Experimental study of influence of temperature, salt, and pH on the rheological behavior of eco-friendly water-based drilling fluid

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Received: 18/10/2024
Revised: 13/11/2024
Accepted: 02/12/2024

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Abstract— We used nonionic polysaccharides and polyethylene glycols of intermediate molecular weight as environmentally friendly and highly effective additives in water-based bentonite drilling fluids to inhibit syneresis, provide good slurry rheological profiles at elevated temperatures, and maintain these properties in a saline well environment. The effects oResearchers looked into how temperature, salt type and concentration, and pH affect the flow characteristics of an eco-friendly drilling fluid made from two types of Algerian bentonite (Mos-b and Mag-b) and two water-soluble polymers (hydroxyethyl cellulose and polyethylene glycol). steady shear rheological data to the Herschel-Bulkley (H-B) and Cross models to calculate rheological parameters such as yield stress, consistency index, flow behaviour index, zero shear viscosity, infinite shear viscosity, and characteristic constant of time. The results showed that the highest levels of yield stress, consistency index, and viscosity were found at 65°C for Mos-b and 75°C for Mag-b. These levels went down as the pH went down and when sodium chloride (NaCl) and potassium chloride (KCl) were added to the drilling fluid. The addition of KCl significantly reduced the rheological parameters. The behavior of the base drilling fluid containing Mos-b is more stable and provides superior rheological properties at elevated temperatures and in saline environments compared to the base drilling fluid containing Mag-b.

Keywords — : **Water-based mud, Bentonite, Polymers, Temperature, Salt, pH, Rheological properties.**

I. INTRODUCTION

In the past few decades, demand for oil and gas has increased due to the utility of these products for industrialization and developing living standards. Unfortunately, the high demands result in increasing the depletion rate of near-surface reservoirs around the world and in the production loss of many oilfields. These problems require the industry to look for new oilfields that are located in more challenging reservoirs, such as the deeper ones and those with high pressure and high temperature (HPHT) conditions. Thus comes the challenge of maintaining desirable rheological properties of the drilling fluids in deep and ultra-deep wells. High temperatures and pressures negatively affect the performance of drilling fluids while drilling in deep or ultra-deep wells for oil, gas, or geothermal reservoirs. Also, while drilling salt beds or in offshore activities where the drilling fluids are prepared using saltwater, these fluids may become contaminated. Particularly, bentonite gels develop, which result in the increase in fluid loss causing permeability damage, which can be prejudicial not only to the drilling activity but also to later production [18], [13], and cause deterioration of the rheological properties of drilling fluids [15],[19],[9]. At high temperatures and in formations where salt can be present and contaminate the drilling fluids, special formulations and systems must be used.

For this purpose, we make various improvements to the drilling fluid, but we observe some imperfections in all casesResearchers Borthakur et al. [8] conducted a study and evaluated the effectiveness of partially hydrolyzed polyacrylamide (PHPA) on the rheological properties of water-based mud, concluding that this polymer can function as a viscosifier in water-based drilling mud, even at reservoir temperatures below 120°C. .Kelessidis et al. [14] thought that adding salt lowers the viscosity at all shear rates for the three bentonite concentrations that were looked at: 2%, 5%, and 6.42%. Abu-Jdayil [2] has concluded that the presence of electrolytes in a concentration range of 0.02–0.2 M led to a decrease in the apparent viscosity of the bentonite suspensions. Uti and Joel [25] have compared the effect of different salts on the hydration of bentonite, and this comparative study showed that as salt concentration increases, the plastic viscosity decreases. Chang and Leong (2014) have investigated the effects of Li, Na, K, and C ions on bentonite gels, and they have found that gels with the highest ionic strength displayed the lowest viscosity at any given shear rate. Amani et al. [4] have investigated the effect of salinity on the viscosity of water-based drilling fluids at elevated pressure and temperature, and they have concluded that viscosity has decreased with an increase in salinity. Ahmad et al. [3] have used nanoparticles and water-soluble polymers to improve drilling fluid properties, and they have found that the plastic viscosity decreased with the increase in temperature from 25 °C to 85 °C. Vryzas et al. [26] looked at how temperature changed the rheological properties of neat aqueous Wyoming sodium bentonite dispersions and found that as the temperature went up, the plastic viscosity went down. Therefore, all the aforementioned investigations showed that exposing fluids to these conditions led to modifications and alterations in their rheological characteristics, thereby negatively impacting drilling fluid functionality.

The majority of the research in the aforementioned studies concentrated on creating suitable additives to mitigate the negative effects of salt and temperature on the rheological characteristics of water-based drilling fluids. The impact of these two factors on the rheological characteristics of drilling fluids, particularly their viscosity, received less attention. This demonstrates that a thorough investigation into drilling operations at high temperatures and in salt-based drilling fluids is lacking. This study aims to shed additional light on the mechanisms of bentonite-polymer interactions in high-temperature and salt environments, while also evaluating hydroxyethyl cellulose (HEC) and polyethylene glycol (PEG) as functional additives for drilling fluids. We conducted a series of laboratory tests to assess the impact of temperature, salt, and pH on the rheological properties, particularly the viscosity of an eco-friendly water-based drilling fluid, which we formulated using Algerian bentonites and two water-soluble polymers, as reported by Ouaer et al. [20]. Based on the laboratory results, we discuss the influence of the above parameters on the rheological properties of the eco-friendly water-based drilling fluid.

II. MATERIALS AND METHODS

A. Materials

The constituent materials of the study are Na-bentonite and Ca-activated bentonite, as reported by the supplier. ENOF (Algerian Public Company of the Mining Products non-ferrous and useful Substances) kindly provided these two bentonite samples from the Algerian fields of "Mostaganem" and "Maghnia," respectively. Table 1 displays the X-ray fluorescence (XRF) analysis of the studied bentonites. Comparatively, the ratio of {(Na2O + K2O)/(CaO + MgO)} for these two types of bentonite is found to be higher for Mos-b than Mag-b. The particle size of the bentonite samples is less than 70 µm. Ouaer and Gareche [20, 21] provide a full description of the two polymers used in this investigation.

Table 1: Result of XRF analysis of bentonites

Elements (wt %)	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	Na_2O	CaO	K_2O	MgO	SO_3	P_2O_5	PAF
Mostaganem bentonite	60.49	13.87	0.29	3.14	3.54	3.95	1.69	2.37	0.24	0.08	10.35
Maghnia bentonite	58.54	16.03	0.16	2.17	3.58	0.82	2.01	7.26	0.14	0.05	9.26

B. Experimental methods

The preparation method greatly influences the ultimate state of drilling fluids and, consequently, their rheological behaviour. Therefore, we meticulously carried out all experiments under identical circumstances to enable comparison of the outcomes.

To achieve optimal swelling of bentonite and a thorough dispersion of these clay particles in water, the first step in the drilling fluid formulation involved gently immersing 3 weight percent of bentonite powder in distilled water, with constant stirring. We added 0.5 weight percent of HEC powder and 0.2 weight percent of PEG to the mixture after four hours of agitation to prevent foam and syneresis. We then mechanically stirred the mixture for 20 hours at 450 RPM.

After altering the samples to various values using 0.1 N NaOH and 0.1 N HCl solutions, we used a pH meter (HANNA instruments, HI 2211) with a glass rod and a precision of 0.01/unit of pH. We added bentonite and polymers to the appropriate electrolyte solution to investigate the effects of the electrolyte concentrations (NaCl and KCl). We studied five electrolyte concentrations: 0.0 wt% (using deionized water as the standard solution), 0.5 wt%, 1.0 wt%, 1.5 wt%, and 2.0 wt%.

We did rheological experiments with an Anton Paar Physica MCR-301 controlled-stress rheometer that had a coaxial cylinder shape (Re = 14.464 mm, Ri = 13.325 mm, h = 39.997 mm) and a temperature that was kept at 25 ± 0.1°C.

We obtained the flow curves by applying an increasing shear stress ramp at 20 s for each stage, and we measured them at a shear rate ranging from 10-3 to 103 s-1. We initiated the temperature sweep measurements after reaching temperature equilibrium, conducting them at various temperatures ranging from 25 to 75°C.

Before each test, we gently agitated the samples for 20 minutes, and then carefully placed the suspensions onto the rheometer's measuring geometries. To achieve the identical structural state of reference, samples were likewise subjected to a preshear of 1000 s^{-1} in the measuring geometry before being allowed to rest for 60 s.

III. Results and discussion

A. Rheological behavior

1. Base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG)

The rheological data of the base drilling fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) are described mathematically using the Herschel-Bulkley (H-B) model, which is defined as follows

$$\tau = \tau_c + k\,\dot{\gamma}^{n} \qquad (1)$$

where (τ) is the shear stress (Pa), (τc) is the yield stress (Pa), (k) is the consistency index (Pa.sn), (γ˙) is the shear rate (s-1) and (n) is the flow index. The rheological parameters of the model are summarized in Table 2. According to the results, the yield stress reaches maximum at 65°C and at pH= 8.44. It decreases with the increase in the NaCl and KCl concentration, but this decrease is more significant in the case of NaCl, whereas, the consistency index decreases more significantly when adding KCl. The latter results demonstrate that NaCl addition destroys the three-dimensional network, which leads to a significant reduction in yield stress, but the KCl addition reduces the swelling behavior of the bentonite suspensions by preventing water and polymer to penetrate the bentonite interlayer, which reduces significantly the consistency index.

Based on the correlation coefficient (R2) mentioned in Table 2, the rheological behavior of the base tested fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) has described well by the H-B model over the full shear rate range. Figure 1 demonstrates how extremely well rheological data have been fitted by the model for the base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) at 35°C and natural pH giving correlation coefficient 0.9999.

Table 2: H-B model parameters calculated for the base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG)

Drilling fluid	**τ_c (Pa)**	**k (Pa.s^n)**	**n (-)**	**R^2**
Base fluid (25°C, natural pH)	4.4688	1.6759	0.4699	0.9997
Base fluid (35°C, natural pH)	2.3610	1.0930	0.5086	0.9999
Base fluid (55°C, natural pH)	1.2697	2.7016	0.4072	0.9994
Base fluid (65°C, natural pH)	4.7866	2.6452	0.3341	0.9991
Base fluid (75°C, natural pH)	3.3830	1.3395	0.4610	0.9999
Base fluid+0.5 wt% NaCl (25°C)	2.5856	1.1116	0.5215	0.9973
Base fluid+1.0 wt% NaCl (25°C)	0.8244	1.0116	0.5220	0.9973
Base fluid+1.5 wt% NaCl (25°C)	0.7384	1.1483	0.5063	0.9963
Base fluid+2.0 wt% NaCl (25°C)	0.4892	0.8660	0.5272	0.9972
Base fluid+0.5 wt% KCl (25°C)	2.4239	0.7592	0.5378	0.9893

Drilling fluid	**τ_c (Pa)**	***k* (Pa.s^n)**	***n* (-)**	**R^2**
Base fluid+1.0 wt% KCl (25°C)	2.3540	0.6902	0.5510	0.9892
Base fluid+1.5 wt% KCl (25°C)	1.9657	0.6343	0.5691	0.9912
Base fluid+2.0 wt% KCl (25°C)	1.9685	0.6968	0.5599	0.9916
Base fluid (25°C, pH=3.64)	1.9749	0.3404	0.6231	0.9999
Base fluid (25°C, pH=6.89)	3.7405	0.5592	0.5847	0.9997
Base fluid (25°C, pH=8.44)	5.2489	0.6896	0.5694	0.9991
Base fluid (25°C, pH=12.01)	2.4445	1.9365	0.4579	0.9999

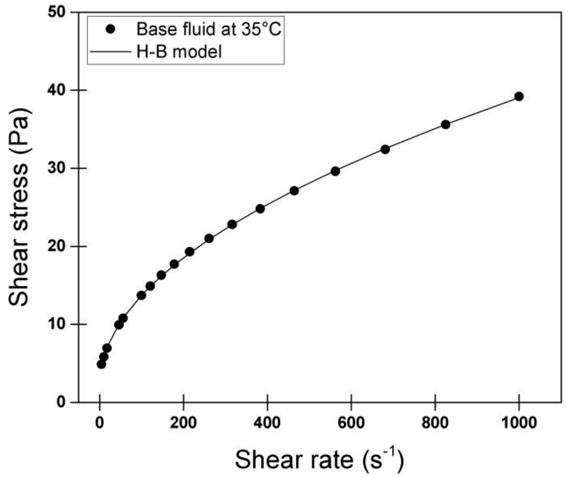

Figure 1: Rheological data fitted by the H-B model for the base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) at 35°C and natural pH.

2. Base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG)

The flow curves of the base tested drilling fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) are similar to those reported by Ouaer and Gareche [20] on HEC solutions and they can be correlated by the Cross model except for the base fluid tested at 75°C where the H-B is suitable. The cross model is expressed by Cross:

$$\tau = \left(\eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + \lambda \dot{\gamma}^m}\right).\dot{\gamma} \quad (2)$$

where (τ) is the shear stress (Pa), ($\dot{\gamma}$) is the shear rate (s^{-1}), (η_0) is the zero shear viscosity, (η_∞) is the infinite shear viscosity, (λ) is a characteristic constant of time and (m) is a dimensionless constant.

The results show that the behavior of HEC is predominated than that of the bentonite suspensions. This effect may be attributed to the nature of Mag-b, which is an activated calcium bentonite.

Table 3 presents rheological parameters of the Cross model for the tested fluids. It can be noticed that (η_0), (η_∞) and (λ) decrease with increasing temperature to 55°C and they increase at 65°C. These parameters decrease also with increasing NaCl and KCl concentration and they reach a minimum at pH= 3.10.

The correlation coefficient (R^2) calculated for all the tested fluids shows that the Cross model describes well the rheological behavior of these fluids except for the base fluid tested at 75°C, which has been described well by the H-B model. Figure 2 shows the rheological data of the base fluid tested at 25°C fitted by the Cross model and of the base fluid tested at 75°C fitted by the H-B model, giving correlation coefficient 0.9999 and 0.9981 respectively.

The behavior of the based fluid is transformed from the Cross to the H-B model when subjecting the fluid to elevated temperature of 75°C. The elevated temperature leads to phase separation and the fluid comes more resistant to flow. In this case, the fluid has a yield stress and the rheological data are well fitted by the H-B model, in contrast to the other tested fluids where the yield stress is disappeared.

Table 3: Cross model parameters for the base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG)

Drilling fluid	η_0 (Pa.)	η_∞ (Pa.s)	ƛ (s)	m (-)	R^2
Base fluid (25°C, natural pH)	0.6020	0.0147	0.0695	0.8236	0.9999
Base fluid (35°C, natural pH)	0.4060	0.0127	0.0480	0.8328	0.9998
Base fluid (55°C, natural pH)	0.2040	0.0067	0.0599	0.7047	0.9998
Base fluid (65°C, natural pH)	0.2460	0.0139	0.0737	0.7076	0.9989
Base fluid+0.5 wt% NaCl (25°C)	0.4220	0.0116	0.0597	0.7813	0.9999
Base fluid+1.0 wt% NaCl (25°C)	0.3260	0.0121	0.0491	0.7940	0.9999
Base fluid+1.5 wt% NaCl (25°C)	0.5730	0.0173	0.0362	0.8712	0.9999
Base fluid+2.0 wt% NaCl (25°C)	0.3320	0.0117	0.0515	0.7846	0.9999
Base fluid+0.5 wt% KCl (25°C)	0.3180	0.0110	0.0511	0.7854	0.9999
Base fluid+1.0 wt% KCl (25°C)	0.1930	0.0111	0.0333	0.8019	0.9999
Base fluid+1.5 wt% KCl (25°C)	0.3390	0.0111	0.0499	0.7893	0.9999
Base fluid+2.0 wt% KCl (25°C)	0.3060	0.0111	0.0497	0.7840	0.9999
Base fluid (25°C, pH=3.10)	0.1190	0.0109	0.0243	0.7776	0.9999
Base fluid (25°C, pH=6.09)	0.2910	0.0116	0.0519	0.7784	0.9999
Base fluid (25°C, pH=8.80)	0.3520	0.0121	0.0572	0.7806	0.9999
Base fluid (25°C, pH=12.06)	0.5900	0.0181	0.0327	0.9687	0.9998

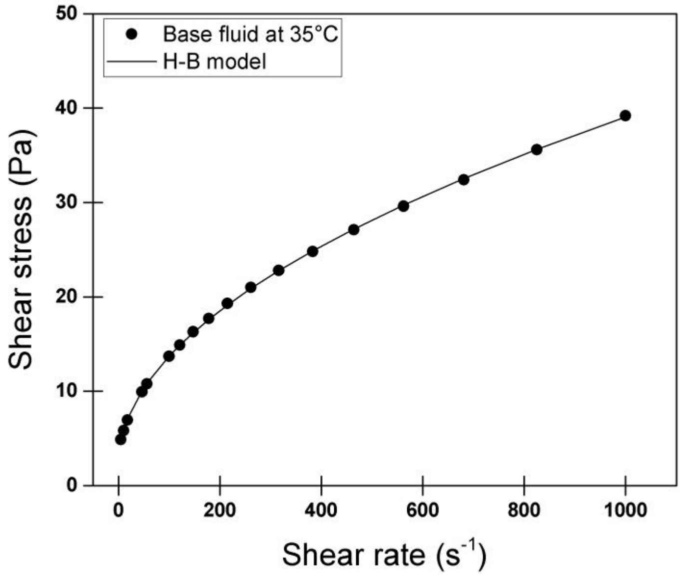

Figure 1. Rheological data fitted by the H-B model for the base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) at 35°C and natural pH.

B. Base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG)

The flow curves of the base tested drilling fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) are similar to those reported by Ouaer and Gareche, [20] on HEC solutions and they can be correlated by the Cross model except for the base fluid tested at 75°C where the H-B is suitable. The cross model is expressed by Cross:

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The results show that the behavior of HEC is predominated than that of the bentonite suspensions. This effect may be attributed to the nature of Mag-b, which is an activated calcium bentonite.

Table 3 presents rheological parameters of the Cross model for the tested fluids. It can be noticed that (η_(0)), (η_∞) and (λ) decrease with increasing temperature to 55°C and they increase at 65°C. These parameters decrease also with increasing NaCl and KCl concentration and they reach a minimum at pH= 3.10.

The correlation coefficient (R2) for all the tested fluids shows that the Cross model does a good job of explaining how these fluids behave rheologically. The only fluid that doesn't do well with this model is the base fluid that was tested at 75°C. Figure 2 displays the rheological data of the base fluid at 25°C, fitted by the Cross model, and the base fluid at 75°C, fitted by the H-B model, yielding correlation coefficients of 0.9999 and 0.9981, respectively.

Elevating the fluid to 75°C transforms its behaviour from the Cross to the H-B model. The elevated temperature leads to phase separation, and the fluid becomes more resistant to flow. In this case, the fluid exhibits a yield stress, and the H-B model accurately fits the rheological data, unlike the other tested fluids where the yield stress has vanished.

Table 3: Cross model parameters for the base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG).

Drilling fluid	η_0 (Pa.s)	η_∞ (Pa.s)	λ (s)	m (-)	R^2
Base fluid (25°C, natural pH)	0.6020	0.0147	0.0695	0.8236	0.9999
Base fluid (35°C, natural pH)	0.4060	0.0127	0.0480	0.8328	0.9998
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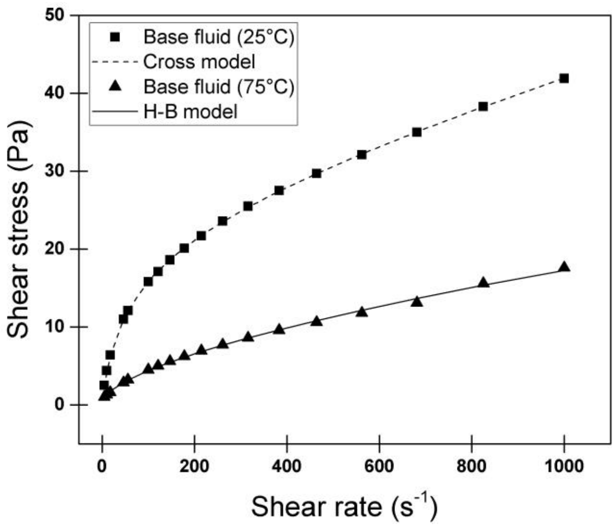

Figure 2. Rheological data fitted by the H-B and Cross models for the base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) at 35°C and 75°C respectively.

B. Effect of temperature on the viscosity of eco-friendly water-based drilling fluid

In figure 3 (a and b) the curves of viscosity versus shear rate of all ten samples at the tested temperatures are plotted. It has been observed, on the one hand for (Mos-b/HEC/PEG) for the temperatures below 55°C (≤ 55°C) that the viscosity decreases with increasing temperature, while for the temperatures above 55°C, the viscosity increases. It is also obvious that all (Mos-b/HEC/PEG) samples have a shear thickening behavior at low shear rate, this behavior is more significant for the curve measured at 65°C, which lets us predict the presence of a cloud point around this temperature. On the other hand, for (Mag-b/HEC/PEG), it is clear for the temperatures below 65°C (≤ 65°C), that the appearance of the viscosity curves remains the same, where the viscosity decreases with increasing temperature and exhibits a Newtonian plateau at low shear rate. While for the curve measured at 75°C the viscosity increases and exhibits a shear thickening behavior at low shear rate, indicating that the cloud point for (Mag-b/HEC/PEG) is around 75°C.

These findings suggest that (HEC) regulates the thermal behaviour of the mixtures (Mos-b/HEC/PEG) and (Mag-b/HEC/PEG). Like other cellulose derivatives, this polymer has a distinctive temperature known as the cloud point or gelation area. Phase separation of the polymer happened at this temperature, making it more flow-resistant. An increase in hydrophobic contacts between macromolecular chains causes a change in the internal structure of the macromolecule around the critical temperature, leading to phase separation. Otherwise, a rise in molecular free volume and a concurrent decrease in intramolecular and/or intermolecular interactions can explain the drop in viscosity up to a specific temperature. After that, the viscosity increases significantly [1],[12],[5].

It is also found that the transition sol-gel occurs at a lower temperature for (Mos-b/HEC/PEG) mixture than that for which it appears for (Mag-b/HEC/PEG) mixture. The type of bentonite would probably have an effect on the thermodynamics of fluids and change the cloud point (gelation temperature).

If the viscosities of the two mixtures (Mos-b/HEC/PEG) and (Mag-b/HEC/PEG) are compared, it can be noticed that the mixture (Mos-b/HEC/PEG) have higher viscosities than the mixture (Mag-b/HEC/PEG) for all the tested temperatures. This effect can be also attributed to the type of bentonite i.e. Mos-b has a high swelling capacity than Mag-b.

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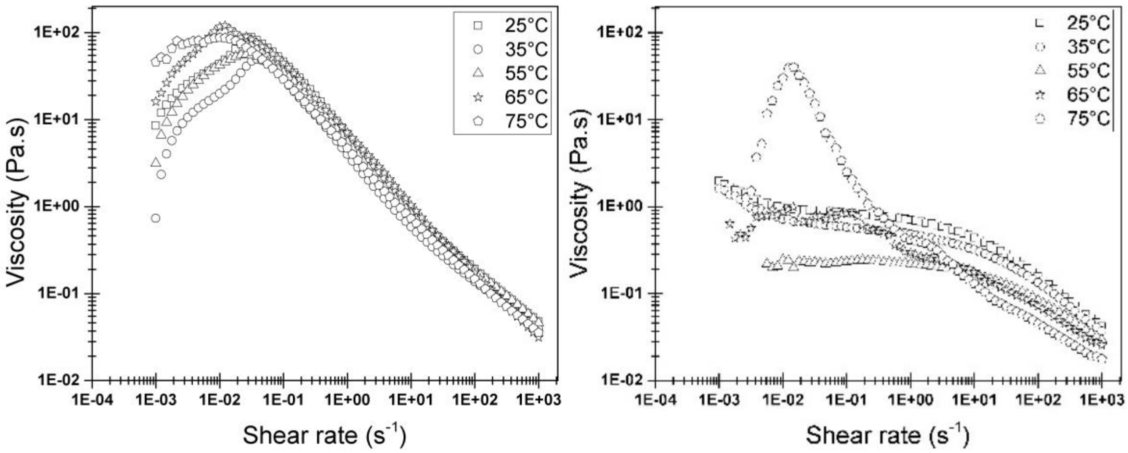


(a) (b)

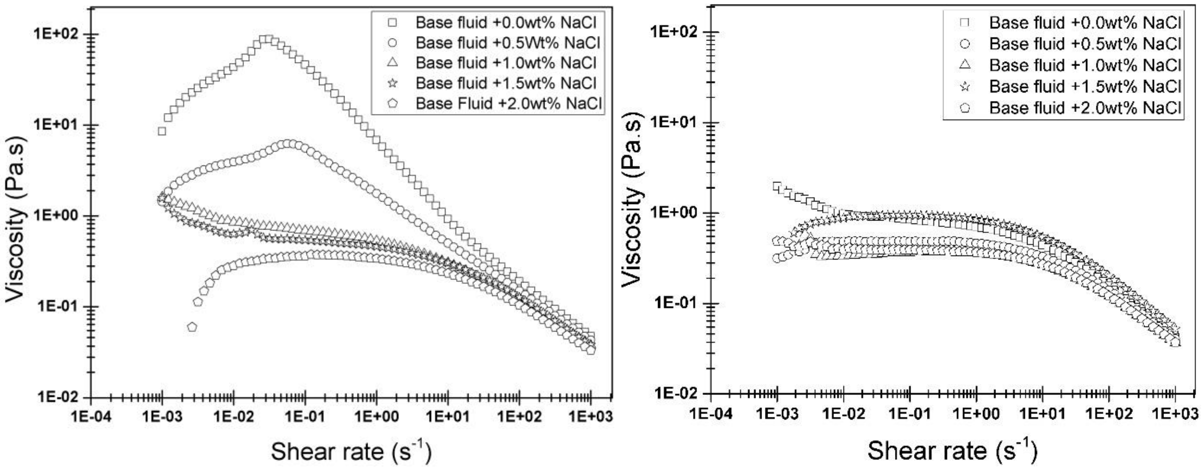
Figure 3. The effect of temperature on the viscosity: (a) for 3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG, (b) for 3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG.

C. Effect of salt on the viscosity of eco-friendly water-based drilling fluid

Figure 4 (a and b) and figure 5 (a and b) show the changes of apparent viscosity with NaCl and KCl concentration, respectively for the base fluids (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) and (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG). From these figures, it is obvious that the effect of adding salt to the base fluids is to reduce the viscosity of these fluids whatever the type of salt. However, the degree of the viscosity reduction changes depending on the type of bentonite and salt. For the base fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG), the viscosity decreases more significantly when adding KCl, where this latter changes the rheological behavior of the base fluid and transform the shear thickening to a Newtonian plateau at low shear rate at a concentration of 0.5wt%. The decrease in viscosity remains constant as KCl concentration raises from 1.0wt% to 2.0wt%. While the NaCl addition leads to a Newtonian plateau in behalf of shear thickening at low shear rate at a concentration of 1.0wt%. The decrease in viscosity is continuous with increasing NaCl concentration.

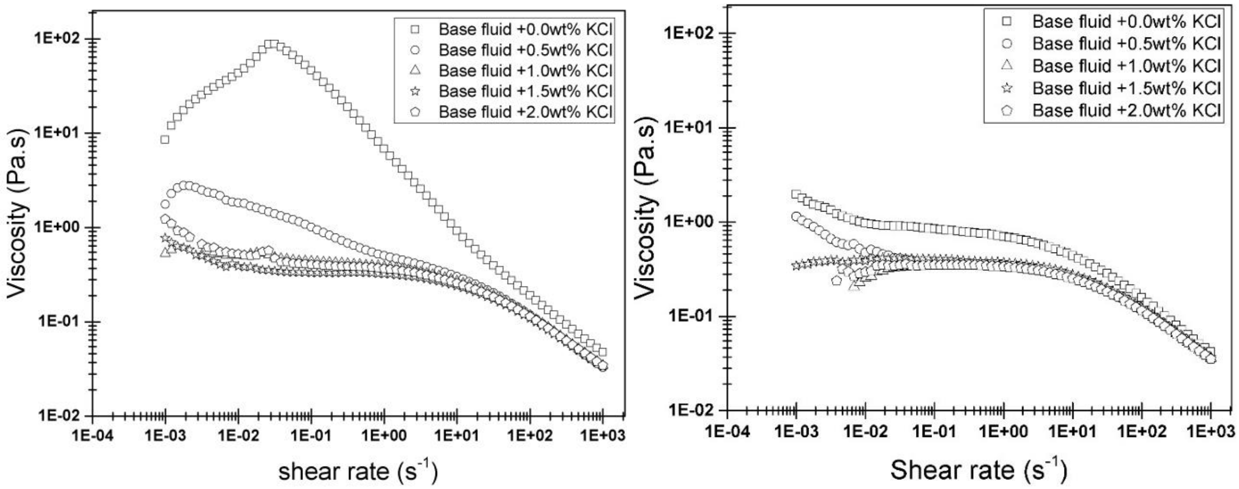
For the base fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG), the viscosity also decreases more significantly when adding KCl, but it remains constant after the first decrease whatever the concentration of NaCl or KCl.

The effect of decreasing viscosity with the addition of salt may be due to the compression of bentonite electrical double layer (Permien and Lagaly 1994a). The system viscosity is decreased as a result of electrical double layer compression, which stops water and polymers from penetrating the bentonite interlayer. These results also indicate that the NaCl/KCl addition to the systems (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG)/ (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) destroys the three-dimensional network, thus a reduction in viscosity is observed and this reduction becomes more important with the KCl addition for the two types of bentonite. The latter effect may be due to the nature of K^+, which is a cation less hydrated and occupies less space in the interfoliar space (Benyounes and Benmounah, 2015), hence variations in the swelling behavior of bentonite will created. The stabilization of viscosity after adding a certain concentration of NaCl/KCl to the systems (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG)/ (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) may be due to the limitation of cation exchange phenomenon because the interfoliar space of the bentonite layer is saturated.



(a) (b)

Figure 4: The effect of NaCl concentration on the viscosity: (a) for 3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG, (b) for 3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG

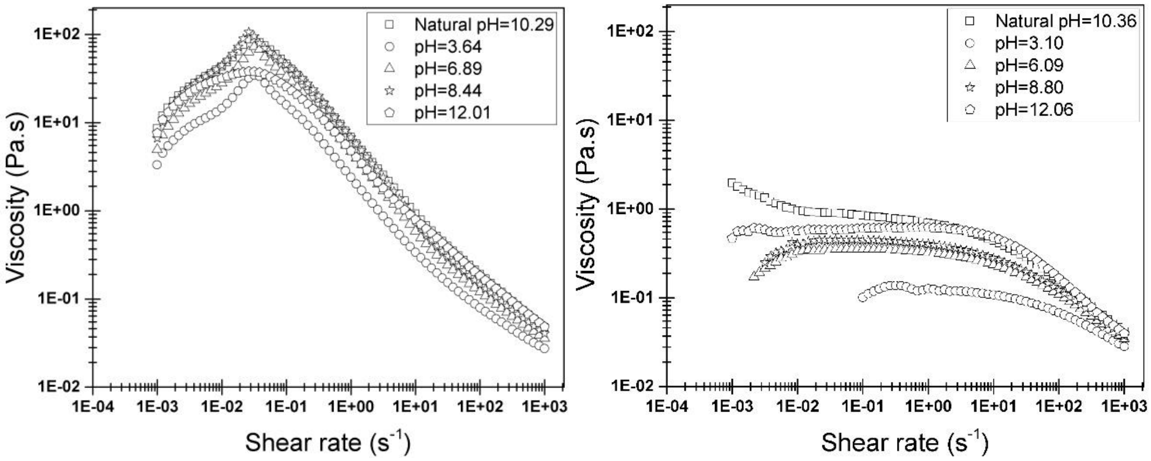


(a) (b)

Figure 5: The effect of KCl concentration on the viscosity: (a) for 3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG, (b) for 3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG

D. Effect of pH on the viscosity of eco-friendly water-based drilling fluid

The relationship between the viscosities of the tested fluids (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) and (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG) with pH variations is shown in figure 6 (a and b). As shown, the viscosity shows a minimum in the low pH region (about 3.64 and 3.10 for the fluids (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) and (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG, respectively). The results show also that the apparent viscosity presents a maximum, for all the imposed shear rates, at a pH value lower than the natural pH, (pH= 8.44) for the fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG) and higher than the natural pH, (pH= 12.06) for the fluid (3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG). The variation from the maximum to the minimum is significant for the fluid (3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG). The location of maximum viscosities at high pH values can be attributed to the band like structures resulting from FF (Face-to-Face) association, this association gives larger flakes and stronger gels as reported by Duran et al. [11] and Tombácz and Szekeres [24]. The difference between the values of the pH in which the viscosity of the tested fluids is high is due to the fact that Mos-b is a raw material, while Mag-b is a purified bentonite with sodium carbonate (Na_2CO_3), which indicates that the layers of Mag-b are somehow cemented as a result of the activation process. Based on these results, it can be concluded that alkaline pH leads to a stronger three-dimensional network and results in stronger gels, which explains the high viscosity values of drilling fluids. Furthermore, the pH value at which the maximum viscosity is reached is relatively dependent on the type of bentonite.



(a) (b)

Figure 6: The effect of pH on the viscosity: (a) for 3wt% Mos-b+ 0.5wt% HEC+ 0.2wt% PEG, (b) for 3wt% Mag-b+ 0.5wt% HEC+ 0.2wt% PEG

IV. Conclusion

It was looked at how temperature, pH, and salt (NaCl and KCl) affect the flow characteristics of an eco-friendly drilling fluid made from two types of bentonites (Mos-b and Mag-b) and two water-soluble polymers. The H-B model has fitted the rheograms of the base drilling fluid (3 wt% Mos-b + 0.5 wt% HEC + 0.2 wt% PEG) very well. The Cross model does a good job of fitting the flow curves of the base fluid (3 wt% Mag-b + 0.5 wt% HEC + 0.2 wt% PEG), with the exception of a temperature of 75°C, where a yield stress appears. This suggests that the H-B model is a better fit for the data. Hence, the addition of HEC and PEG in Mag-b suspension allows getting closer to the behavior of the polymer solution; this is due mainly to the activation process of Mag-b.

The rheometric analysis, conducted as a function of temperature, revealed a decrease in viscosity with temperature up to a critical value known as the gelation temperature, which is approximately 65°C and 75°C for the base fluids (3 wt% Mos-b + 0.5 wt% HEC + 0.2 wt% PEG and 3 wt% Mag-b + 0.5 wt% HEC + 0.2 wt% PEG), respectively. We observed a sudden jump in viscosity at the indicated critical temperatures. We attributed the difference in the critical temperatures of the two base fluids to the type of bentonite, likely influencing the fluid's thermodynamics and altering the cloud point (gelation temperature).

The addition of salt (NaCl and KCl) to the base fluids decreases the viscosity of the tested fluids. The viscosity decrease is more significant when KCl is added to both tested fluids. Generally, the compression of the electric double layer, which disrupts the network structure, is responsible for the viscosity decrease. The less hydrated cation "K+" creates variations in the swelling behavior of bentonite, which significantly reduces viscosity due to the KCl addition.

For the range of pH values studied, a maximum apparent viscosity at all shear rates has been observed at the highest pH region, which can be attributed to the band-like structures resulting from FF (face-to-face) association.

Because it thermogelates at higher temperatures and acts like stronger gels at alkaline pH, these results suggest that the environmentally friendly drilling fluid (bentonite/HEC/PEG) can be used for drilling fluid purposes, especially for moving and suspending cuttings. This behavior is more important for the base fluid (3 wt% MosB + 0.5 wt% HEC + 0.2 wt% PEG), which demonstrates that natural bentonites are more reliable than the activated ones. Additionally, we advise employing a NaCl or KCl concentration of no more than 1 weight percent to prevent the degradation of drilling fluids' rheological properties. In addition to being suitable for use in geothermal wells, the suggested drilling fluid composition (bentonite/HEC/PEG) can improve well service fluids for oil and gas exploration and production. It may provide the necessary viscosity with the temperature rise, which is a beneficial property for drilling fluids, as well as an effective yield stress, which is preferred to raise the fluid's solid carrying capacity. Moreover, a high concentration of NaCl or KCl at room temperature (surface) lowers the viscosity and yield stress, which is advantageous for the simple removal of drilled solids from the shale shaker.

In drilling fluids applications, where controlling the rheological behavior of aqueous dispersions is crucial, rigid biopolymers with viscosifying or gelifying properties, like xanthan gum [17], or high molecular weight polymers, such as cellulose derivatives [6], are used as additives to the bentonite suspensions. The increase in bentonite-polymer viscosity was due mainly to network structure formation within the suspension. However, certain conditions such as high salt contamination, high temperature, and low pH regions limit this increase in viscosity.

Therefore, it was crucial to develop a drilling fluid that could maintain a near-stable viscosity under various conditions.

V. References

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NOMENCLATURE

Roman Symbols

FF	Face-to-Face
H−B	Herschel-Bulkley
HEC	hydroxyethyl cellulose
HPHT	high pressure and high temperature
k	consistency index (Pa. s^n)
Mag−b	Maghnia bentonite
Mos−b	Mostaganem bentonite
m	dimensionless constant
n	flow index
PEG	polyethylene glycol
R^2	correlation coefficient

Creek Symbols

$\dot{\gamma}$	shear rate (s^{-1})
λ	time constant (s)
η_0	zero shear rate viscosity (Pa.s)
η_∞	infinite shear rate viscosity (Pa.s)
τ	shear stress (Pa)
τ_c	yield stress (Pa)