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Application of Nonionic Polysaccharides for Eco-Friendly Water-Bentonite-Based Drilling Fluid and the Effect of Temperature, Salt, and pH on their Rheological Behavior

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Abstract

Nonionic polysaccharides and polyethylene glycols of intermediate molecular weight were used as an environmentally friendly and highly effective additive in water-based bentonite drilling fluids for inhibiting syneresis, providing good slurry rheological profiles at elevated temperatures and giving such properties in a saline well environment. The impacts of temperature, salt type and concentration and pH on the rheological properties of an eco-friendly water-based drilling fluid formulated based on two different Algerian bentonites namely, Mostaganem and Maghnia bentonite (Mos−b and Mag−b) and two water-soluble polymers (Hydroxyethyl cellulose and polyethylene glycol) were investigated. The rheological data in steady state shear were fitted to the Herschel-Bulkley (H−B) and Cross models to find the rheological parameters such as yield stress, consistency index, flow behavior index, the zero shear viscosity, the infinite shear viscosity and the characteristic constant of time. Results showed that yield stress, consistency index and viscosity reached maximum at a temperature of 65 and 75 °C for Mos−b and Mag−b respectively, and that the decrease in pH and the addition of sodium chloride (NaCl) and potassium chloride (KCl) decrease the rheological properties of the drilling fluids. The decrease in rheological parameters was more important in the case of KCl addition. 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 fluid containing Mag−b.

Keywords: *Polymers; Nonionic polysaccharides; Bentonite; Temperature; Salt; Rheological behavior.*

1. Introduction

In the past few decades, demand for oil and gas has increased due to the utility of these products to industrialization and to develop living standards. Unfortunately, the high demands result in increasing the exhaustion rate of oil and gas reservoirs around the world and in the production loss of many oilfields. These problems require industry to look for new oilfields, which are located in more challenging reservoirs such as the deeper one and the one with elevated pressure and temperature conditions. Thus, comes the challenge of maintaining desired rheological properties of the drilling fluids in deep and ultra-deep wells. When drilling in deep/ultra-deep wells for oil, gas or geothermal reservoirs, high temperatures and high pressures adversely alter the performance of drilling fluids. In addition, these fluids can be also contaminated during drilling of salt beds or in offshore operations, where seawater is used in preparing the drilling fluids [14]. Particularly, the gel formation in bentonite dispersions develops, which results in the increase in fluid loss causing permeability damage, which can be prejudicial not only to the drilling activity, but also to later production [10, 13, 17], and cause deterioration of the rheological properties of drilling fluids [3, 8, 10, 18]. At high temperatures and in formations, where salt can present and contaminate the drilling fluids, particular formulations and systems should be used.

Different drilling fluids improvements are made for this purpose, but in all cases, some imperfections are observed. Alderman *et al.* [3] have studied the rheological properties of different muds formulated based on bentonite and other additives such as polymers (lignosulphonate and synthetic polymer deflocculants) and surfactants. Consequently, they have reported that the high-shear viscosity decreased with increasing temperature for all the examined muds. Kelessidis *et al.* [16] have observed that salt addition decreases the apparent viscosity at all shear rates for the three-studied bentonite concentrations of 2%, 5% and 6.42%. Abu-Jdayil [1] has concluded that the presence of electrolytes in a concentration range of 0.02–0.2 M leads to a decrease in the apparent viscosity of the bentonite suspensions. Uti and Joel [24] have compared the effect of different salts on the hydration of bentonite and this comparative study showed that the plastic viscosity decreases when salt concentration increases. Chang and Leong [9] have investigated the effects of Li, Na, K and Cs 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 the increase in salinity. Ahmad *et al.* [2] have used nanoparticles and water-soluble polymers to improve drilling fluid properties and they have found that the plastic viscosity decreases with the increase in temperature from 25°C to 85°C. Vryzas *et al.* [25] have examined the effect of temperature on the rheological properties of neat aqueous Wyoming sodium bentonite dispersions and they have noticed that plastic viscosity decreases with increasing temperature. Hence, all the mentioned studies show that changes and alterations took place in the fluid rheological properties when they were subjected to these conditions, and these changes will negatively affect the functionality of drilling fluids [14].

In all studies cited above, most efforts concentrated on the development of adequate additives to counteract the prejudicial impact of temperature and salt on the rheological behavior of water based drilling fluids and not so much on the understanding of the impact of these two parameters on the rheological behavior of drilling fluids and in particular on the viscosity of these fluids. This shows a shortage of a comprehensive inquiry on the part of the drilling operations at high temperature and in salt-based drilling fluids.

This study is dedicated to shed some supplemental light into the mechanisms of the bentonite-polymer interactions in high temperature and salt environments and to evaluate hydroxyethyl cellulose (HEC) and polyethylene glycol (PEG) as functional additives for drilling fluids. A series of laboratory experiences have been carried out to evaluate the effect of temperature, salt and pH on the rheological properties, especially on the viscosity of an eco-friendly water-based drilling fluid formulated based on two different Algerian bentonites and two water-soluble polymers as stated in Ouaer *et al.* [21]. The influence of the above parameters on the rheological properties of eco-friendly water-based drilling fluid is discussed based on laboratory results. This study is a continuation of the previous study [21].

2. Materials and methods

2.1. Materials

The constitute materials of the study are Na-bentonite and Ca-activated bentonite as reported by the supplier. These two bentonite samples are sourced from the Algerian fields of "Mostaganem" and "Maghnia" respectively, and they are provided kindly by ENOF (Algerian Public Company of the Mining Products non-ferrous and useful Substances). The results of X-ray fluorescence (XRF) analysis of the two studied bentonites are shown in Table 1. Comparatively, the ratio of {(Na_2O + K_2O) / (CaO + MgO)} for these two types of bentonite is found to be higher for Mos−b than Mag−b, which refers the different nature of the two bentonite . The particle size of the bentonite samples is less than 70 µm [21]. The detailed description of the two polymers used in this study can be found in Ouaer and Gareche [19], Ouaer and Gareche [20], and Ouaer *et al.* [21].

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
Mos−B	60.49	13.87	0.29	3.14	3.54	3.95	1.69	2.37	0.24	0.08	10.35
Mag−B	58.54	16.03	0.16	2.17	3.58	0.82	2.01	7.26	0.14	0.05	9.26

2.2. Experimental methods

For preparing samples containing bentonite, HEC and PEG, firstly, a 3 wt% of bentonite powder was slowly added to demineralized water under mechanic stirring to ensure the homogeneity of the dispersion and to achieve the best swelling of bentonite. A fixed amount of 0.5 wt% of HEC powder was added to the mixture after 4 h of agitation, and a 0.2 wt% of PEG was subsequently introduced into the blend to avoid foam and syneresis phenomena. The obtained mixture was then mechanically stirred at 450 RPM for 20 h [21].

The samples were adjusted to different pH values using 0.1 N NaOH and 0.1 N HCl solutions and pH measurement procedure can be found in Ouaer and Gareche [20] and Ouaer *et al.* [21]. The effect of electrolyte concentrations (NaCl and KCl) was studied by adding bentonite and polymers in the appropriate electrolyte solution. Five electrolyte concentrations, the 0.0 wt% (distilled water as the standard solution), 0.5 wt % , 1.0 wt %, 1.5 wt % and 2.0 wt % were studied.

To analyze the rheological behavior of the studied drilling fluids, an Anton Paar-Physica/MCR-301 rheometer was used, it was equipped with coaxial cylinder geometry (Re = 14.464 mm, Ri = 13.325 mm, h = 39.997 mm). This geometry was chosen to minimize evaporation of the fluids at elevated temperatures.

Flow curves were obtained by increasing the shear rate from 10^{-3} to 10^{3} s^{-1}. The shear rate was ramped up logarithmically with a constant measuring-point duration of 20 s. The measurements were repeated with longer time in order to confirm the results. For temperature sweep, measurements were carried out at different temperatures ranged from 25 to 75°C, and they were started after achieving the temperature equilibrium [19-21].

Before each test, the samples were gently stirred for 20 min, afterwards, the suspensions were carefully loaded to the measuring geometry of the rheometer. In the measurement geometry, samples were also subjected to a preshear of 1000 s^{-1} to avoid wall slip phenomenon. Then they were left at rest for 60 s to have the same structural state of reference [20-21].

3. Results and discussion

3.1. Rheological behavior

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

The rheological data of the base drilling fluid 1 (BF1) (3 wt % Mos−b + 0.5 wt % HEC + 0.2 wt % PEG) are described mathematically using the Herschel-Bulkley (H−B) model, which is expressed as follows [15]:

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

where (τ) is the shear stress (Pa); (τ_c) is the yield stress (Pa); (k) is the consistency index (Pa.s^n); ($\dot{\gamma}$) is the shear rate (s^{-1}) and (n) is the flow index. The rheological parameters of the model are mentioned in Table 2.

Table 2. H−B model parameters calculated for the BF1

Drilling fluid	τ_c (Pa)	k (Pa.s^n)	n (-)	R^2
BF1 (25°C, natural pH)	4.4688	1.6759	0.4699	0.9997
BF1 (35°C, natural pH)	2.3610	1.0930	0.5086	0.9999
BF1 (55°C, natural pH)	1.2697	2.7016	0.4072	0.9994
BF1 (65°C, natural pH)	4.7866	2.6452	0.3341	0.9991
BF1 (75°C, natural pH)	3.3830	1.3395	0.4610	0.9999
BF1+0.5 wt% NaCl (25°C)	2.5856	1.1116	0.5215	0.9973
BF1+1.0 wt% NaCl (25°C)	0.8244	1.0116	0.5220	0.9973
BF1+1.5 wt% NaCl (25°C)	0.7384	1.1483	0.5063	0.9963
BF1+2.0 wt% NaCl (25°C)	0.4892	0.8660	0.5272	0.9972
BF1+0.5 wt% KCl (25°C)	2.4239	0.7592	0.5378	0.9893
BF1+1.0 wt% KCl (25°C)	2.3540	0.6902	0.5510	0.9892
BF1+1.5 wt% KCl (25°C)	1.9657	0.6343	0.5691	0.9912
BF1+2.0 wt% KCl (25°C)	1.9685	0.6968	0.5599	0.9916
BF1 (25°C, pH=3.64)	1.9749	0.3404	0.6231	0.9999

Drilling fluid	τ_c (Pa)	k (Pa.s^n)	n (-)	R^2
BF1 (25°C, pH=6.89)	3.7405	0.5592	0.5847	0.9997
BF1 (25°C, pH=8.44)	5.2489	0.6896	0.5694	0.9991
BF1 (25°C, pH=12.01)	2.4445	1.9365	0.4579	0.9999

According to the results, the yield stress increases dramatically at 65°C and at pH = 8.44 (Fig 1a and 1b). It decreases with the increase in the NaCl and KCl concentration, but this decrease is more significant in the case of NaCl (Fig 1c), whereas, the consistency index decreases more significantly when adding KCl. The latter result demonstrates that NaCl addition destroys the three-dimensional network, which leads to a significant reduction in yield stress [21], 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 [5].

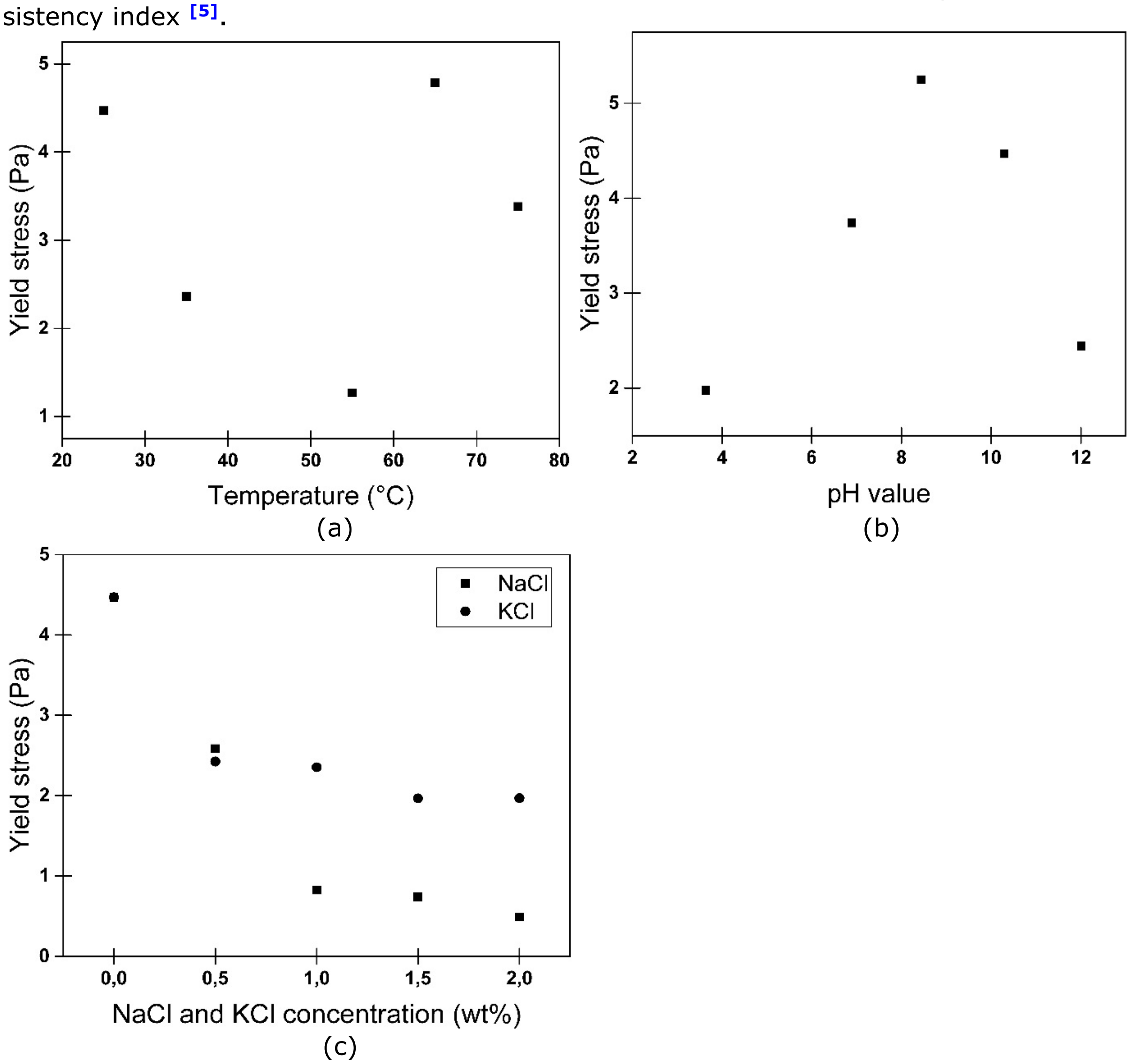

Figure 1. Evolution of the yield stress of the BF1 as a function of temperature, pH and salt concentration

Based on the correlation coefficient (R^2) mentioned in Table 2, the rheological behavior of the BF1 has described well using the H−B model over the full shear rate range. Figure 2 shows how extremely well rheological data have been described by the model for the BF1 at 35°C and natural pH giving correlation coefficient 0.9999.

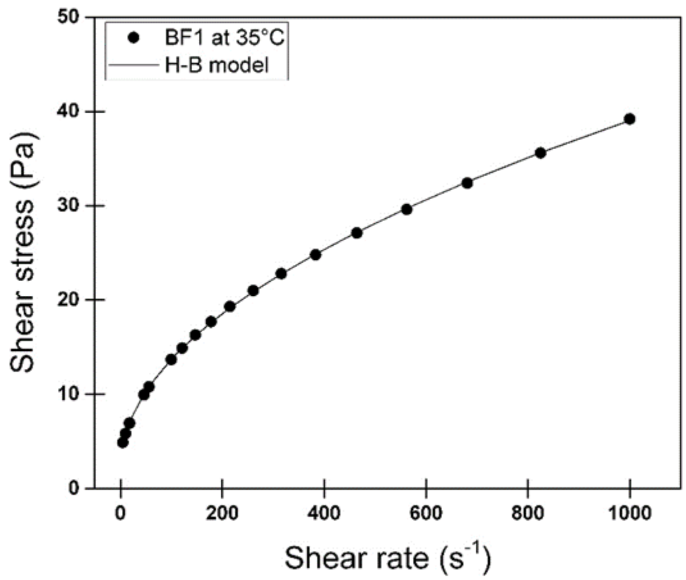

Figure 2. Rheological data fitted to the H−B model for the BF1 at 35°C and natural pH

The shear thickening behavior, which appears in the flow curves of this fluid is the result of the stiffer inner structure due to the formation of entanglements of polymer coils and the increase in the intermolecular interactions.

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

The flow curves of the base tested drilling fluid 2 (BF2) (3 wt % Mag−b + 0.5 wt % HEC + 0.2 wt % PEG) are similar to those reported by Ouaer and Gareche [19] 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 as follows [11]:

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

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 the rheological parameters of the Cross model for the tested fluid. 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 also decrease with increasing NaCl and KCl concentration and they reach a minimum at pH = 3.10.

Table 3. Cross model parameters for the BF2

Drilling fluid	η_0 (Pa.s)	η_∞ (Pa.s)	λ (s)	m (-)	R^2
BF2 (25°C, natural pH)	0.6020	0.0147	0.0695	0.8236	0.9999
BF2 (35°C, natural pH)	0.4060	0.0127	0.0480	0.8328	0.9998
BF2 (55°C, natural pH)	0.2040	0.0067	0.0599	0.7047	0.9998
BF2 (65°C, natural pH)	0.2460	0.0139	0.0737	0.7076	0.9989
BF2+0.5 wt% NaCl (25°C)	0.4220	0.0116	0.0597	0.7813	0.9999
BF2+1.0 wt% NaCl (25°C)	0.3260	0.0121	0.0491	0.7940	0.9999
BF2+1.5 wt% NaCl (25°C)	0.5730	0.0173	0.0362	0.8712	0.9999
BF2+2.0 wt% NaCl (25°C)	0.3320	0.0117	0.0515	0.7846	0.9999
BF2+0.5 wt% KCl (25°C)	0.3180	0.0110	0.0511	0.7854	0.9999
BF2+1.0 wt% KCl (25°C)	0.1930	0.0111	0.0333	0.8019	0.9999
BF2+1.5 wt% KCl (25°C)	0.3390	0.0111	0.0499	0.7893	0.9999
BF2+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
BF2 (25°C, pH=6.09)	0.2910	0.0116	0.0519	0.7784	0.9999
BF2 (25°C, pH=8.80)	0.3520	0.0121	0.0572	0.7806	0.9999
BF2 (25°C, pH=12.06)	0.5900	0.0181	0.0327	0.9687	0.9998

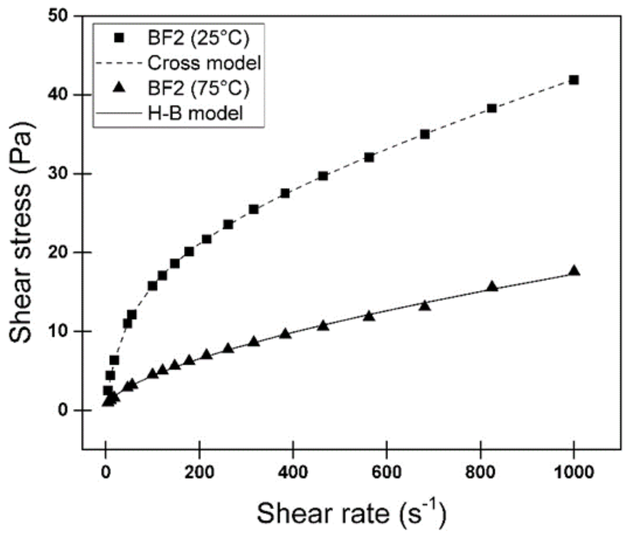

Figure 3. Rheological data fitted to the H−B and Cross models for the BF2 at 25°C and 75°C respectively

The correlation coefficient (R^2) calculated for all the tested fluids (BF2) 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 3 shows the rheological data of the base fluid tested at 25°C fitted to the Cross model and of the base fluid tested at 75 °C fitted to the H−B model, giving correlation coefficient 0.9999 and 0.9981 respectively.

The behavior of the based fluid is well described using 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 to the H−B model, in contrast to the other tested fluids, where the yield stress is disappeared.

3.2. Effect of temperature on the rheological behavior of eco-friendly water-based drilling fluid

In Figure 4a-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 the BF1 at temperatures below 55°C (≤ 55°C) that the viscosity decreases with the increase in temperature, whereas for the temperatures above 55°C, the viscosity increases. It is also obvious that all BF1 samples have a shear thickening behavior at low shear rates, this behavior is more significant for the curve measured at 65°C, which indicates the existence of a cloud point around this temperature. On the other hand, for the BF2, it is clear for the temperatures below 65°C (≤ 65°C), that apparition of the viscosity curves remains the same, where the viscosity decreases with the increase in temperature and exhibits a Newtonian plateau at low shear rates. While for the curve measured at 75°C, the viscosity increases and exhibits a shear thickening behavior at low shear rates indicating that the cloud point for the BF2 is around 75°C. The results indicate that both fluids exhibit thermo- thinning behavior, which is became thermos-viscosifying one above certain temperature

These observations indicate that the thermal behavior of the mixture BF1 and BF2 is controlled by (HEC). This polymer is a temperature-sensitive thickening polymer. The chain of HEC are water-soluble at low temperatures, which leads to decrease the viscosity with heating, but the temperature raise upon the cloud point leads to an hydrophobic and self-assembled reversibly chains into a 3-dimensional network structure and thus the occurrence of thermo-viscosity behavior [7]. More explanation of this phenomenon can be found in Ouaer *et al.* [21].

It is also found that the transition sol-gel takes place at a lower temperature for the BF1 than that for which it appears for BF2. The type of bentonite would probably have an impact on the thermodynamics of fluids and change the cloud point (gelation temperature).

If the viscosities of the two mixtures BF1 and BF2 are compared, it can be noticed that the BF1 has higher viscosities than the BF2 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.

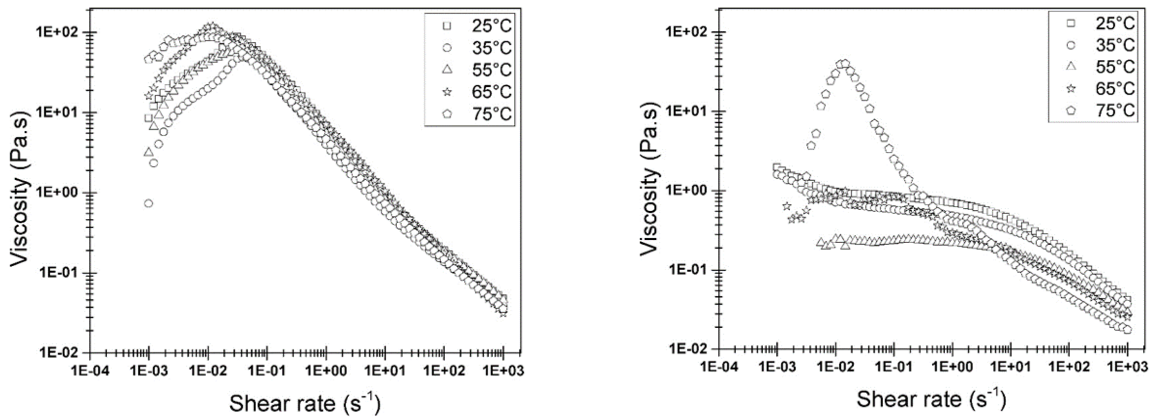

Figure 4. The effect of temperature on the viscosity: (a) for BF1, (b) for BF2

3.3. Effect of salt on the rheological behavior of eco-friendly water-based drilling fluid

Figure 5a-b and Figure 6a-b show the changes of apparent viscosity with NaCl and KCl concentrations, respectively, for the base fluids BF1 and BF2. 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 BF1, the viscosity decreases more significantly when adding KCl, where this latter changes the rheological behavior of the base fluid and transforms the shear thickening to a Newtonian plateau at low shear rate at a concentration of 0.5 wt %. The decrease in viscosity remains constant as KCl concentration increases from 1.0 wt % to 2.0 wt %. While the NaCl addition leads to a Newtonian plateau on behalf of shear thickening at low shear rate at a concentration of 1.0 wt%. The decrease in viscosity is continuous with the increase in NaCl concentration.

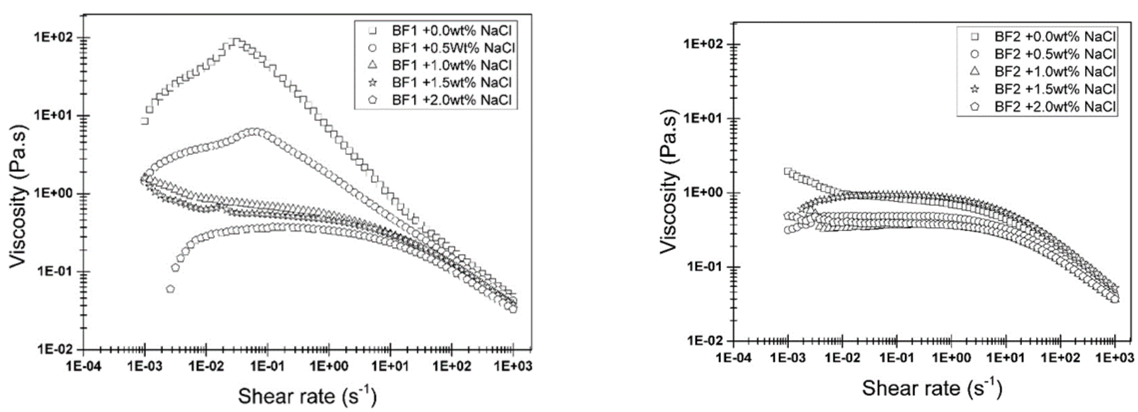

Figure 5. The effect of NaCl concentration on the viscosity: (a) for BF1 (b) for BF2

For the BF2, 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 addition of salt to the drilling fluids leads to the compression of bentonite electrical double layer, which decreases the viscosity [21]. The compression of the electrical double layer prohibits water and polymer to penetrate the bentonite interlayer and consequently the mixture viscosity is reduced [21]. These results also indicate that the addition of NaCl / KCl to the systems BF1/BF2 deteriorates 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 [6], 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 BF1/BF2 may be due to the limitation of cation exchange phenomenon because the interfoliar space of the bentonite layer is saturated.

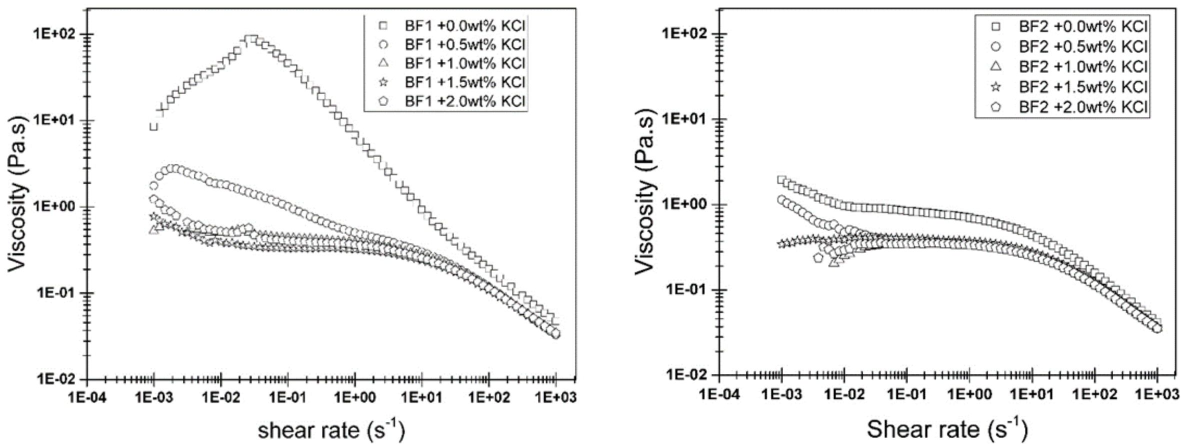

Figure 6. The effect of KCl concentration on the viscosity: (a) BF1, (b) for BF2

3.4. Effect of pH on the rheological behavior of eco-friendly water-based drilling fluid

The relationship between the viscosities of the tested fluids BF1 and BF2 with pH variations is shown in Figure 7a-b. As shown, the viscosity shows a minimum in the low pH region (about 3.64 and 3.10 for the BF1 and BF2, 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 BF1 and higher than the natural pH (pH = 12.06) for the BF2. The variation from the maximum to the minimum is significant for the BF1.

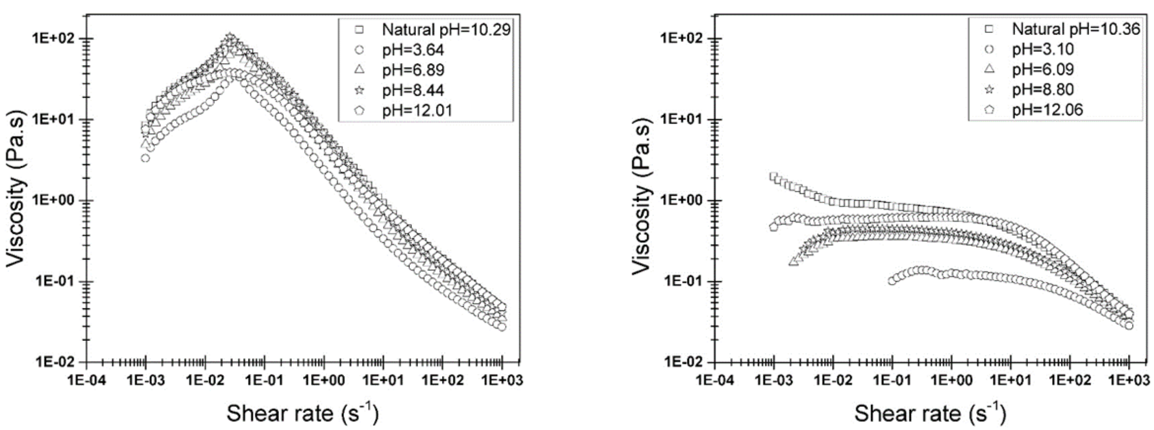

Figure 7. The effect of pH on the viscosity: (a) for BF1 (b) for BF2

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.* [12], and Tombácz and Szekeres [23]. 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 [21]. Furthermore, the pH value at which the maximum viscosity is reached is relatively dependent on the type of bentonite.

4. Conclusions

The effects of temperature, pH and salt (NaCl and KCl) on the rheological properties of eco-friendly water-based drilling fluid formulated based on two different bentonites (Mos−b and Mag−b) and two water-soluble polymers have been studied. The rheograms of the BF1 have been fitted very well to the H−B model. While the Cross model results in good fit for the flow curves of the BF2 except for a temperature of 75°C, where a yield stress appears recommending the H−B model as a good model to fit the data. Hence, the addition of HEC and PEG to Mag−b suspension allows getting closer to a behavior of the polymer solution; this is due mainly to the activation process of Mag−b.

A rheometric analysis as a function of temperature indicated a reduction of viscosity with temperature up to critical value well known as the gelation temperature closes to 65°C and 75°C for the BF1 and BF2 respectively. A sudden jump of viscosity had been observed at the indicated critical temperatures. The difference between the critical temperatures of the two base fluids was attributed to the type of bentonite, which would probably have an impact on the thermodynamics of fluids and change the cloud point (gelation temperature).

Addition of salt (NaCl and KCl) to the base fluids decreases the viscosity of the tested fluids. This decrease of viscosity is more significant in the case of KCl for both tested fluids. The important reduction of viscosity causes by the KCl addition is attributed to the variations in the swelling behavior of bentonite created by the less hydrated cation "K^+".

In the range of pH values studied, a maximum on the 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.

Based on these results, it can be concluded that the BF1 is suitable for drilling fluid applications, especially for the transport and suspension of cuttings, which demonstrates that natural bentonites are more reliable than the activated one. From the results, it is also recommended do not exceed 1 wt % of NaCl or KCl to avoid the degradation of the rheological properties of drilling fluids. The studied formulation of drilling fluids (Bentonite/HEC/PEG) can improve the well service fluids for oil and gas exploration and production and can be used in the geothermal wells. It can exhibit good rheological properties when the temperature increases, which is an advantageous feature in drilling fluids. Moreover, for easy removal of drilled solids on the shale shaker, the drilling engineers can use a high concentration of NaCl or KCl at ambient (surface) temperatures, which results in a lower viscosity and reduces the yield stress.

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*

Greek 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)*

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