Influence of temperature and pH on polyacrylamide-based drilling fluid: Characterization and rheological study

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KEYWORDS

ABSTRACT

Polyacrylamide (PAM) is a biodegradable polymer with good lubricity in friction reduction. However, there is insufficient guidance on the dosage of PAM and poor rheological information on the effects of temperature and pH. This study aimed to investigate the characterization of the material and rheological analysis regarding the effects of concentration, pH, and temperature of PAM. In material characterization, PAM has been shown to offer hydrophilic surfaces. In a rheological study, 1000 ppm PAM was the critical association concentration, as the rheological properties below 1000 ppm PAM were superior. This was due to the dispersion stability effect caused by the polymer concentration. Additionally, a low concentration of polymer contributes to bridging flocculation with an unstable rheological profile and low association networking. When the polymer concentration is further increased to the saturated adsorption level, the rheological profile of PAM above 1000 ppm is significantly affected as a result of the alternation from steric stabilization to depletion flocculation in a polymer system. Furthermore, the rheological performance of PAM was significantly affected by temperature and pH, showing better performance after heating to 60 °C and at pH = 10. Future studies can further develop modified PAM with specific additives at an optimized temperature and pH to investigate the rheological performance of drilling.

1. Introduction

Polymers have dominated industry in the last century, consecutively becoming an alternative to former materials, such as steel, non-ferrous metals, wood, glass and paper [1]. Today, the technology related to polymers has matured with fundamental evolution in most applications, such as transporttation, medicine, communication, and many other fields [2]. Electrical appliances cables, plastic utensils in the kitchen, car body constructions in transportation, and countless other applications rely nowadays on polymers. Meanwhile, the concept of 'green chemistry' is being explored in the foundation field to minimize the environmental footprint and cost-effectiveness.

Commercially, polyacrylamide (PAM) is a common additive in geotechnical drilling because it is cheap and biodegradable [3] compared to traditional additives such as bentonite, which has limitations in degradation, flocculation, and stability. Furthermore, PAM has high strength and a uniform composition [4], which can improve permeability and rheological stability in drilling operations.

As shown in Table 1, the usage of the bentonite product is higher than that of PAM; therefore, the cost of PAM is lower than that of bentonite. Meanwhile, a high facility cost is required in bentonite-based drilling compared to PAM-based drilling due to the high shear mixer involved in bentonite-based drilling. In addition, the mixing rate of bentonite is slower than that of PAM. Hence, bentonite-based drilling plants require buffer and minimal storage preparation with higher footprint sites, associated with 25 to 50 times higher concentrations than PAM [5]. Technically, the water-based drilling fluid always has high torque and drag in the operating mechanism, which can cause poor rheological problems, such as pipe sticking, poor borehole cleaning, and others. Using bentonite, the rheological performance of water-based drilling worsens under conditions such as the formation of a thicker filter cake, a low penetration rate, and low well bore cleaning [6]. Hence, PAM is encouraged to advocate in the geotechnical field, as it is a water-based lubricant, which is conducive to drilling operations in reducing friction and drag.

However, the use of polymers in water-based drilling is fraught with concerns, such as the lack of official guidelines, incompatibility with salt water, and other factors [7]. Likewise, there is a general guideline on the polymer concentration (0.5 to 2 kg/m³) that is used in excavation, but the optimal dosage of PAM is poorly specified for drilling. Therefore, this study aimed to optimise the concentration of PAM in drilling operations.

Table 1. Comparison between bentonite and PAM [5].

Drilling additive	Bentonite	PAM
Product usage	25 – 50 kg/m³	0.5 – 2.0 kg/m³
Production cost	Expensive (RM 15 – 25/m³)	Cheap (RM 9 – 15/m³)
Facilities requirement	High shear mixer, hydration tanks, slurry recirculation	Simple venturi eductor, hydration tank, slurry recirculation
Facilities cost	High (involved high shear with high power)	Low (direct mixing without a shear mixer)
Mixing rate	Slow (a few hours)	Fast (a few minutes to a half hour)
Site of footprint	High	Low (25 – 50 times lower concentration than bentonite)

Table 2. Comparison of drilling research in terms of PAM concentration, temperature, and pH.

PAM concentration	Temperature, °C	pH	Aims and findings	Reference
500 – 2000 ppm	Ambient to 100	Ambient to 10	To optimize the concentration of PAM. To study the effect of pH and temperature on optimized PAM. 1000 ppm was the critical association concentration. PAM achieved a better rheological performance at 60 °C and pH = 9 – 10.	Current study
0.6 w/v %	40 – 80	7 – 9	To test the use of functionalized silica as a calcium carbonate inhibitor in modified PAM. The low dosage of the inhibitor can improve the inhibition efficiency with different temperatures and pH.	Ismail *et al.* [20]
0.05 – 0.2 w/v	25 – 65	-	To design the grafting of PAM onto xanthan for polymer flooding. The viscosity of the grafted xanthan-PAM was higher than that of the pure xanthan, which demonstrated better thermal resistance in the graft copolymer.	Chami *et al.* [21]
5 – 7.5 wt %	75	4 – 6	To study the impact of aluminum acetate on polyacrylamide-based gel with bentonite as a crosslinker. The size of nanoparticles sped up the gelation process of the polymer composite gel at 75 °C and pH = 5.	Hamza *et al.* [22]
5 – 12.5 wt %	21 – 96	-	To design loss circulation materials by using PAM with a crosslinker. The viscosity of the PAM decreased when the temperature was increased. 7.5 wt % PAM corresponded to the best result for the reference bentonite in terms of plastic viscosity and apparent viscosity. However, the yield point for all concentrations of PAM was lower than that of the reference bentonite. The high molecular weight of PAM resulted in a viscosity that was relatively higher than that of the reference bentonite. The viscosity of the PAM decreased with increasing temperature.	Magzoub *et al.* [12]
1 – 1.2 wt %	100 to 150	-	To enhance modified PAM in high-temperature drilling. The gelation time of the improved polymer was not affected by the temperature at 140 °C. The PAM was hydrolyzed at a temperature above 90 °C.	Xie *et al.* [10]
0.01 – 0.08 wt %	120	7	To investigate the effect of thermal heating and nanoparticles on the rheological performance of modified PAM. The results revealed that the heating made the nanoparticles effective in terms of flow resistance with a decrease in apparent viscosity. However, the pH of the drilling fluid was not affected by the addition of nanoparticles.	Gudarzifar *et al.* [19]
-	-	7 – 8	To study the effect of nanoparticles in a bentonite-based drilling fluid. The addition of nanoparticles caused in a decline in the pH of the drilling fluid.	Kusrini *et al.* [17]
0.5 wt %	25 – 70	-	To study the effect of modified silica/PAM at high temperatures. The results demonstrated that the viscosity of modified silica/PAM decreased with increasing temperature.	Yegane *et al.* [13]
0.3 w/v %	180 – 220	-	To compare the various rheology modifiers in a bentonite-based drilling fluid. The results demonstrated that the amphoteric polymer had a better rheological performance at 180 – 220 °C than bare PAM.	Hamad *et al.* [23]
-	80	8 – 10	To study the effect of nanoparticles on the rheological properties of polyamine-based drilling fluid. The addition of nanoparticles did not affect the pH of the drilling fluid.	Medhi *et al.* [18]
1.5 – 2 %	30 – 120	-	To study the effect of graphene oxide composite on the rheological and thermal performance of modified PAM. The apparent viscosity of modified PAM decreased with increasing temperature.	Lyu *et al.* [14]
-	-	7 – 12	To study the effect of pH on the rheological properties of water-based drilling fluid (bentonite). The results demonstrated better rheology and filtration properties at pH = 9 – 10.	Gamal *et al.* [16]
0.2 – 0.5 wt %	20 – 50	-	To study the rheological properties of polyacrylamide. The viscosity decreased with increasing temperature.	Yang [15]

Biodegradable lubricants undergo degradation processes such as physical and chemical degradation. Physical degradation in a lubricant can be caused by shear stress, heating, and other factors, while evaporation of the lubricant and impurities that exist due to debris and pollution can cause chemical degradation in the lubricant [8]. Hence, temperature and pH in drilling are often the rheological problems related to the degradation of PAM as a lubricant. Furthermore, the elasticity of the polymer is affected by temperature, demonstrating a lower Young's modulus of the polymer at higher temperatures [9].

Generally, PAM can withstand temperatures below 80 °C because a higher temperature can deteriorate drilling performance when excessive hydrolysis occurs [10,11]. In several studies, the viscosity of PAM or modified PAM decreased with increasing temperature [12-15]. Most studies addressed the effectiveness of modified PAM in terms of viscosity and thermal stability, as summarized in Table 2 [10,12-23]. Unfortunately, there is insufficient information on the effect of temperature on the rheological performance of bare PAM. Therefore, a rheological study was performed to thoroughly investigate the effect of temperature from ambient temperature to 100 °C in this study.

A study found that the rheological behavior of the drilling fluid can be significantly improved from pH 9 to 10 [16]. Furthermore, Kusrini *et al.* [17] explored that the pH was able to be reduced from 8.36 to 7.78 in a graphene oxide-based drilling fluid. On the contrary, Medhi *et al.* [18] and Gudarzifar *et al.* [19] investigated the rheological performance of nano-composite-based drilling fluid, where the pH was insignificantly affected. Veritably, previous studies on the effect of pH on bare PAM had received less attention, where the focus was more on the effect of additives in drilling, as shown in the comparison in Table 2. Therefore, this study has extensively investigated the effect of pH on bare PAM.

Ultimately, the main objective of this research was to investigate the rheological properties of PAM in drilling applications. Furthermore, the research was aimed at contributing to a deeper understanding of the effects of optimized pH and temperature on the optimized concentration of PAM. Due to practical constraints, this study is insufficient to provide a comprehensive overview of the effects of pH and temperature

at each concentration of PAM. The findings of this study will enrich knowledge of drilling applications and serve as a basis for future research, as well as advocate for the concept of "green chemistry" in drilling technology.

2. Experimental

2.1. Materials preparation

The PAM-based drilling fluid studied here was composed of polyacrylamide (PAM) particles and water. It was synthesized using a white granule form of PAM powder in Figure 1 (25 % hydrolysis degree, 0.76 g/cm³ bulk density) and distilled water by direct mixing in the polymerization process. A relative speed was applied in the mixing process, stirring at room temperature using a Joanlab overhead stirrer. The concentration of PAM was in the range of 500-2000 ppm.

Figure 1. White granule form of PAM powder.

2.2. Materials characterization

2.2.1. Fourier transform infrared spectroscopy (FTIR)

A chemical functional group of substances can be analyzed to understand the chemical properties of bonding and elemental analysis in a molecule. In this investigation, the chemical structure of the PAM fluid was analyzed using FTIR (Spectrum 400, Perkin Elmer). A drop of PAM fluid was added between KBr plates as a liquid sample for FTIR analysis. The spectra were scanned eight times at a resolution of 4 cm^{-1} within a range of 4000-500 cm^{-1}.

2.2.2. Surface tension measurement

The surface tension test can be used to understand the attractive force of molecules exerted on the surface of a liquid toward each other. This study was carried out with the measurement of the surface tension of the PAM fluid at room temperature using a Du Noüy ring technique using a force tensiometer (Sigma 700, Biolin Scientific). A platinum-iridium ring was applied to test the force exerted to be lifted from the fluid surface after immersion in that ring of PAM fluid.

2.2.3. Contact angle measurement

The contact angle test is adopted to identify the wettability of the substrate surface using a static sessile drop method. In this study, the contact angle between PAM fluid droplets on a glass substrate was measured at room temperature using OneAttension software using an optical tensiometer (Attension® Theta Lite, Biolin Scientific). First, a glass was prepared as a substrate, followed by dispensing certain amount of PAM fluid into a syringe. Lastly, a PAM fluid droplet was dropped from that syringe onto the glass slide surface, and the image was captured.

2.3. Rheological testing

Rheological tests are performed to understand the nature of fluid flow. This research is carried out with the rheological studies of the PAM fluid using a 6-speed rotational viscometer (model number: HTD-6ST, Qingdao Heng Taida). This viscometer consists of a bob (radius: 1.7245 cm; length: 3.8 cm) and a vessel (holding 350 mL volume of fluid). The viscosity measurement with various shear rates (3, 300, and 600 rpm) was a preliminary study to determine the fluid behavior of the PAM-based drilling fluid. Fluid viscosity was obtained directly from the dial reading of the 6-speed rotational viscometer. The rheological behavior of the drilling fluid was further investigated by a 6-speed rotational viscometer, using the equation according to the Bingham Plastic model:

$$\text{Apparent Viscosity, AV} = 0.5 \times \Phi600 \qquad (1)$$

$$\text{Plastic Viscosity, PV} = \Phi600 - \Phi300 \qquad (2)$$

$$\text{Yield Point, YP} = \frac{(2 \times \Phi300 - \Phi600)}{2} \qquad (3)$$

$$\text{Gel strength} = 0.511 \times \Phi3 \qquad (4)$$

where $\Phi600$ is the dial reading at 600 rpm, $\Phi300$ is the dial reading at 300 rpm and $\Phi3$ is the dial reading at 3 rpm in mPa.s. This rheological study was repeated at least 3 times for consistent reproducibility.

2.3.1. PAM concentration

The rheological tests began started with the optimization of the PAM concentration. The rheological study to determine the effect of the PAM concentration was conducted under ambient conditions. The ambient temperature and the pH are 25-30 ℃ and 5.5-6.0, respectively.

2.3.2. Temperature and pH

The optimized PAM concentration was further applied to the following rheological studies to manipulate the effect of temperature and pH. The effect of temperature in the rheological tests of the PAM-based drilling was carried out at ambient pH, but with the manipulation of the temperature from ambient temperature to 100 °C. The ambient pH is approxi-mately 5.5-6.0. However, the rheological study of the effect of pH on PAM-based drilling was conducted at ambient tempera-tures with the manipulation of pH from ambient pH to 11. The ambient temperature is approximately 25 and 30 ℃.

3. Results and discussion

3.1. Characterization analysis

Based on the FTIR spectrum of the PAM fluid as depicted in Figure 2, the carbonyl group stretching vibration and the amide group stretching vibration were found at the peaks of 1650 and 3424 cm^{-1}, respectively. 2905 and 2974 cm^{-1} were the peaks that corresponded to the C-H bond stretching vibration. The peak at 1378 cm^{-1} was for the C-N stretching, whereas the peak at 1449 cm^{-1} was for the ring structure vibration of the methyl C-H bend [24,25].

In FTIR peak analysis, the carbonyl group (1650 cm^{-1}) showed weaker adsorption than the HC bond (2905 and 2974 cm^{-1}) and C-N stretching (1378 cm^{-1}), indicating the weaker bonding of the carbonyl group within the PAM fluid. Weaker bonding in the carbonyl group exists in the PAM fluid as a result of the hydrolysis of PAM. The carbonyl group of polyacrylamide can be attacked by positively protonated water during the hydrolysis of PAM [26], forming the hydrogen bond between the water molecule and the PAM molecule during the hydrolysis of PAM. Therefore, C-H bonding and C-N stretching in PAM fluid were developed with a strong intensity in FTIR analysis in this study.
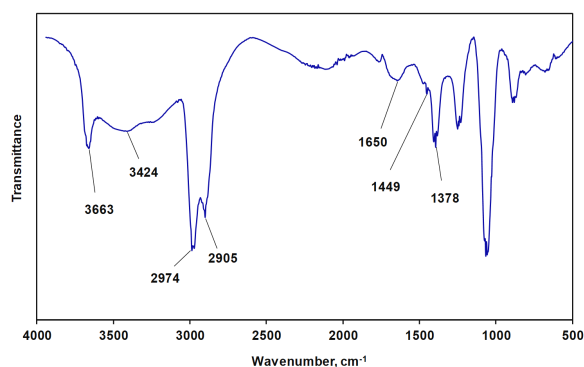
Figure 2. FTIR spectrum of the PAM fluid.

An OH-stretching group was usually present in the spectra range between 3000 to 3700 cm^{-1}, which can be used to analyze the water molecule involved in the hydrolysis of PAM for PAM fluid synthesis. For example, OH-stretching from water molecules was attributed to a peak of 3663 cm^{-1} because this peak is more intense than a peak at 3424 cm^{-1}. However, the stretching of the amide group was assimilated to the broad peak at 3424 cm^{-1}. Hence, amides demonstrate hydrogen bonding, causing a broadened N-H stretching peak in FTIR analysis. In conclusion, the structure of the PAM fluid conformed to FTIR analysis.

The surface tension of the PAM fluid was 43.834 mN/m. Meanwhile, the PAM fluid demonstrated a contact angle mean of 42.19°, which represents a hydrophilic fluid.

3.2. Rheological analysis

3.2.1. Effect of PAM concentration

In fluid mechanics, the viscosity of the fluid can theoretically be identified either in terms of kinematic viscosity or dynamic viscosity. Kinematic viscosity is a standard property of a Newtonian fluid, which can demonstrate constant viscosity with different shear rates. However, the viscosity of a non-Newtonian fluid is usually dependent on shear rate and is known as dynamic viscosity. The viscosity in the preliminary study was defined in terms of dynamic viscosity because the viscosity of the PAM fluid was affected by the shear rate (3, 300, and 600 rpm), as shown in Figure 3a. The dynamic viscosity of the PAM fluid increased when the shear rate was increased at each concentration of PAM. Therefore, the PAM fluid was considered a non-Newtonian fluid in this study.

Since the PAM fluid behaved as a non-Newtonian fluid during dynamic viscosity measurement, the rheological properties of the PAM fluid were simulated by a 6-speed rotational viscometer using the Bingham Plastic model, which was calculated mathematically from viscometer readings (dynamic viscosity at 300 and 600 rpm). According to Equation (1), the viscosity is obtained at a fixed shear rate, known as AV. As depicted in Figure 3b, the AV of the PAM fluid increased when the concentration of PAM increased, which can be related to the dynamic viscosity at 600 rpm with an increased shear rate in Figure 3a. As a result, PAM-based drilling fluid has a shear thickening behavior, as its AV increased with increasing shear rate [27,28].

Similarly, the PV of PAM also increased when the concentration of PAM was increased in the drilling fluid. Theoretically, PV is the rheological parameter that depends on the concentration, shape, and size of the solid in the drilling fluid to monitor the internal resistance of the fluid flow. In this study, the concentration of PAM can affect the PV of PAM. After the high concentration of PAM was applied, there were excessive colloidal polymer particles in the drilling fluid, causing high PV, which may increase the mechanical friction between the polymer particles and slow down the penetration of drill bits in drilling operations [29,30].

Meanwhile, the YP of PAM increased as the concentration of PAM increased. This phenomenon is caused by electrochemical changes in the fluid. An increase in YP can cause the attraction of particles by higher electrochemical charges within the polymer in the drilling fluid [27]. The higher electrochemical charges within the polymer in this study were attributed to the long-chain effect of the polymer. In relation to the PV of PAM, the drilled colloidal polymers increased, causing the attractive forces between the particles to increase with the electrochemical changes with a higher concentration of PAM. Therefore, a higher YP was achieved along with an increase in the concentration of PAM.

In particular, gel strength at 10 seconds and 10 minutes also increased when the concentration of PAM was increased in this study. The gel strength is also related to the attractive force between the particles under static conditions. However, the gel strength showed a large gap between 10 seconds and 10 minutes when more than 1000 ppm of PAM was applied in this study, indicating that the gel strength behaved as a progressive gel strength. Furthermore, the 1000 ppm PAM gel strength demonstrated a marginal difference between 10 seconds and 10 minutes below, which can promote better drilling operations, as its behavior is flat gel strength., Progressive gel strength is typically undesired as it requires a high pump recirculation power, causing drilling problems such as pipe sticking and poor wellbore cleaning [31,32]. Therefore, a flat gel strength was achieved below 1000 ppm PAM.

During various concentrations of PAM, the rheological behavior of PAM, including dynamic viscosity, AV, PV, YP and gel strength, showed a similar trend, as depicted in Figure 3a-c. Below 1000 ppm, each rheological parameter fluctuated. Subsequently, all rheological parameters increased sharply above 1000 ppm. It can be observed that the rheological behavior of the drilling fluid was affected by the dispersion stability of the polymer. When the polymer concentration increased, there was an alternation between stabilization and flocculation during polymer dispersion. The steric stabilization of polymer particles occurs when there is a sufficient polymer chain covering the surface of the polymer particles. The depletion flocculation occurs at moderate to high polymer concentrations because of the existence of a nonadsorbing polymer. A high polymer concentration can lead to depletion stabilization, which provides colloidal stability [33]. The rheological performance of the drilling fluid in this study was high at 2000 ppm PAM due to the effect of dispersion stability in the polymer.
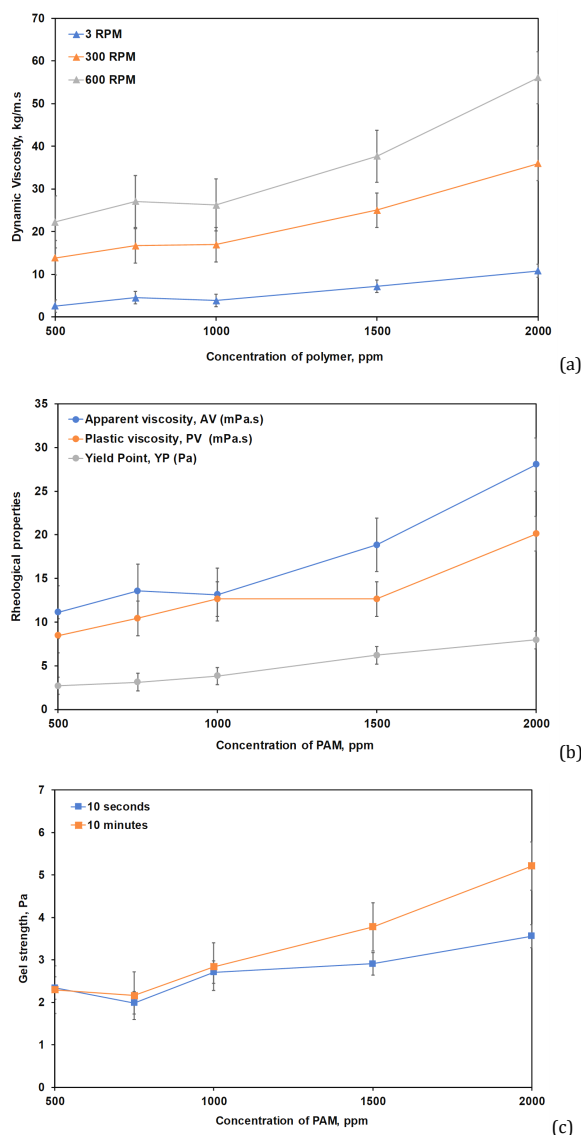
Figure 3. Effects of PAM concentration on (a) dynamic viscosity, (b) rheological properties, and (c) gel strength.

Lower polymer coverage and unstable association networking contributed to the weak rheological profile in this study, which can be observed from 500 to 1000 ppm PAM. However, the rheological profile has a drastic incline after 1000 ppm of PAM is applied. This is due to the PAM concentration not exceeding the saturation adsorption, which is related to the transition from steric stabilization to depletion stabilization in a polymeric system. Research has shown that the appearance of agglomeration could cause the incline of the viscosity of the polymer, which is induced by the bridging of the polymer in a system [34,35]. Furthermore, the hydrophobic group from non-adsorbing polymer increases when the PAM concentration increases, which can cause changes from the intramolecular to the intermolecular association. Hence, there is a development of supramolecular agglomeration. Therefore, the viscosity of the drilling fluid increased drastically above 1000 ppm, which is defined as the concentration of critical associations [34,35]. Therefore, 1000 ppm of PAM was the critical association concentration of the polymer used in this study.

3.2.2. Effect of temperature and pH

Based on Figure 4a, the AV and PV of PAM decreased once the temperature increased from ambient to 60 °C, while the YP of PAM increased. Subsequently, there were inverted trends for AV, PV, and YP after further heating to 80 °C. Meanwhile, PAM had the lowest AV and PV as well as the highest YP after heating at 60 °C. The rheological performance of the drilling fluid is influenced by the flocculation and adsorption capacity during endothermic heating. As the gel-like floc was formed with a larger molecule size at high temperatures, this study showed that PV increased with the incline of heating temperature from 60 to 80 °C [3,36]. Theoretically, the viscosity of the polymer decreases with increasing temperatures, but it does not always conform and can certainly be considered with other factors, such as the nature of the polymer, the degree of hydrolyzation, the molecular weight, and the salt concentration [37]. In this study, the heating process may have enhanced the rate of the hydrolysis reaction. During heating, the PAM fluid would undergo hydrolysis with the shearing process in rheological tests, causing cross-linking strength enhancement within polymer molecules.
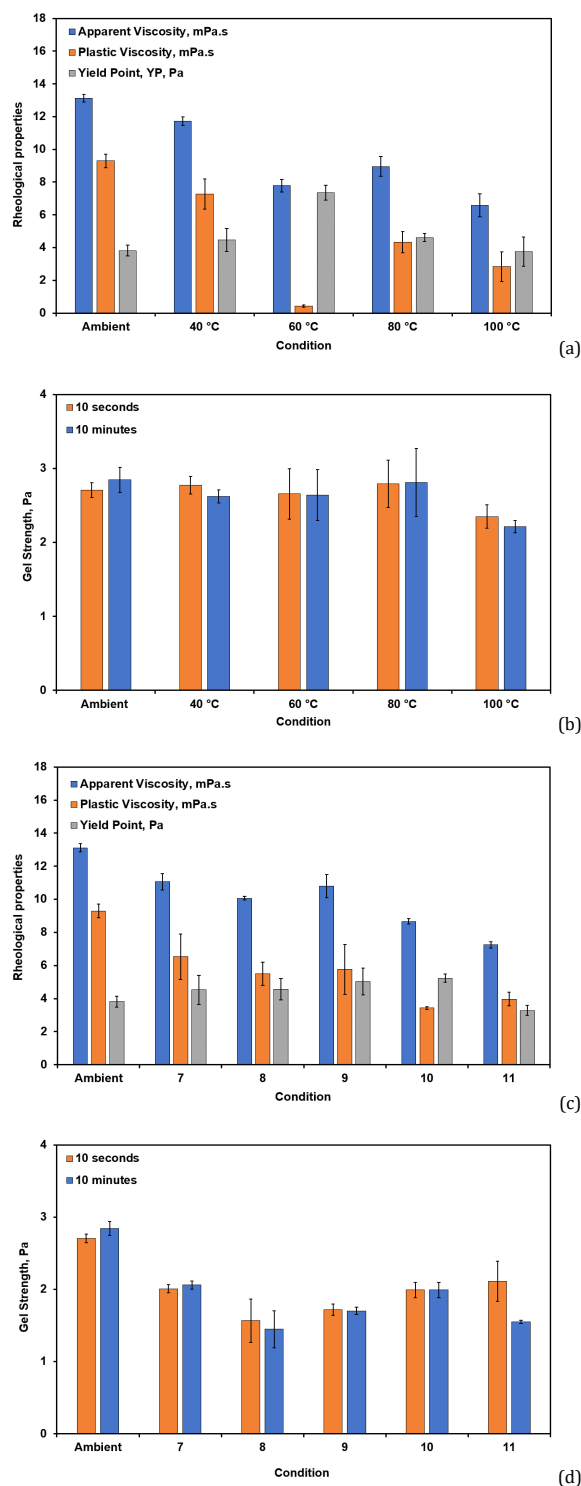
Figure 4. Effect of temperature on (a) rheological properties and (b) gel strength of 1000 ppm PAM. Effect of pH on (c) rheological properties and (d) gel strength of 1000 ppm PAM. Notes: The ambient temperature and pH are 25 -30 °C and 5.5 – 6.0, respectively.

The formation of large flocs by crosslinking can increase the viscosity of the fluid under high-temperature shear [38]. Therefore, the formation of colloidal floc and the viscous condition after heating at 80 °C caused an increase in AV and PV with a decrease in YP in rheological tests.

After further heating at 100 °C, AV and PV declined, while YP inclined due to the excessive hydrolysis. Generally, the order of hydrolysis depends on the mass load, temperature, and chemical involved in the process. In this study, the higher order

of hydrolysis was caused by the higher temperature at 100 °C, which led to a poor rheological profile. As shown in Figure 4b, the gel strength was not significantly affected by the temperature from ambient temperature to 80 °C, demonstrating better thermal stability with consistent gel strength as temperature increased. However, the gel strength declined after heating at 100 °C. The fracture of the polymer structure by heating was triggered by heating with a higher hydrolysis degree, which led to the poorest gel strength in this study. In summary, the PAM
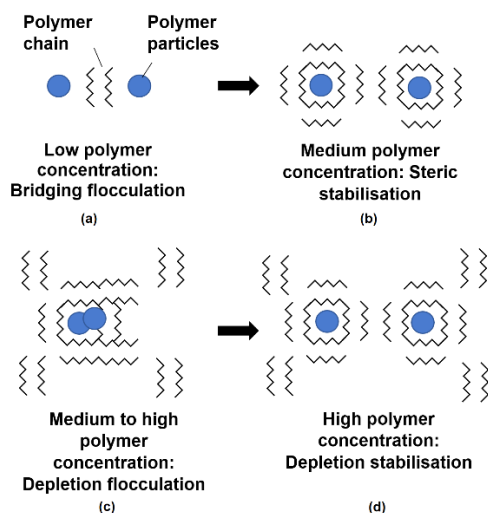
Figure 5. Polymer dispersion stability (a) Bridging flocculation, (b) Steric stabilization, (c) Depletion flocculation, and (d) Depletion stabilization [33].

fluid at high temperatures encountered a higher degree of hydrolysis [39], resulting in changes in the rheological properties in this study.

Figure 4c shows the effect of pH on the rheological studies of PAM. The ambient conditions of the PAM were prepared using distilled water with a pH in the range of 5.5 to 6.0. The drilling design was favorable at pH = 10, since the rheological performance of the drilling achieved the lowest PV and the highest YP. In general, salinity can affect the chemical properties of a polymer. Furthermore, hydroxide and carbonate ions from soda ash can affect rheological performance under basic conditions. In addition, these ions can increase the pH of the drilling fluid, preventing corrosion in drilling operations. Meanwhile, the polymer has become anionic after adding soda ash to the drilling fluid, which can enhance the viscosity and size of the polymer in the presence of salt with limited water availability. Therefore, the gel strength of the PAM fluid was not significantly affected due to the lack of hydrogen bonding formed between the water molecules and the polymer [40]. In general, there was a decreasing trend in AV and PV, with an increasing trend in YP. The desired flat gel strength of PAM was obtained at pH = 9-10 because there was an insignificant difference in gel strength between 10 seconds and 10 minutes, as shown in Figure 4d.

3.3. Mechanism on dispersion stability of polymer

A polymer system is largely dependent on the dispersion stability of the polymer. Meanwhile, the dispersion stability of the polymer is interrelated with the concentration of the polymer. With the help of Figure 5, the dispersion stability can be elucidated with the effect of the polymer concentration. Bridging flocculation probably exists at an extremely low polymer concentration. In addition, there is a low amount of polymer exerted fully on the surface of the polymer particles, causing the polymer chains to bridge between two polymer particles, as illustrated in Figure 5a. After further increasing the polymer concentration, the polymer in Figure 5b shows a sufficient amount of polymer chain covering the surface of the polymer particle, known as steric stabilization. At this stage, polymer particles can be considered to be stabilized at medium polymer concentrations [33].

While the polymer is applied from moderate to high concentrations, the non-adsorbing polymers are presented in the continuous phase of the polymer system, causing depletion flocculation. This phenomenon causes an increase in the attractive force between polymer particles in a polymer system, as shown in Figure 5c. This may be attributed to the exclusion of polymer particles from a narrow region with their osmotic effect in a polymer system. Eventually, a repulsive interaction between polymer particles is mitigated by the attractive force in a depletion flocculation phenomenon, which leads them to be flocced [33].

Depletion stabilization occurs when there is a higher polymer concentration. This stage has concerns about polymer agglomeration. Therefore, the polymer chain must be sufficient to cope with the surface of the polymer particles in stabilization of depletion, as shown in Figure 5d. Furthermore, the quantity of polymer chain is controlled by the sufficient repulsive force between polymer particles in depletion stabilization to prevent flocculation of the depletion [33].

In this study, the concentration of PAM was significantly affected by the stability of the dispersion, as this rheological profile can be illustrated from bridging flocculation to steric stabilization to depletion flocculation. It is attributed to the rheological profile of PAM. As shown from 500 – 1000 ppm PAM with low polymer coverage, this caused an unstable rheological profile due to low polymer particle interaction and association in a polymer system. When PAM increased from 1000 to 2000 ppm, it showed a dramatic incline in the rheological profile, probably alternating from steric stabilization to depletion flocculation in a polymer system.

While the interaction of polymer particles depends on the stability of dispersion associated with the concentration of the polymer, the condition of the fluid may also influence the interaction of polymer particles in a polymer system [33]. For example, the fluid temperature affects the interaction of polymer particles when there is a maximum threshold level of pH and the temperature of the polymer. In this study, large flocs formed in 1000 ppm of PAM fluid after heating at 80 °C because heating can improve the degree of flocculation [20,21]. Therefore, the rheological profile of PAM is significantly affected by temperature.

4. Conclusions

The analysis of the results can be concluded as follows: (i) The dispersion stability can influence the rheological properties of PAM. In this study, 1000 ppm was the critical association concentration of PAM, (ii) The rheological performance of PAM was significantly affected by temperature and pH.

High thermal heating can increase the rate of polymer degradation. A more basic pH condition could improve the rheological performance of polymer-based drilling. In short, the

flocculation phenomenon is reasonably associated with the concentration of PAM and fluid conditions, such as temperature.

Future research can extend the investigation of the issue of resolving the degree of flocculation in a PAM-based drilling fluid, as well as the degradation issue in a polymer. It is suggested that PAM is modified with a surfactant to mitigate flocculation by steric repulsion in a polymer system. In addition, the modification of PAM can be incorporated with nano-materials, enhancing the lubrication and rheological behavior in the water-based drilling fluid. Additionally, insight on modified PAM can extend the explanation of the rheological properties with respect to the pH and temperature effect. In the future, it may also be necessary to delineate the rheological behaviors between bare PAM and modified PAM.

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