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Research Article

Rheological Properties of Bentonite/Polymer Based Drilling Fluid Under Different pH Conditions

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Abstract

To success the drilling operations, different criteria must be taken in account. One of the most important criterion is the design and performance of drilling fluids, which is greatly related to their rheological properties. Furthermore, it is crucial to study the rheological behavior of water-based drilling fluid based on bentonite/polymer. The current study aims at addressing the influence of pH on the rheological properties of bentonite/polymer based drilling fluid, furthermore, recommending the best range of pH, which provides high performance and safety of this drilling fluid. The obtained results showed that shear stress increased when increasing pH. It can be also noticed that the plastic viscosity (PV) and yield point (YP) of the drilling fluid 1 (F1) increased in high pH region and decreased in the other pH region. The plastic viscosity of the drilling fluid 2 (F2) is not significant. The higher value of YP/PV is located at a pH of 8.44, and this ratio decreases when increasing pH. These findings proved that keeping pH superior to 7 and inferior to 12 resulted in good rheological properties of drilling fluids that will help to remove the rock cuttings from the borehole to surface, and minimize the total cost of the drilling operations.

Keywords

Bentonite-Polymer Mud, Water-Based Drilling Fluids, pH Effect, Rheological Behavior, Sodium Bentonite

1. Introduction

In order to extract hydrocarbons from the reservoir, drilling operation must be performed. The technique widely used is the rotating method. This method cannot be achieved without using drilling fluid. This latter is of paramount importance in the petroleum drilling and should be selected carefully to reach the rock reservoir and extract oil or gas safely and with economical strategy. Minimizing the drilling fluids cost is in otherwise minimizing the total cost of the drilling operation because the drilling fluids cost can attain to 25 until 40% of the total cost of the drilling operation [8]. Many problems can be encountered during oil and gas drilling, which will cost more the drilling operation. The proportion of the drilling fluid cost to the overall drilling cost is influenced by various agents, including, the kind of the drilled texture, the hole placement, and lot of other problems that can be encountered during the drilling processes [16].

Generally, it can be found three types of drilling fluids, such as, water-based fluid, oil-based fluid, or gaseous fluid, and all kinds cited above are utilized in different formations and for achieving a well-specified objective with several additives for multiple purposes. According to Ribeiro et al. [23]; and Parkash, Sharma, and Bhattacharya [20] water-based drilling fluids are the most used because they are considered environmentally acceptable in relation to the use

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of non-aqueous ones. Water-based drilling muds especially bentonite-water dispersions have immense importance in oil and gas industry and being used worldwide for making water-based drilling muds due to its unique excellent swelling and gel formation properties [2]. The basic functions of drilling muds are: to control stability of wellbore, to remove the rock cuttings from the borehole to surface, to cool and lubricate the drilling bit, to overcome the friction between drilling pipe and borehole walls, and to block pores in the shale to prevent fluid loss [27].

Bentonite is a well-known type of clay found abundantly in nature, and has different properties. Montmorillonite, the main constituent of bentonite, is a nano-structured nano-porous mineral made from 2:1 (three) layer alumino-silicate. The main purpose of using bentonite with the drilling fluids is to develop and maintain the drilling fluids rheological properties to the required specifications. The rheological properties of bentonite dispersions such as apparent viscosity, yield stress and viscoelastic moduli are very important for drilling fluids. These properties are mainly governed by the associations among the particles of bentonite [2].

There are three types of associations among the bentonite particles in aqueous dispersions namely face to face (FF), edge to edge (EE) and face to edge (FE) [9, 11]. EE and FE association form a three-dimensional network similar to a card house structure and FF association forms a band structure in bentonite dispersions [24]. The gel formation in bentonite dispersions is due of two mechanisms; first is the strong electrostatic force of attraction between positively charged edges and negatively charged surfaces. The second mechanism is EE and FF interactions through double layer repulsion among the particles [14]. These associations are accountable for customizing the rheological properties of bentonite dispersions and these associations are incredibly affected by concentration and type of electrolytes, pH, temperature, and concentration of bentonite.

Using bentonite alone cannot satisfy the rheological and filtration properties of drilling fluids. It represents several drawbacks such as, reducing productivity of the drilling operations, provoking formation damage, and leading to differential pipe sticking [19]. Therefore, the introduction of other additives to formulate drilling fluids is of paramount importance to improve the effectiveness of this fluid. Different additives can be used and among them, the water-soluble polymers can be found. It is also found that degradable, nontoxic and environmentally friendly water-soluble polymers are the most performant additives [19]. Hydroxyethyl cellulose (HEC) and polyethylene glycol (PEG) are one of the functional additives that can be lead to an appropriate formulation of drilling fluid.

For petroleum engineers, information on bentonite/polymer based mud rheology is essential, and this property must be invariant to ensure the successful of drilling operations. These rheological properties are measured continuously during drilling and adjusted by the addition of different additives in order to meet the required specifications. The evaluation of bentonite and polymers concentration should be carried out as this concentration influences the drilling fluid rheology [15]. Far to the bentonite and polymers concentration, other parameters affect the mud rheological behavior such as, high pressure, high temperature conditions, the pH value and different types of salt. Otherwise, the drilling fluid additives must keep the best profile of rheology when encountering the cited above conditions.

Recently, Reinoso et al. [22] have studied the rheological behavior of xanthan gum solutions that have been used in the oil industry for flooding, drilling and completion operations. The rheology of the drilling fluid has been modified using the above polymer and it becomes suitable for application at high temperature.

Zhou et al. [29] have studied the effect of modifying montmorillonites by cationic and anionic surfactants on the rheological properties of oil-based drilling fluids. They have concluded that cationic–anionic organomontmorillonites (CA-OMt) have better properties in relatively low oil-water ratio oil-based drilling fluids than DG-OMt. Otherwise, the CA-OMt has the potential to be widely used in oil-based drilling fluids.

Abu-Jdayil and Ghannam [1] have modified the rheological properties of sodium bentonite-water dispersions by adding low viscosity carboxymethyl cellulose (CMC). The study showed that the desired rheological properties can be obtained with less bentonite concentration by adding CMC polymer, and the undesirable effects of high bentonite concentrations can be avoided.

Razi et al. [21] have studied the effect of guar gum polymer and lime powder addition on the fluid loss and rheological properties of the bentonite dispersions. They have reported that the addition of guar gum could adequately improve the rheological properties and fluid loss, while the lime powder addition resulted in increasing the fluid loss of bentonite dispersions.

Beck et al. [7] have studied the effect of mud rheology on rate of penetration (ROP) and they have improved that bentonite-based mud alters the ROP. Consequently, it is recommended to use small possible amount of bentonite to formulate the drilling fluid, in otherwise, it will be so better to find an alternative.

From the above reported studies, it is obvious that both bentonite and polymers have an effect on the drilling fluid rheological behavior. Furthermore, bentonite-based drilling fluid will affect the drilling operations cost by altering the ROP. All works discussed above have focused on the effects of different additives on the mud rheology. Another recent study done by Li et al. [13] has been focalized on the pH effect on the bentonite-based mud rheology containing chitin nanocrystals as an additive. The latter study exhibits that moving from neutral to acidic pH improve the drilling fluid rheology, while this acidic pH might lead to the corrosion of tubular. The discussion reported by Li et al. [13] denotes a lack of a comprehensive investigation on the section of pH effect on the mud rheology.

This work is devoted to illustrate the changes in bentonite-polymer based mud rheology when changing its pH. The studied drilling fluid is an environmentally friendly one, formulated based on two different Algerian bentonites and two water-soluble polymers as stated in Ouaer et al. [19]. The obtained results will help drilling engineers to understand the modifications of drilling fluid rheological properties induced by changing the pH.

This article is organized as follows; Section 2 describes the different methods and materials used in the study. In Section 3, the results of the study are shown and discussed, and in section 4, the main conclusions are recapitulated.

2. Materials and Experimental Study

2.1. Materials

The drilling fluid used in the current study contains different components where the water/bentonite are the main one. The composition of the used water-based drilling fluid based on bentonite/polymer is shown in table 1. The prepared drilling fluid is constituted from water as a base fluid, two different types of bentonite i.e. Na-bentonite and Ca-activated bentonite, obtained from the Algerian fields of "Mostaganem" and "Maghnia" respectively, and two water-soluble polymers namely, hydroxyethyl cellulose (HEC) and polyethylene glycol (PEG).

The two types of bentonite are used to testify which type is more stable in different pH conditions, and according to these types of bentonite, the obtained drilling fluids are named F1 (fluid formulated with Mostaganem bentonite), and F2 (fluid formulated with Maghnia bentonite). HEC used in this study is of high molecular weight (~ 9.5×10^5 g/mol) [17]. It is used for controlling and stabilizing the rheological behavior of drilling fluid. The molecular weight of the used PEG is about 6000 g/mol. This polymer prevents foam and syneresis in the bentonite/HEC system [19]. The pH of the base fluid is changed by adding droplets of HCl or NaOH of 0.1 N to the suspension water/bentonite/polymer.

Table 1. *Composition of the studied water-based drilling fluid.*

Component		Amount (wt%)	Function
Fluid 1 (F1)	**Fluid 2 (F2)**		
Water	Water	96.3	Base fluid
Mostaganem Bentonite (Mos-B)	Maghnia Bentonite (Mag-B)	3	Viscosifier
HEC	HEC	0.5	Rheology modifier and stabilizer
PEG	PEG	0.2	Prevention of foam and senyresis

2.2. Experimental Study

The water-based drilling fluid samples were prepared by respect of this protocol:

1) An amount of 3 wt% of bentonite was added bit by bit to demineralized water under permanent mixing to fully squander the clay particles in water and to fulfill the best swelling of the bentonite.
2) 0.5 wt% of HEC powder was immersed in the system water/bentonite after 4 hours of agitation.
3) At the same time, 0.2 wt% of PEG was also added to the mixture.
4) The acquired system (water/bentonite/HEC/PEG) was then let under mechanical mixing at 450 RPM for 20 hours.

The adjustment of the drilling fluid pH was carried out by adding a droplet of HCl or NaOH of 0.1 N, and the values were measured using pH meter (HANNA instruments, HI 2211) with a precision of ±0.01.

The rheological behavior was obtained using an Anton Paar-Physica/MCR-301 rheometer with a geometry of coaxial cylinder geometry. These measurements were carried out at constant temperature of 25 ± 0.1 ℃ and atmospheric pressure.

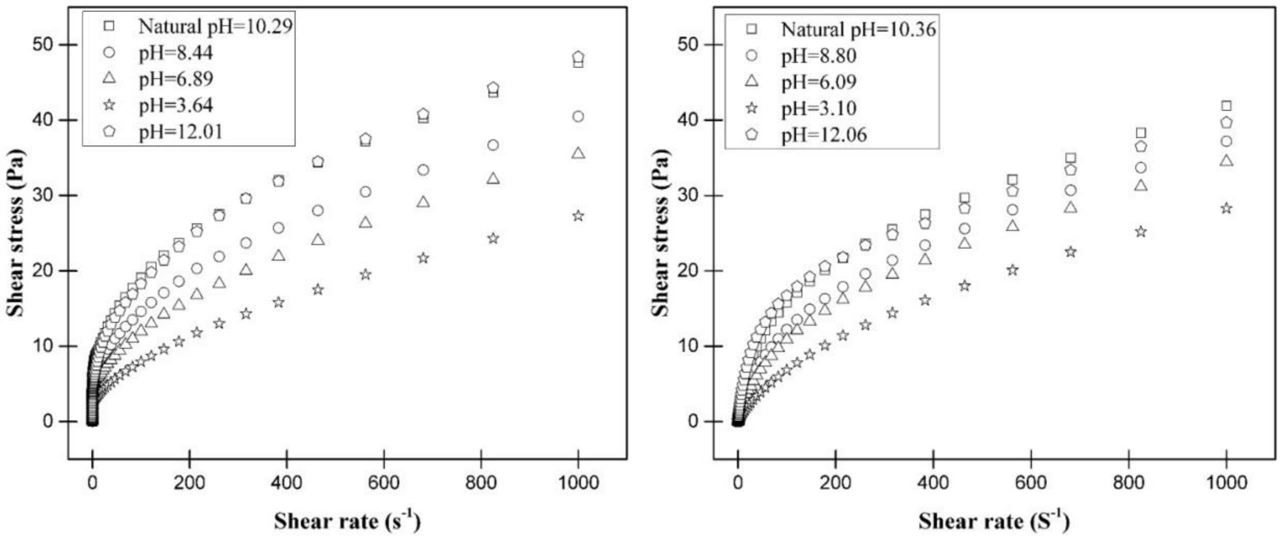
An increasing shear rate from 10^{-3} to 10^{3} s^{-1} was applied to obtain the flow curves of the studied drilling fluid. The shear rate was ramped up logarithmically with a constant measuring-point duration of 20 s.

To produce valuable and good results, before starting the rheological tests, the samples were softly agitated for 20 min, thereafter, the mud was closely loaded to the measuring geometry of the rheometer. Samples were also exposed to a preshear of 1000 s^{-1}, and afterwards, they were left at rest prior to the measurements for 60 s to have the identical structural state of reference [18, 19].

3. Results and Discussion

3.1. Flow Curves Behavior

The variation of flow curves (shear stress vs. shear rate) as function of pH of the two tested fluids (F1 and F2) was shown in figure 1 (a) and (b). As indicated in the figure, the shear stress increases when increasing the pH of drilling fluids (F1 and F2), and these increase is more significant for F1 than F2. The increase in shear stress as function of pH indicates an increase of the plastic viscosity (PV). The obtained results can be assigned to FF association of bentonite platelets, which results in band like structures. The FF association forms robust gels and huge flakes as stated by Tombácz and Szekeres [25]; and Duran et al. [10]. It can be also confirmed from these flow curves that F2 does not have a yield point. The latter statement is attributed to the predominance of HEC behavior, and this effect is due to the nature of Mag-B, which is an activated calcium bentonite. Consequently, for F2, we studied the effect of pH on PV only.



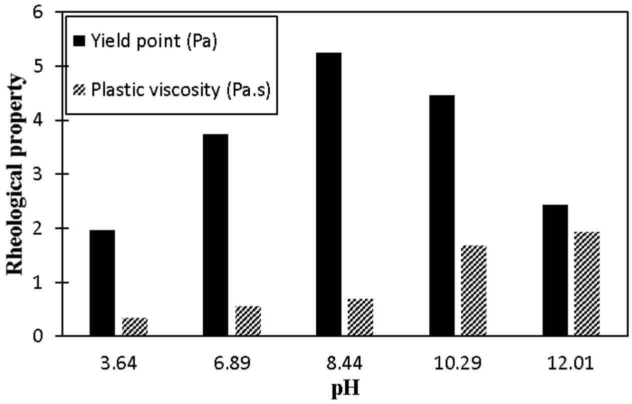
(a) (b)

Figure 1. *Flow curves behavior as a function of pH: (a) for F1, (b) for F2.*

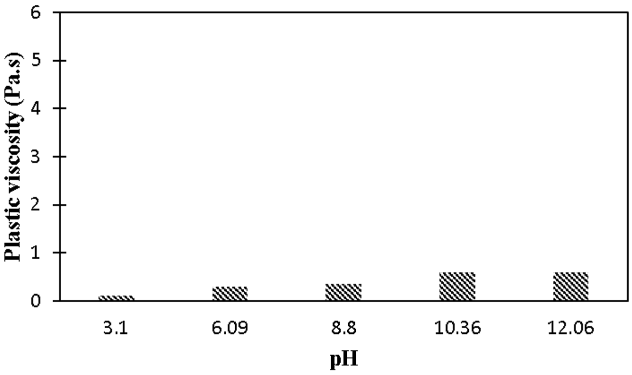
3.2. Rheological Properties

Yield point (YP), which represents the required stress to start the flow of drilling fluids, is a key control parameter. Drilling engineers use this parameter to forecast the drilling fluid capability to transport cuttings to the surface. It is preferable to use a drilling mud with a higher value of YP, which ensures the hole cleaning operations since it has a high carrying capacity of drilled cuttings and solid particles mud [3]. In other term, the YP can be defined as a measure of the strength of the three-dimensional network structure formed by the particles in bentonite suspension [12]. In the current study, measurements of the YP and the PV were carried out over the pH range. The changes of YP and PV induced by changing pH value of F1 were mentioned in figure 2 (a). It is obvious, that the increase in pH from 3.64 to 12.01 resulted in increasing the PV from 0.3404 to 1.9365 Pa.s. The change from the maximum to the minimum was considerable. It can be also noticed that the YP was minimum in the low and high pH zone of between 3 and 7, and 10 and 12, respectively. This YP reached the maximum at pH = 8.44, which was a value lower than the natural pH of the tested drilling fluid. In an earlier study done by Velde [26], the results are opposite to these results, and the difference can be attributed to the type of bentonite. The rheological behavior such as the YP-pH relationship of water-based drilling fluids is generally controlled by sodium-montmorillonite (Na^+-Mt) [4, 28]. The YP-pH behavior displayed by calcium-montmorillonite (Ca^+-Mt) is very distinct to that displayed by Na^+-Mt, in addition, Ca^+-Mt demands high solid content to evolve a YP. The location of YP at alkaline pH region can be attributed to the interaction between Na^+-Mt and sepiolite that are the two most rheologically active clay minerals. In despite, F1 is formed from a bentonite contained high CaO content of 3.95 wt%. Consequently, Soluble Ca^{2+} ions will conduct to set the maximum YP to an alkaline pH, and this effect is attributed to the formation of Ca^{2+} hydrolysis product bridging the particles more strongly [6, 30], and exchanging with Na ions to form a non-swelling Ca-montmorillonite [5, 19].

Figure 2 (b) showed the variation of PV of F2 as function of pH. As it can be seen, the PV of F2 is moderate and increases slightly when increasing pH of the fluid. F2 did not develop a YP due to the low solid content used (3 wt%) as it was a calcium bentonite. The evolution of PV of F2 versus pH takes the same manner as that of F1, but the variation from the minimum to the maximum is not significant. The dissimilarity between the values of PV of F1 and F2 can be attributed to the certainty that Mos-B is a raw substance, whereas, Mag-B is an activated bentonite with sodium carbonate (Na_2CO_3). The activation process makes the layers of Mag-B somehow cemented, which conducts to reduce the polymer adsorption on the bentonite platelets, and reducing the bentonite swelling.



(a)



(b)

Figure 2. *Evolution of YP and PV as function of pH: (a) for F1, (b) for F2.*

Based on the obtained results, the lower values of pH will prevent the swelling of bentonite and the adsorption of polymer on the bentonite platelets, which results in decreasing the viscosity of drilling fluid. Moreover, that will not help to carry more cuttings and drilled solids and that is became clear by the lower values of YP at low pH. On other hand, increasing more the pH of drilling fluid (pH >= 12) will also reduce the carrying capacity of the mud by reducing the YP of the fluid.

Another important parameter of drilling mud is the ratio of YP to PV (YP/PV), it indicates the drilling operation conditions [8]. For High-angle wells, the hole cleaning is well done, if the fluid flow is turbulent, because the mud rheological properties does not affect the cuttings carrying capacity. If the turbulent flow can not be maintained or the borehole diameter is enlarged, A high YP/PV should be kept due to the fact that the cuttings carrying capacity is affected by the mud rheology in laminar flow. Hence, the cuttings carrying capacity increases with the increase of the ratio of YP to PV [8].

The changes of YP/PV ratio with pH of F1 are mentioned in figure 3. The high value of YP/PV, which is equal to 7.61 is located at pH of 8.44. This ratio is decreased to a minimum at pH of 12.01. These results reflect the YP-pH results that are mentioned above.

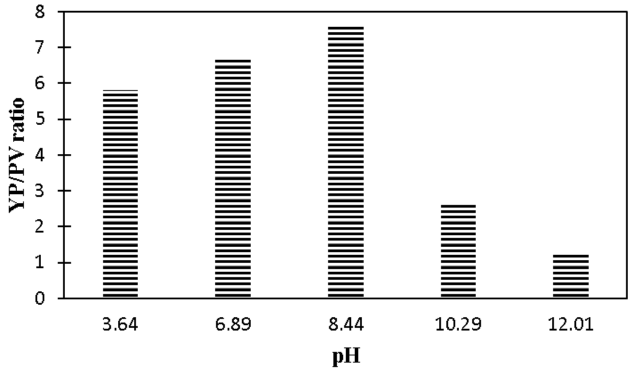


Figure 3. *Evolution of YP/PV ratio as function of pH for F1.*

4. Conclusions

The effect of pH on the rheological properties of water-based drilling fluid based on bentonite/polymer have been experimentally investigated. The main conclusions of the study are summarized as follows:

1) Changing the pH of water-based drilling fluid based on bentonite/polymer affects significantly the rheological behavior of this fluid.
2) Increasing the pH results in increase the shear stress over the same shear rate, and this enhancement is considerable for F1 than F2.
3) YP and PV of F1 increase in the high pH region and decrease in the low pH region.
4) The PV of F2 is not significant compared to that of F1 and increases slightly when increasing pH.
5) The higher value of YP/PV is located at a pH of 8.44, and this ratio decreases when increasing pH.
6) The rheological properties of F1 are more stable and suitable in the range of pH of between 7 and 12.

Based on the obtained results, it can be concluded that the changes in pH values will induce significant modification in the rheological behavior of water-based drilling fluid based on bentonite/polymer. From the study, it can be recommended to use a pH value superior to 7 and inferior to 12, which will enhance the rheological properties of drilling mud. It is also suitable to use sodium bentonite than calcium bentonite, which offers considerable YP, and consequently a high solids carrying capacity.

Given the extensive scope of studying the rheological behavior of bentonite/polymer based drilling fluids under various pH conditions, it is recommended to complement rheological tests with additional measurements such as zeta potential measurements, Fourier Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy (SEM), as well as filtration tests to gain a deeper understanding of the behavior. These supplementary tests will contribute to fill the gaps observed in terms of analyzing the microstructure of ternary water-bentonite-polymer system.

Abbreviations

Ca^{+}-Mt: Calcium-Montmorillonite
CA-OMt: Cationic–Anionic Organomontmorillonites
CMC: Carboxymethyl Cellulose
EE: Edge to Edge
FE: Face to Edge
FF: Face-to-Face
F1: Fluid 1
F2: Fluid 2
HEC: Hydroxyethyl Cellulose
Mag-B: Maghnia Bentonite
Mos-B: Mostaganem Bentonite
Na^{+}-Mt: Sodium-Montmorillonite
PEG: Polyethylene Glycol
PV: Plastic Viscosity
ROP: Rate of Penetration
YP: Yield Point

Author Contributions

Hocine Ouaer is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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