

Several mud samples were prepared and tested in the laboratory to evaluate the new product in various testing conditions. The mud formulations used freshwater, seawater, and saturated brine as base fluids. Seawater salinity ranges between 34,000 to 41,000 ppm, depending on the location and depth. Seawater with around 34,483 ppm salinity was used for typical seawater mud formulation. Three different brine formulations were prepared in the lab, using sodium chloride and calcium chloride, to represent saturated brines (110,000, 220,000, and 330,000 ppm). Table 1 illustrates the chemical composition of the base fluids used in this study.

Table 1: Composition of the base fluids used in this study

Salt	Concentration, g/L			
	Typical Seawater	Brine 1	Brine 2	Brine 3
NaCl	26.699	85	170	255
$CaCl_2$	1.467	25	50	75
KCl	0.7245	-	-	-
$MgCl_2$	4.948	-	-	-
$MgSO_4$	6.796	-	-	-
$SrCl_2$	0.0396	-	-	-
$NaHCO_3$	0.1928	-	-	-
TDS, ppm	34,483	110,000	220,000	330,000

Several mud additives were added to the base fluid to formulate the drilling mud. Sodium carbonate (soda ash) was introduced to treat the water and maintain calcium levels (hardness). Caustic soda was added to maintain the pH between 9.5-10.5. Hydroxyethyl cellulose (HEC) was used to increase the mud viscosity. In addition to the fluid loss control additive, calcium carbonate was introduced as a bridging agent to improve fluid loss control. Sodium chloride or barite was added to increase the mud weight to the desired value. Different mud samples were mixed by changing the fluid loss control additive. The new fluid loss control additive (SNF FLA) was evaluated and compared with other incumbent products used in the industry, such as low-viscosity polyanionic cellulose (PAC-L) and carboxymethyl cellulose (CMC). A defoamer was added to the mud to remove the formed foam when needed. All mud formulations are described in Table 2. SNF FLA is an acrylamide-based synthetic polymer produced by liquid polymerization and then dried to a fine powder using a drum drying process. The product was uniquely designed to have a branched chemical structure with some special monomers. This particular structure was intended to improve the performance and stability of drilling mud systems in harsh drilling conditions.

Table 2: Drilling mud formulations used in this study

Product	Function	Mixing time, min	Concentration, lb/bbl			
			8.6ppg Freshwater	8.6 ppg seawater	Saturated brine	13 ppg weighted mud
Freshwater/brine	Base fluid	-	Freshwater: 350 mL	Seawater: 350 mL	Brine: 350 mL	Freshwater: 290 mL
Soda ash	Maintain water hardness	5	1	2	2	2
Caustic soda	Increase pH	5	pH: 9.5-10.5	pH: 9.5-10.5	pH: 9.5-10.5	pH: 9.5-10.5
HEC	Increase viscosity	15	1.25	1.25	1.25	1.25
Fluid loss additive	Minimize fluid loss	10	0.5-2.0	0.5-2.0	2	2
Calcium carbonate	Bridging agent	5	15	10	10	-
Sodium chloride	Weighting material	10	-	16	-	-
Barite	Weighting material	10	-	-	-	250
Defoamer (if needed)	Remove foam	1	0.5	0.5	0.5	0.5

3. Experimental Procedure

Mud samples were prepared in the lab using a variable-speed mud mixer. Mud additives were individually added to the base fluid and mixed, following the order and mixing time described in Table 2. The mixing speed was gradually increased as the mud thickened to maintain enough vortex and adequately mix all the mud additives. After mud preparation, mud samples were tested by measuring pH, density, rheological properties, and fluid loss. The experimental procedures are explained in detail in the subsequent sections. To evaluate the new product thoroughly, a wide range of testing conditions was used in this study by changing additive type and concentration, salinity, temperature, and mud density. The experimental matrix followed in this study is described in Table 3.

Table 3: Experimental matrix followed in this study

Parameter	Range
Additive	PAC-L, CMC, SNF FLA
Concentration	0.5-2 lb/bbl
Salinity	Freshwater to saturated brine (up to 330,000 ppm)
Density	8.6-13 ppg
Hot Rolling Temperature	75-450°F

3.1 Rheological Properties

The effect of the different fluid loss control additives on the mud rheological properties was evaluated. Grace M3600 viscometer with an R1-B1 geometry was used to measure the rheological properties. Measurements were conducted at room temperature (75°F) and atmospheric pressure. The shear rate (rotational speed) was changed, and the corresponding shear stress values (dial readings) were recorded. The yield point and plastic viscosity were calculated from the dial reading at 600 and 300 RPM, using Equations 1 and 2.

$$\text{Plastic viscosity (PV)} = \emptyset_{600} - \emptyset_{300} \quad (1)$$

$$\text{Yield point (YP)} = \emptyset_{300} - \text{PV} \quad (2)$$

3.2 Fluid Loss Tests

Low pressure (LP) filter press is a quick evaluation tool designed to test the mud filtration properties following the API standard procedure. It was primarily used to evaluate the filtration performance of the base mud and the drilling mud containing SNF FLA, PAC-L, and CMC at various concentrations. The filtration experiments were conducted at room temperature, and a pressure of 100 psi was applied using nitrogen gas. As per the API Recommended Practice (13B-1 and 13B-2), a standard 2.7µm filter paper was used as a filtration medium with a diameter of 3 ½ in. Filtrate was collected for 30 minutes, and the formed filter cake was characterized.

Afterward, the new product's high-temperature high-pressure (HTHP) filtration performance was evaluated at 500 psi differential pressure and 300°F temperature using the HTHP filter press. Since the HTHP cell has a filtration area of 3.55 in^2, which is half that of the standard filtration cell (7.1 in^2), the cumulative filtrate volume after 30 minutes is doubled to calculate the API fluid loss and compare the results to the standard filtration test.

3.3 Thermal Stability

Since the new product was developed to drill high-temperature geothermal wells, more experiments were performed to evaluate its thermal stability. A bentonite-based mud was used for this part of the study, containing 15 lb/bbl of bentonite, 2 lb/bbl of fluid loss control additive, and 30 lb/bbl of Rev Dust™. Rev Dust™ is calcium montmorillonite added to simulate the effect of reactive solids and cutting fines in the drilling fluid system (Lau and Davis 1997). This mud system was used to perform the QC check on high-temperature fluid loss control products. Several mud samples were prepared and hot rolled for 16 hrs at different temperatures, up to the maximum operating temperature of the roller oven (450°F). The samples were then cooled down and tested at room temperature using the standard filtration test. The filtration tests were conducted before and after hot rolling, and fresh mud samples were prepared for each testing temperature. The significant deterioration in fluid loss control with temperature indicates poor thermal stability.

4. Results and Discussions

4.1 Effect of Concentration

A series of experiments were conducted first to generate a loading curve to help optimize the product dosage in the mud system. In this part of the study, the concentration of the fluid loss control additives varied from 0.5 to 2.0 lb/bbl. Its effect on mud rheological properties and filtration performance was investigated at room temperature. The products tested are SNF FLA, PAC-L, and CMC. Figure 1 compares the filtration performance of all freshwater mud samples containing fluid loss control products with various concentrations. The base mud sample yielded a high fluid loss of 62.5 mL/30 min. The filtration performance was significantly improved by increasing the concentration to around 1.5 lb/bbl. Adding more than that concentration showed no further improvement in fluid loss control. At 1.5 lb/bbl, CMC and PAC-L reduced the filtrate volume by 34% and 61%, respectively. SNF FLA showed almost a flat filtration curve with freshwater mud. It was found very effective in improving the filtration performance at a concentration as low as 0.5 lb/bbl. The filtrate volume was reduced by 77-82% with a concentration of only 0.5-1.0 lb/bbl. Filtration performance also greatly affects the drilling efficiency, cost, and time. Reducing mud losses helps mitigate drilling challenges, such as wellbore instability, differential sticking, casing and cement placement, and formation damage. These formidable complications burden geothermal drilling by increasing the nonproductive time, which can also be reflected in the drilling cost (Magzoub et al., 2020).

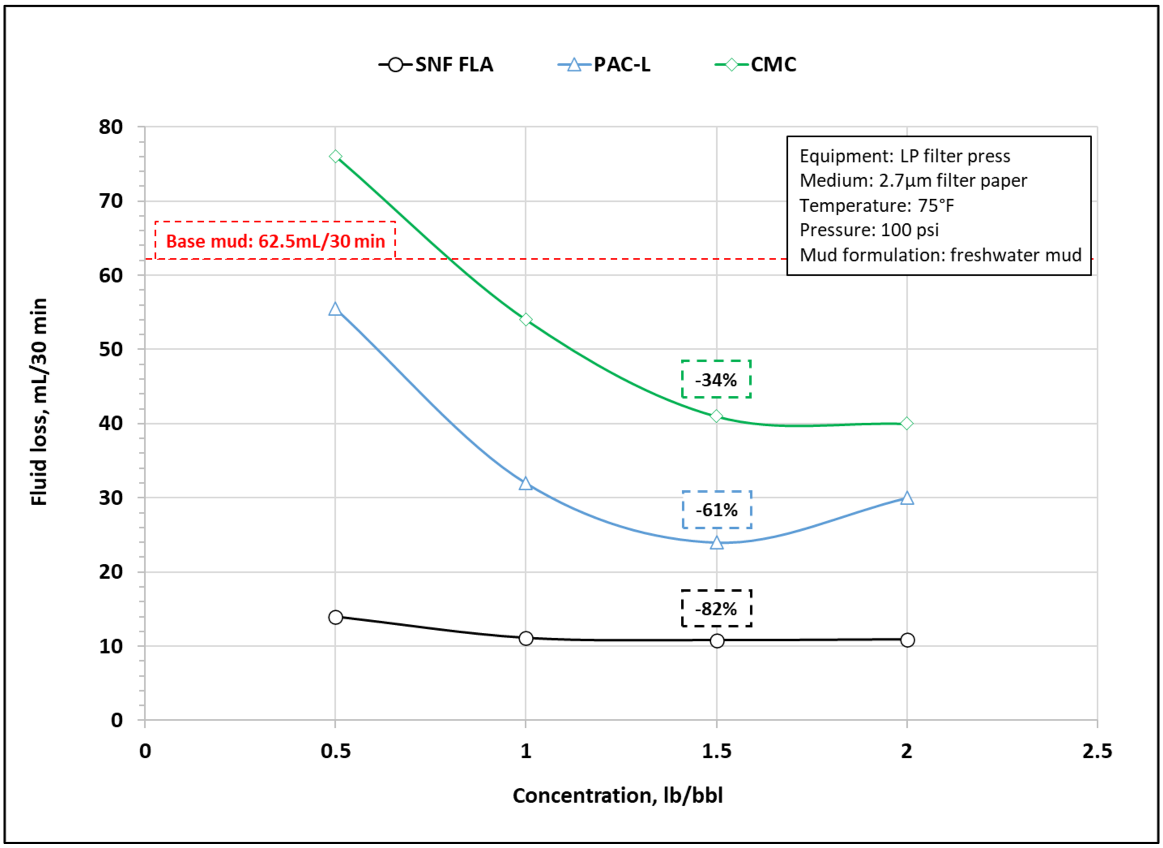

Figure 1: Effect of additive concentration on filtration performance of freshwater mud.

Rheological properties are crucial in optimizing drilling operations. They impact drilling parameters such as hole cleaning, fluid stability, torque and drag, and wellbore hydraulics (Da Silva and Naccache, 2016; Gamwo and Kabir, 2015; Monteiro et al., 2005; Pakdaman et al., 2019). Therefore, the industry has put great efforts into selecting mud additives, optimizing mud formulation, and monitoring the drilling mud properties throughout drilling operations (Mohamed et al., 2020). A thorough laboratory evaluation is usually performed on new products before field implementation. This study also investigated and compared the SNF FLA effect on rheological properties with other natural products.

Figure 2 compares the impact of all products on the rheological properties of freshwater mud at various concentrations. Without any fluid loss control additive, the base mud has a yield point (YP) of 16.6 lbf/100ft^2 and a plastic viscosity (PV) of 12.7 cP. As the dosage was increased with all products, yield point and plastic viscosity increased. At low concentrations (0.5 lb/bbl), there was no significant difference in YP and PV between the additives. However, the difference in rheological properties was distinct at high concentrations. SNF FLA showed the lowest impact on mud rheology compared to the other natural cellulosic polymers. 1.5 lb/bbl of SNF FLA increased the plastic viscosity by 47% and the yield point by 72%. In contrast, PAC-l and CMC (at 1.5 lb/bbl) showed a higher increase in plastic viscosity (77% and 103%) and yield point (84% and 143%). The increase in rheological properties usually improves the cutting removal and suspension; however, after some point, the increased properties negatively impact the drilling efficiency. The surplus plastic viscosity and yield point are unfavorable in drilling operations because they increase equivalent circulating density (ECD) and surge and swab pressures (Agwu et al., 2021). Most geothermal formations are weak with narrow mud windows; thus, the increase in ECD complicates the drilling process by inducing fractures, leading to lost circulation events (Mohamed et al., 2021). The increased plastic viscosity also decreases the rate of penetration (Paiaman et al., 2009). Poor hole cleaning is another negative impact of the substantial plastic viscosity. According to Piroozian et al. (2012), increasing the plastic viscosity, to some extent, in highly deviated and horizontal wells results in a remarkable improvement in hole cleaning, while the excessive viscosities inverse the results.

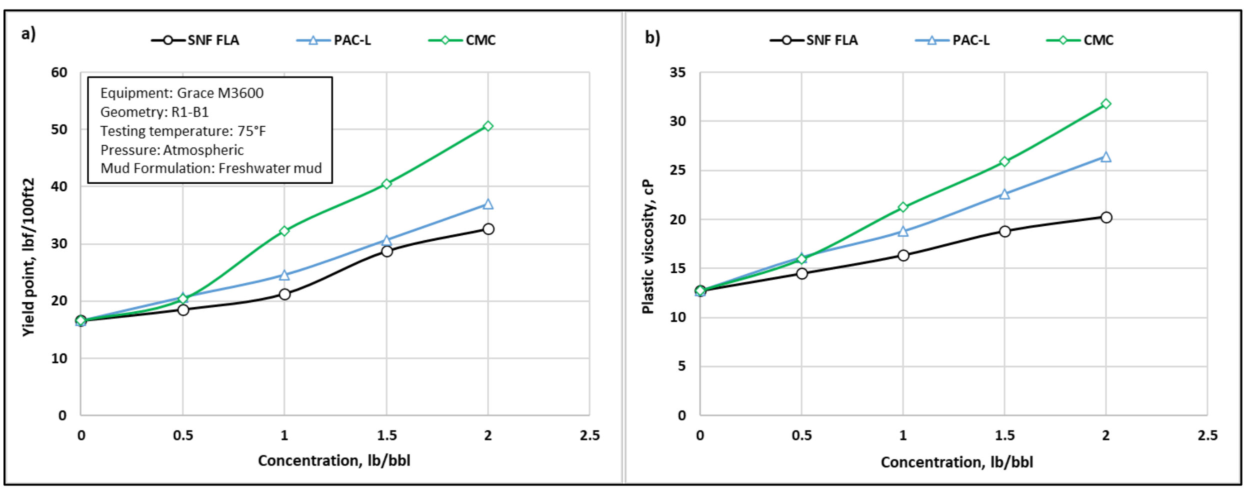

Figure 2: Effect of additive concentration on rheological properties of freshwater mud: a) Yield point, and b) Plastic viscosity.

4.2 Effect of Salinity

After some treatment, using produced brine in drilling and injection processes is very common in the oil and gas industry due to freshwater scarcity in some locations or the high cost associated with water disposal. Natural and modified natural polymers are used extensively in drilling operations because they are known for their resistance to salts. On the other hand, traditionally, acrylamide-based synthetic polymers (PHPA type) used in drilling operations are challenged by high salinity. As salt concentration increases, molecular chains are affected by different mechanisms, depending on the polymer chemistry (Ma et al., 2019). Therefore, the new product was studied at different salinities to ensure that it is effective in reducing fluid loss under a broad range of salinity, where produced brines can be used to prepare the drilling fluid.

Several mud samples were prepared in the laboratory using different water compositions. In addition to freshwater and typical seawater (~34,000 ppm), three different brines were synthesized using sodium chloride and calcium chloride at various concentrations with salinity ranging between 110,000 to 330,000 ppm, as described in Table 1. Mud samples were evaluated by measuring rheological and filtration properties. Figure 3 compares the rheological performance of the new additive and cellulosic polymers at different salinities. The base mud showed a flat curve with a yield point ranging from 14 to 19 lbf/100ft^2 and a plastic viscosity ranging between 12 to 17 cP. The mud samples containing PAC-L and CMC showed a gradual decrease in viscosity and yield point with salt concentration. As salinity increased, salt suppressed the increased polymer viscosity and yielded closer performance to the base mud. In contrast, a slight increase in plastic viscosity was observed with SNF FLA as the salt concentration increased. Plastic viscosity ranged between 17 to 22 cP. SNF FLA exhibited a flat yield point-salinity curve (around 20 lbf/100ft^2) at 34,000 ppm and up to 330,000 ppm, reflecting its high tolerance to salts.

Figure 4 compares the filtration performance of all products tested in this study at different salinities. All samples showed a reduction in filtrate volume with increasing salinity because saturated brines usually yield less fluid invasion than freshwater. A significant reduction in fluid loss was observed with all products. SNF FLA generated the lowest filtrate volume. Its filtration performance was not significantly affected by salinity. An API fluid loss of around 8-13 mL/30 min resulted in all mud formulations. Similarly, PAC-L showed a flat performance with salinity above 34,000 ppm with a higher fluid loss ranging between 13-20 mL/30 min. Conversely, CMC showed the highest fluid loss with a gradual reduction in filtrate volume with salinity up to 220,000 ppm. CMC was ineffective above that salinity and negatively impacted filtration performance, resulting in 64 mL total fluid loss.

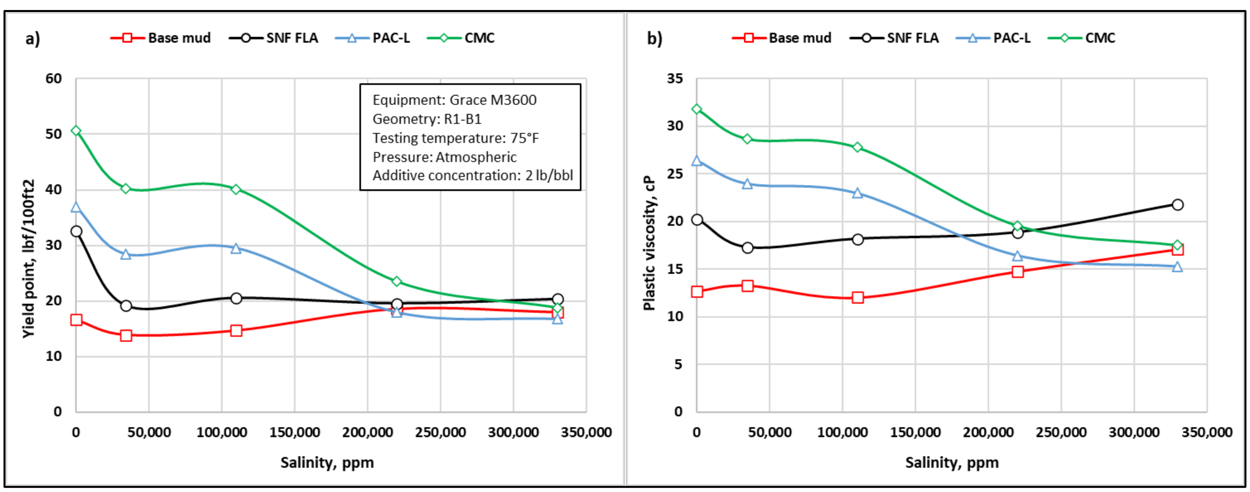

Figure 3: Effect of salinity on rheological properties: a) Yield point, and b) Plastic viscosity.

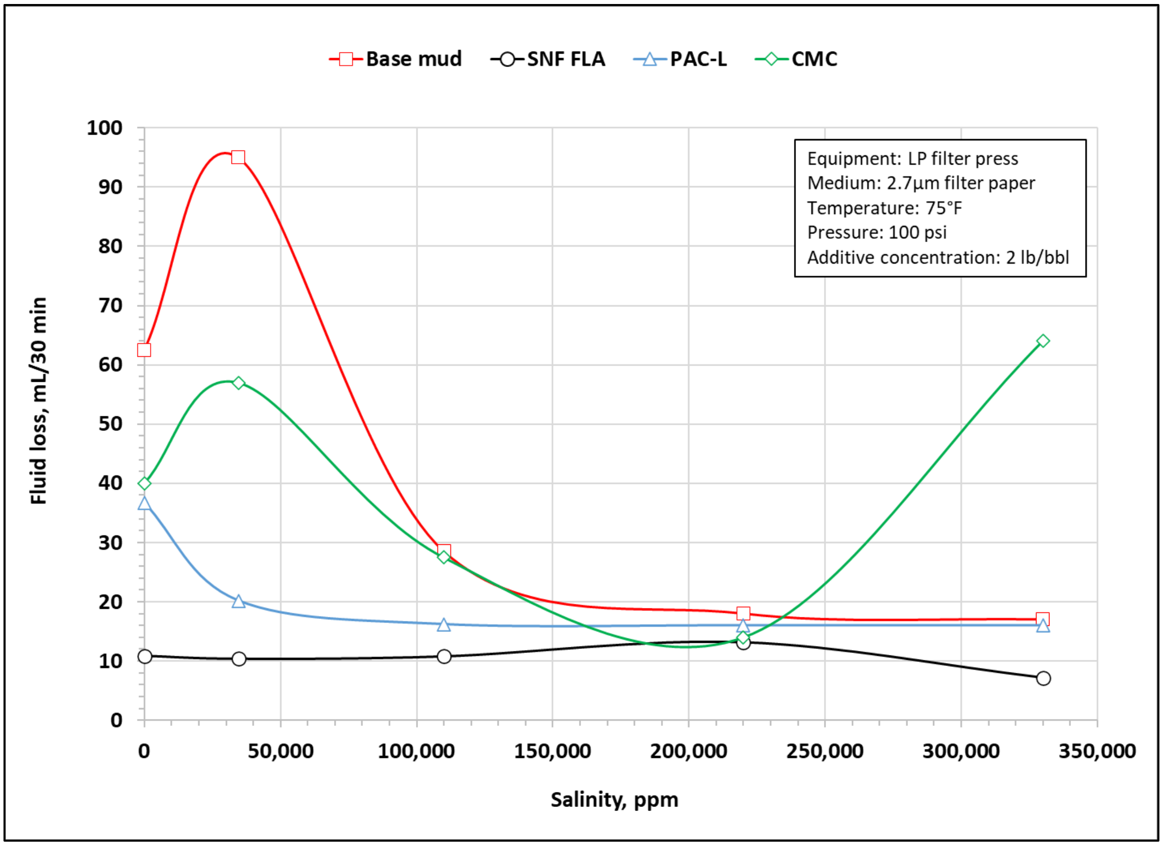

Figure 4: Effect of salinity on filtration performance.

4.3 Effect of Temperature

Temperature is one of the major factors that affect drilling mud properties. As temperature increases, more fluid filtrate tends to invade the drilled formation. The high temperature also accelerates polymer hydrolysis to the point that polymeric products degrade entirely and are no longer effective in reducing fluid loss. To evaluate SNF FLA, a thermal stability study was conducted by hot rolling the mud samples for 16 hrs at different temperatures. The fluid loss was then measured after hot rolling and compared to the base drilling mud. As illustrated in Figure 5, all mud samples showed an increase in fluid loss with temperature. The resulting filtrate volume varied differently with each additive. The base drilling mud yielded a fluid loss of 11 mL at room temperature. The fluid loss increased gradually to reach ~16 mL at 350°F. PAC-L and CMC showed around 50% reduction in fluid up to 250°F. Then their filtration performance started to deteriorate drastically, and higher fluid filtrate resulted. This performance is attributed to thermal degradation, which was also confirmed by the change in filtrate/mud color from clear fluid to dark brown. Moreover, SNF FLA filtration performance was also evaluated using the HTHP filtration test after hot rolling for 16 hrs at 350°F. An API fluid loss of only 18 mL/30 min resulted at 300°F temperature and 500 psi differential pressure, confirming the stable filtration performance of the new product when tested at high temperatures.

High temperatures, especially in the presence of divalent ions, cause excessive hydrolysis of the amide groups to carboxylate, which becomes the primary cause of instability of acrylamide-based products. This excessive hydrolysis can break the polymer chains causing polymer precipitation and viscosity loss (Thomas, 2019). A similar phenomenon was observed with cellulosic products at high temperatures and salinity. It was reflected in the viscosity drop and deterioration of the filtration performance of these products. However, the excellent performance of SNF FLA at such high temperatures (up to 450°F) and salinity (up to 330,000 ppm) is attributed to its unique chemistry and polymerization process. Interestingly, the sulfonic acid group in the polymer chain protected the amide group from hydrolysis and consequently provided high thermal resistance.

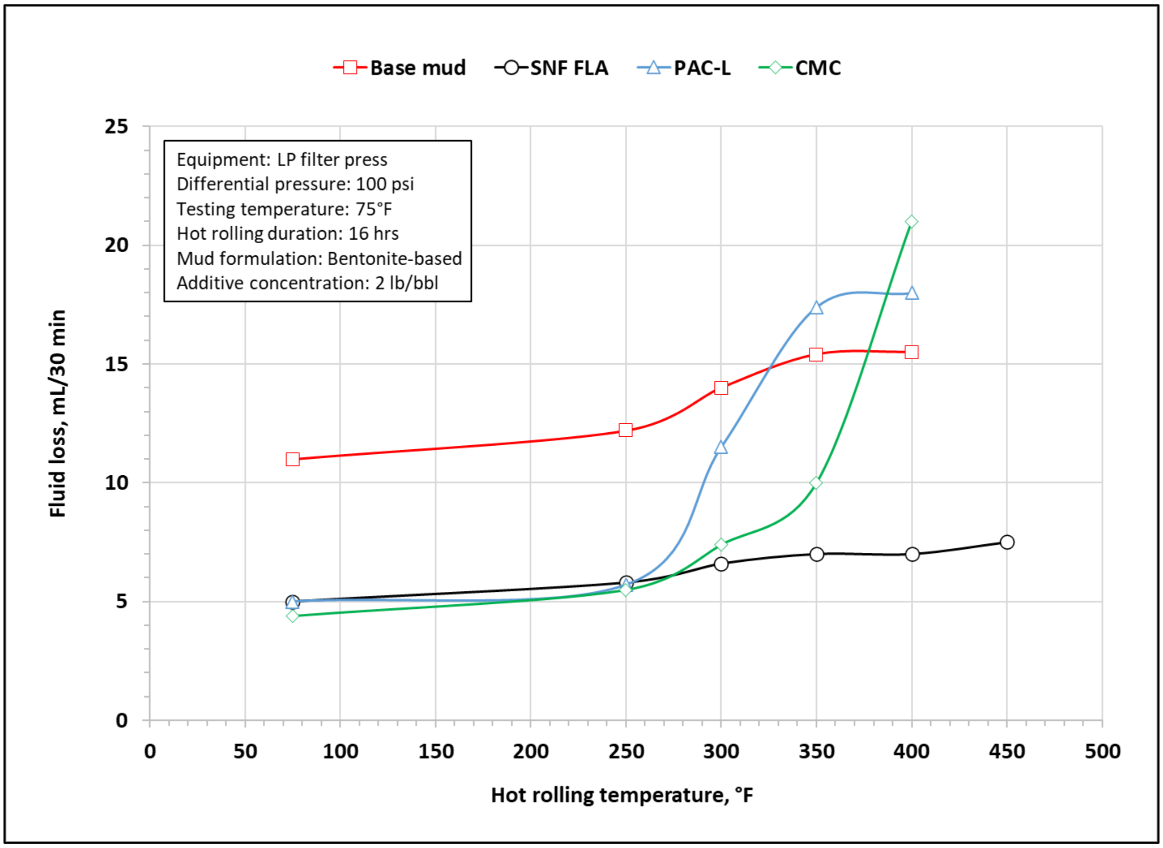

Figure 5: Effect of temperature on filtration performance.

4.4 Evaluation of Weighted Mud System

SNF FLA was also evaluated with barite-weighted mud to ensure its compatibility with weighted mud systems. Barite was added to the mud system to increase the density to 13 ppg. Fluid loss and rheological properties were measured at room temperature. Figure 6 compares the effect of SNF FLA, PAC-L, and CMC on the mud rheological and filtration performance. The base fluid yielded a high filtrate volume of 173 mL/ 30 min. All products showed a very high reduction in fluid loss. No significant difference was observed between products, and fluid loss was around 13.5 to 15 mL. However, SNF FLA improved filtration performance with a minimal increase in plastic viscosity and yield point (15% and 2.9%, respectively). While 85% and 120% increase in plastic viscosity were observed with PAC-L and CMC, respectively. The yield point increased by 67-174%. These surplus rheological properties require additional pump pressure to circulate the drilling mud and negatively impact other drilling parameters such as ECD, surg and swap pressure, rate of penetration, and hole cleaning.

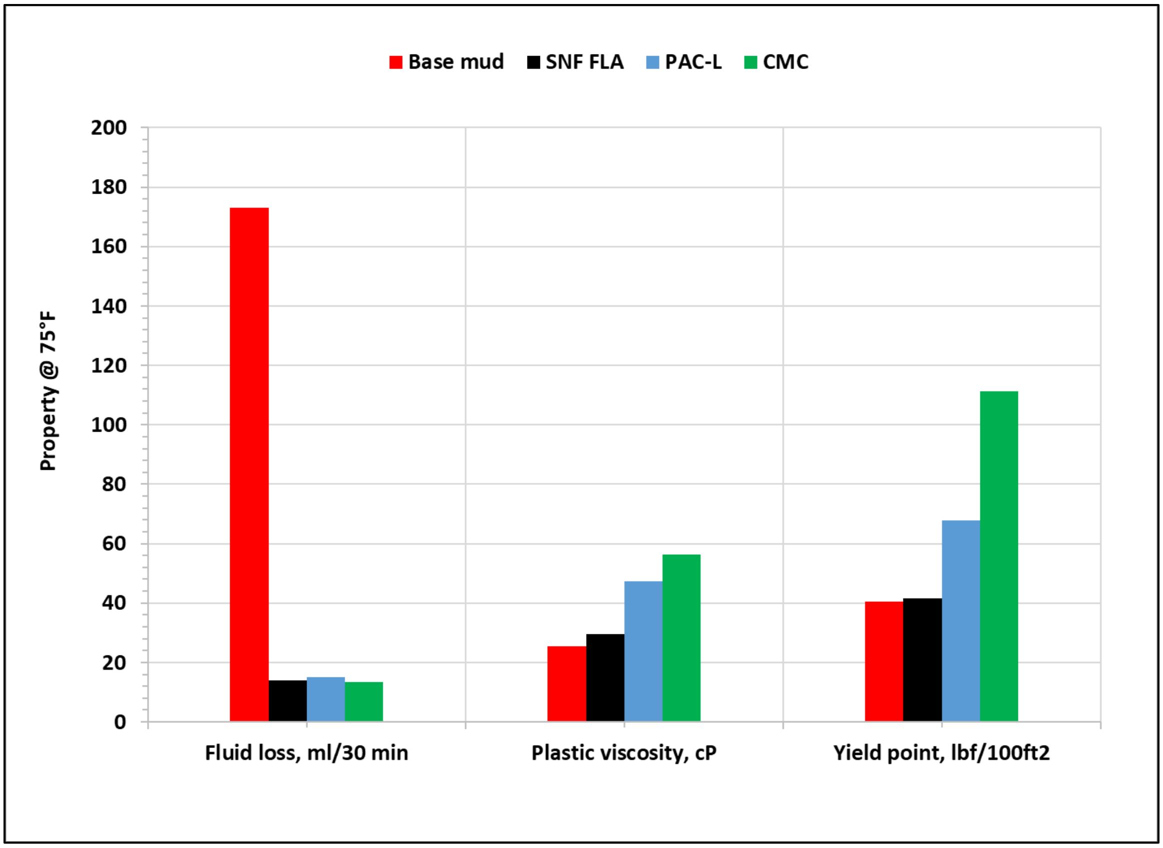

Figure 6: Rheological and filtration properties of 13 ppg barite-weighted mud.

5. Summary and Conclusions

A new synthetic polymer was introduced in this study to improve fluid loss control in water-based mud to drill geothermal wells efficiently. The developed product was thoroughly evaluated in the lab under a wide range of temperatures (75 - 450°F) and water salinity (up to 330,000 ppm) and with various mud systems. This product was also compared with other natural polymers commonly used in the industry to reduce fluid losses, such as PAC and CMC. The effect of these additives on rheological properties was also studied. Based on the obtained results, the following conclusions can be drawn:

- The new synthetic polymer showed an excellent filtration performance with all WBM systems tested in this study; freshwater, seawater, saturated brine, and barite-weighted muds. A high reduction of 82% in fluid loss was observed for freshwater mud containing SNF FLA, while PAC-L and CMC showed a 34-61% reduction.
- As the additive concentration was increased, all products showed an improvement in filtration properties and an increase in mud rheological properties. A concentration of ~1.5 lb/bbl was required to reduce fluid loss significantly. The new product showed less impact on mud viscosity than other products. An increase of 47% in plastic viscosity was observed with SNF FLA at 1.5 lb/bbl while, on the other hand, cellulosic polymers increased the plastic viscosity by 77-103%, which can cause some complications to the drilling operations.

- The unique chemistry of the new polymer made it very resilient to high salinity and temperature up to 330,000 ppm and 450°F, respectively. Almost the same filtration performance was observed throughout that range of salinity and temperature. In contrast, the natural cellulosic products' performance deteriorated drastically above 250°F. SNF FLA was also found compatible with barite-weighted mud with a minor impact on rheological properties.
- Based on the testing results of this versatile additive, it can be used to efficiently drill geothermal, deep-water, high-temperature, and extended-reach wells using a wide range of water salinities. However, a field trial should be conducted to determine the viability and effectiveness of the new product in actual field conditions. Moreover, due to the experimental limitations, further laboratory studies are required to evaluate this product for higher temperatures to extend its applications to drill EGS and supercritical formations.

NOMENCLATURE

API:	American Petroleum Institute
CMC:	carboxymethyl cellulose
EGS:	enhanced geothermal systems
HEC:	hydroxyethyl cellulose
hrs:	hours
HTHP:	high-temperature, high-pressure
lb/bbl:	pound per barrel
LP:	low-pressure
PAC-L:	low-viscosity polyanionic cellulose
PHPA:	partially hydrolyzed polyacrylamide
ppg:	pound per gallon
ppm:	part per million
PV:	plastic viscosity
QC:	quality check
RPM:	revolution per minute
TDS:	total dissolved solids
WBM:	water-based mud
YP:	yield point
$\emptyset_{300}$:	dial reading at 300 RPM
$\emptyset_{600}$:	dial reading at 600 RPM

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