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Research Paper

COMPARATIVE ANALYSIS OF CARBOXYMETHYL CELLULOSE AND PARTIALLY HYDROLYZED POLYACRYLAMIDE – LOW-SOLID NONDISPERSED DRILLING MUD WITH RESPECT TO PROPERTY ENHANCEMENT AND SHALE INHIBITION

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Abstract

During drilling, different problems are encountered that can interfere with smooth drilling processes, including the accumulation of cuttings, reduced penetration rates, pipe sticking, loss of wellbore stability, and loss of circulation. These problems are generally encountered with conventional drilling mud, such as the bentonite–barite mud system. Formation damage is the most common problem encountered in bentonite mud systems with high solid content. In this work, we aimed to formulate two low-solid nondispersed (LSND) muds: carboxymethyl cellulose (CMC)–LSND mud and partially hydrolyzed polyacrylamide (PHPA)–LSND mud. A comparative analysis was performed to evaluate their property enhancements. LSND muds aid in maintaining hole stability and proper cutting removal. The results of this work show that the addition of both CMC and PHPA helps to improve drilling fluid properties; however, the PHPA–LSND mud was found to be superior. Shale swelling is a major concern in the petroleum industry, as it causes various other problems, such as pipe sticking, low penetration rates, and bit wear. The effect of these two LSND polymer muds in inhibiting shale swelling was analyzed using shale collected from the Champhai district of Mizoram, India.

Keywords: CMC, PHPA, Rheological Properties, Filtration Properties, Shale Inhibition.

1. Introduction

When drilling a well in any geological formation, different types of drilling fluids containing various chemicals, polymers, etc. as additives must be applied because one may encounter different geological formations of different ages with varying mineralogical compositions and rock types. To put it simply, during a drilling operation, one must drill the well in a heterogeneous formation because no fields are homogenous in nature [1]. As one must drill in heterogeneous formations, the properties of the utilized drilling fluids or muds must vary; such variations are achieved by adding different additives [2]. A drilling fluid is a suspension of clay particles containing additives in a continuous water or oil phase [3] and is generally applied for different functions, such as cooling and lubricating the drill string and bit, stabilizing the wellbore, maintaining the formation pressure, and carrying drill cuttings from the subsurface to the surface [4]. In the preparation of drilling fluid, bentonite is generally used as the primary clay particle, which acts as a viscosifier, with barite utilized as a weighing material; in addition, other chemicals and additives are applied to enhance the mud properties [5].

When a drilling fluid circulates through a well, it encounters the sidewall of the well, which is highly porous and permeable. The drilling fluid tends to move along the encountered porous formations rather than traveling along the well toward the surface

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because the fluid tends to move along the easiest possible path. The fluid portion of the drilling fluid flows inside the porous formation, leaving behind large solid particles. The solid particles form a layer at the well wall, known as a mud cake, which prevents further movement of fluid into the formation. The fluid portion that moves to the formation is known as the filtrate loss. In some cases, a small amount of solid particles from the drilling fluid may also enter the formation, along with the fluid that is lost in the formation. This phenomenon may cause the pore spaces of the formation to be blocked. The clay particles swell when they come into contact with water. The bentonite and barite that are mixed with the drilling fluid may also enter into the formation and fracture after swell, causing damage to the formation. For this reason, it is very important for mud engineers to minimize the amount of solid particles in the drilling fluid and to maintain constant mud properties [6]. This research paper deals with the formulation of a nondamaging drilling fluid with a low-solid content, i.e., a fluid without the addition of weighing materials (barite); moreover, standard mud properties are maintained in this fluid by the addition of different polymers. In this study, we sought to formulate a mud with the characteristics of both nondamaging mud and low-solid nondispersed (LSND) mud.

Drilling fluids that contain lower levels of solids than conventional clay-based muds at the same density and that can be used for similar purposes are known as LSND muds; these muds sometimes contain less than 5 % low-gravity solids. These low-solid muds are composed of one or more polymers and varying quantities of bentonite; for this reason, these muds are also known as nondispersed polymer muds. The viscosity of the drilling fluid arises either entirely from the polymers or from nontreated bentonite in combination with the appropriate extender polymers. Together, these muds can provide a rheology comparable to that of fluids with higher concentrations of ordinary bentonite. LSND mud is more preferable for hard formations and low penetration rates; meanwhile, these muds are not preferable for areas with long intervals of reactive shales. The main objective in producing an LSND mud is to maintain the total clay solid content at only 4 % or less, which is achieved when polymers combine with the drilled solids and generate flocs [6].

Numerous polymer types have been used in drilling fluid engineering to improve drilling fluid properties and to avoid issues during drilling operations [7]. Carboxymethyl cellulose (CMC) is one such polymer type; this polymer is adsorbed in clay. CMC is an anionic water-soluble, odorless, colorless, and nontoxic commercial product that has been used as a viscosifying and filtrate-loss-reducing agent in drilling fluid for more than half a century. CMC is one of the most widely used cellulosic components in the drilling sector [8]. Specifically, CMC is a water-soluble, high-viscosity sodium carboxymethyl cellulose produced from the carboxymethylation of water-insoluble cellulose. This polymer is used in high-viscous sweeps for drilling surface holes and helps to prevent clay swelling [9]. CMC coats cuttings and protects them from hydration. In addition, CMC enhances drilling fluid properties [10]. CMC is resistant to bacterial attack and can maintain flow properties under high-temperature, i.e., up to 135 °C (275 °F), and high-pressure conditions in the presence of bentonite clay [9].

Partially hydrolyzed polyacrylamides (PHPAs) have a long history in the oil and gas industry [11] and are primarily used as a bentonite additive to reduce fluid loss in permeable formations and to inhibit the swelling of water-sensitive shales [12]. PHPA is a high-molecular-weight polymer that coats the wellbore with a viscous layer by encapsulating the drilled cuttings; in this manner, PHPA provides a barrier to prevent water from coming into contact with clays and shales, which ultimately minimizes dispersion, hydration, and swelling. This coating also helps to improve the solid control efficiency by aiding the intact drill cuttings in traveling up the annulus and by controlling solid build-up in the drilling fluid [13]. Particularly in deep water drilling, fluids containing PHPA are used for offshore drilling worldwide [14]. Moreover, PHPA fluids have been increasingly utilized in civil engineering as a complete replacement for bentonite slurries. According to some authors, the commercial PHPAs used in civil engineering typically have a molecular weight ranging from 14 to 17 million g/mol and a surface charge density (degree of hydrolysis) of 30–45 % [13].

This article reports on the formulation of two LSND muds, which differ from regular muds with a higher solid content. Although the general polymers CMC and PHPA were applied in these experiments, their characteristic relationships were observed, established, and compared as the main focus of this article. In particular, we studied the effect of these polymers in inhibiting shale swelling, as shale sloughing in wells causes multiple difficulties, including pipe sticking and bit wear.

2. Experimental Analysis

2.1. Materials and equipment

In these experiments, distilled water, 2 wt % bentonite, CMC, and PHPA were utilized. The experiments were conducted using a mud weight balance, a Marsh funnel viscometer, an M3600 viscometer, a water analyzer, and a filter press. The CMC and PHPA were manufactured by Himedia and supplied by M/S A & BA Associates. The molecular weight of the CMC was 263.2 g/mol, with a substitution degree of 0.85, a purity of 99.6 %, and a pH of 6.90. The molecular weight of the PHPA was medium to high (approximately 20 parts per million) with a purity of 99.0 %, a neutral pH, and a hydrolysis degree of 25–35 %.

2.2. Methodology

2.2.1. Preparation of the base mud

The amount of raw material required to prepare the base mud, i.e., bentonite, was measured using a weight balance. A bentonite concentration of 2 % was used to prepare the base mud, and the bentonite was mixed with 1000 mL of distilled water using a stirrer. Then, the stirred mud was further mixed in a Hamilton Beach Mixer for approximately 15 min.

2.2.2. Preparation of CMC and PHPA mud

To prepare CMC and PHPA mud, different amounts of CMC and PHPA were mixed with the base mud. The base mud was mixed with 1–5 g of CMC to prepare CMC mud samples, and nine samples were prepared accordingly. Similarly, the base mud was mixed with 1–5 g of PHPA to obtain PHPA mud samples, and nine PHPA mud samples were prepared.

2.2.3. Property analysis of the prepared mud samples

2.2.3.1. Density measurement: The densities of the prepared samples were measured using a mud balance apparatus. The mud balance apparatus consists of a graduated beam with a bubble level, a weight slider along its length, and a cup with a lid on one end. The cup is used to hold a fixed amount of fluid to be weighed. The weight slider can be moved along the beam, and the bubble indicates when the beam is level. The density is read as the point at which the weight slider on the beam is level. The mud balance is the most reliable and simple instrument for measuring the density.

2.2.3.2. Funnel viscosity measurement: The funnel viscosities of the prepared samples were measured using a Marsh funnel viscometer, which consists of a funnel or cone and a cup. A mesh at the top of the funnel removes any unwanted solid particles when the mud is poured through the mesh. First, 950 mL of distilled water is measured from the prepared drilling mud and poured into the funnel. During its use, the funnel is held vertically, with the end of the tube closed by a finger. For the measurement, the finger is released as a stopwatch is started, and the liquid is allowed to flow down into a measuring container. The duration in seconds is recorded as a measure of the viscosity. Three types of viscosity were measured by this method: effective viscosity, apparent viscosity (based on time), and apparent viscosity (based on both time and viscosity) [15]. The following formulas were used to calculate these parameters:

$$\text{Effective viscosity} = \rho\,(t - 25)\ \text{cp}$$

$$\text{Apparent viscosity} = -\,0.0118\,t^2 + 1.6175\,t - 32.168\ \text{cp}$$

$$\text{Apparent viscosity} = \rho\,(t - 28)\ \text{cp}$$

where ρ is the density of the mud, t is the time, and cp is the unit, i.e., centipoize [16].

2.2.3.3. Measurement of electrochemical properties: The electrochemical properties, such as the pH, salinity, and electrical conductivity, of the prepared mud samples were measured using a water analyzer kit.

2.2.3.4. Measurement of rheological properties: The plastic viscosity, yield point, and gel strength were determined using an M3600 viscometer as the temperature varied from 77°F to 95°F. The plastic viscosity and yield point were calculated by the following equations:

$$\text{Plastic Viscosity} = \theta_{600} - \theta_{300}$$

$$\text{Yield Point} = \theta_{300} - \text{Plastic Viscosity}$$

Both the initial gel strength and 10-min gel strength were measured by varying the temperature from 77°F to 95°F.

2.2.3.5. Measurement of filtrate loss and mud cake thickness: The filtrate loss of the prepared mud samples was measured using a filter press instrument. The amount of fluid discharged from the filtrate tube was measured in a graduated cylinder, and the mud cake thickness was measured by a scale placed on the mud cake that had formed on the filter paper.

2.2.3.6. Determination of the effect on shale swelling via a static immersion test: Shales were acquired from Champhai district, Mizoram, and their strength was determined by a shale stability test.

Three similar shale rocks were powdered with a mortar. Equal amounts, i.e., 8 g, of powdered shales were then added to three different nonoptimized (without additives) and optimized (with additives) drilling muds: bentonite mud, bentonite–CMC mud, and bentonite–PHPA mud. The samples were maintained for 48 h, and shale swelling was observed at 2-h intervals. Finally, the shales were dried, and their dry weights were measured. The values for the three types of mud were then plotted and compared. The formula for swelling is given below [10]:

Swelling

%

$$\text{Swelling (\%)} = \frac{\text{Weight of wet rock (g)} - \text{Weight of dried rock after immersion (g)}}{\text{Weight of dried rock after immersion (g)}}$$

3. Results and Discussion

3.1. Density measurement

The density measurements highlight an essential role of additives in maintaining an optimum hydrostatic pressure for efficient drilling. The densities of the CMC and PHPA muds were 1018.52 and 1020.92 kg/m^3, respectively, with the addition of 1 g for each. The densities of the prepared CMC and PHPA muds with increasing concentration are shown in Figures 1 and 2.

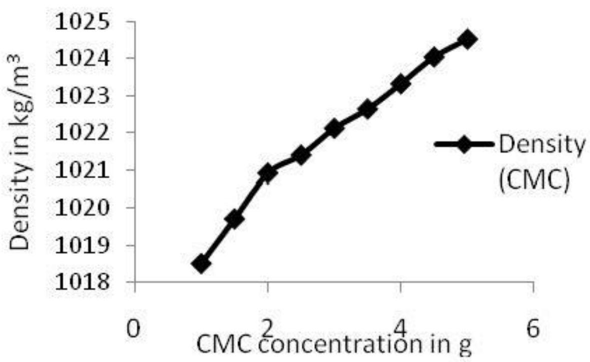

Fig. 1. Variation in density with increasing CMC concentration

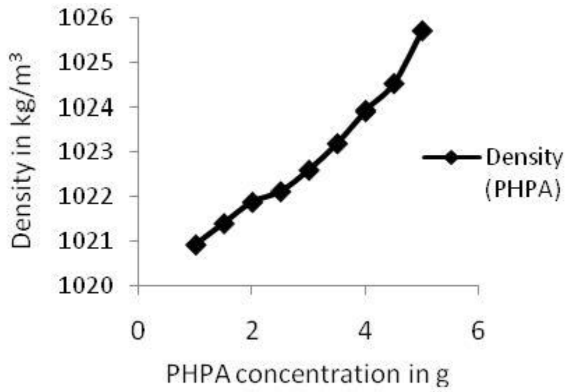

Fig. 2. Variation in density with increasing PHPA concentration

Figures 1 and 2 show that the density increases slightly, from 1018.52 to 1024.52 kg/m^3, with increasing CMC concentration [17]; for PHPA, the density increases from 1020.92 to 1025.71 kg/m^3. This result indicates that as the formation pressure increases, higher concentrations of CMC and PHPA can aid in maintaining the required safety allowance for hydrostatic pressure.

3.2. Funnel viscosity measurement

The effective and apparent viscosities of the CMC and PHPA muds, as determined by a Marsh funnel viscometer, and their variations with increasing concentration are shown in Figures 3 and 4.

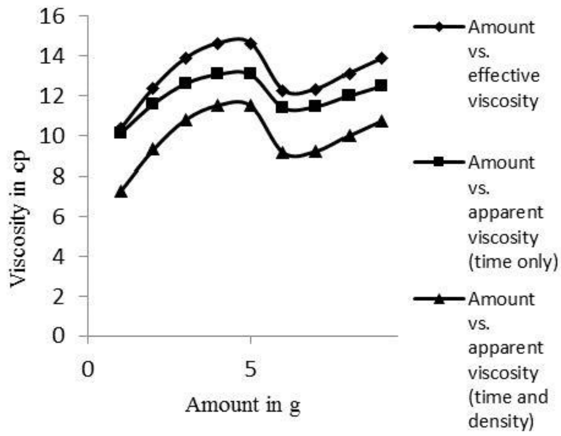

Fig. 3. Variation in viscosity with increasing CMC concentration

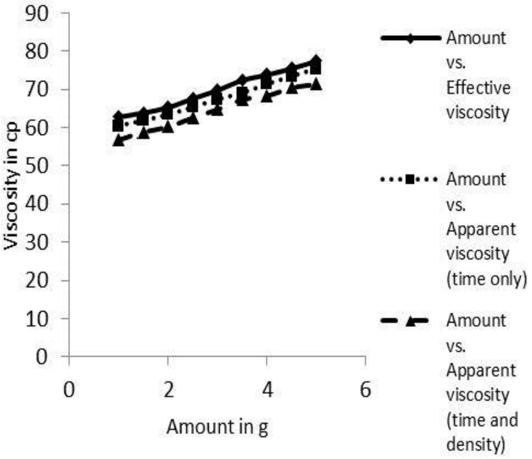

Fig. 4. Variation in viscosity with increasing PHPA concentration

Figures 3 and 4 show that the viscosity first increases with increasing CMC concentration, then decreases, and finally increases again, forming a hump. In contrast, with increasing PHPA concentration, the viscosity shows a constant increase. Various researchers have analyzed the effect of CMC on the rheological properties of drilling fluid, demonstrating that CMC improves the rheological properties [7]. However, PHPA has proven to be a better viscosifier for enhancing rheological properties with greater consistency. Researchers have also reported that the addition of polyacrylamide in CMC mud provides a greater improvement in the rheological properties [18].

3.3. Determination of electrochemical properties

The electrochemical properties of CMC and PHPA mud are shown in Figures 5 and 6, respectively. Figure 5 shows that the pH and salinity remain nearly constant, with only slight variations; however, the electrical conductivity decreases sharply with increasing CMC concentration. In contrast, Figure 6 shows that as the PHPA concentration increases, the pH, salinity, and electrical conductivity all exhibit slight variations, with a weak increasing trend.

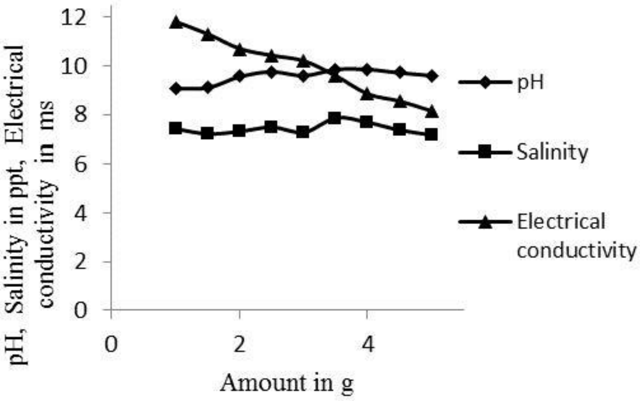

Fig. 5. Variations in electrochemical properties with increasing CMC concentration

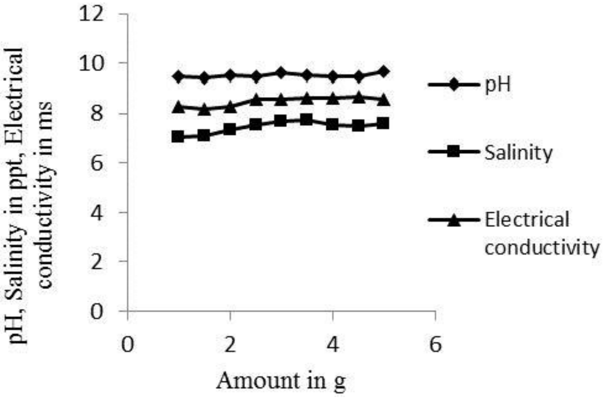

Fig. 6. Variations in electrochemical properties with increasing PHPA concentration

3.4. Rheological properties

Rheological properties play a crucial role in proper operational performance and flow assurance. The variations in rheological properties with increasing CMC and PHPA concentrations [9, 12] are shown in Figures 7–14. These figures show that the plastic viscosity [13], yield point, and gel strength increase as the concentrations of both CMC [19, 20] and PHPA [21] increase. However, the addition of PHPA results in a greater increase in the plastic viscosity and yield point. Therefore, PHPA proves to be a better viscosifier.

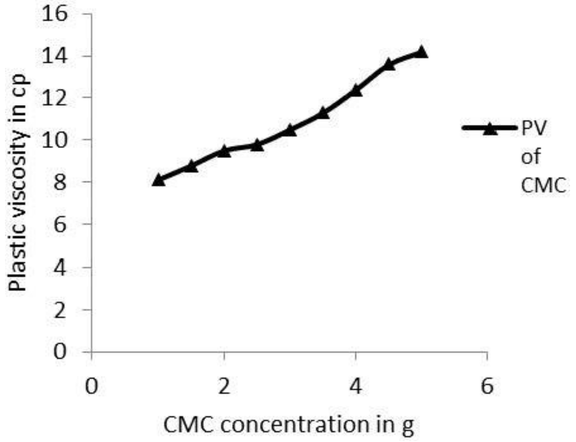

Fig. 7. Variation in plastic viscosity with increasing CMC concentration

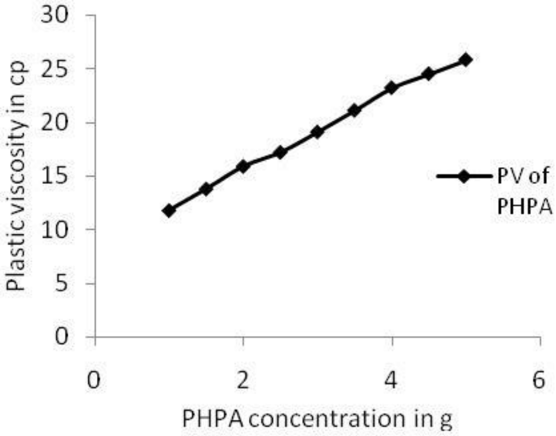

Fig. 8. Variation in plastic viscosity with increasing PHPA concentration

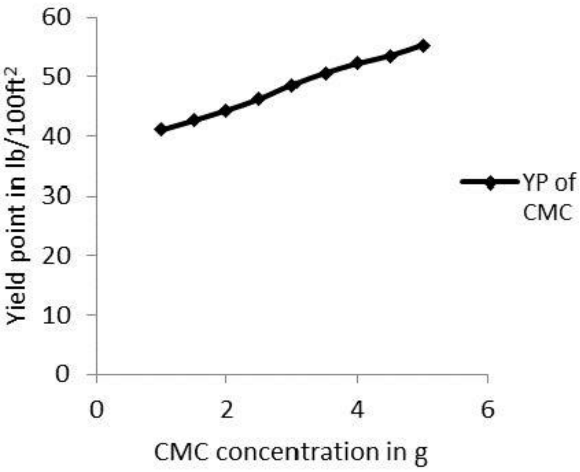

Fig. 9. Variation in yield point with increasing CMC concentration

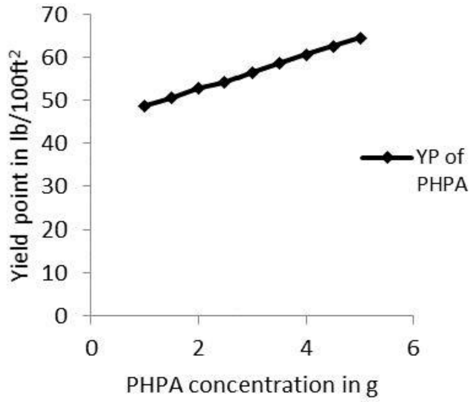

Fig. 10. Variation in yield point with increasing PHPA concentration

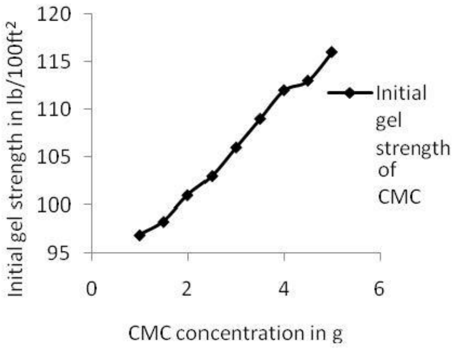

Fig. 11. Variation in initial gel strength with increasing CMC concentration

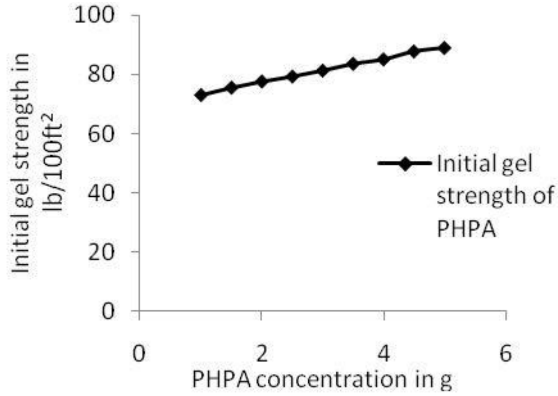

Fig. 12. Variation in initial gel strength with increasing PHPA concentration

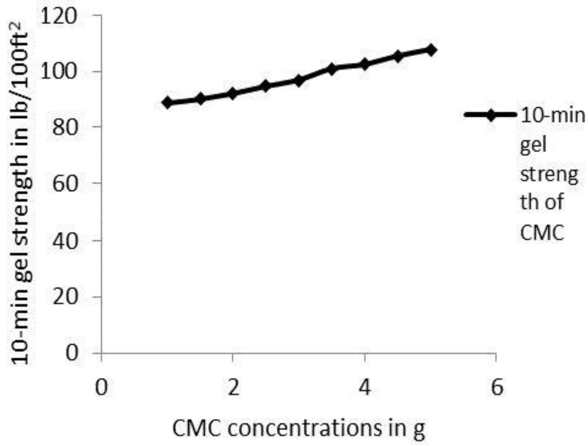

Fig. 13. Variation in 10-min gel strength with increasing CMC concentration

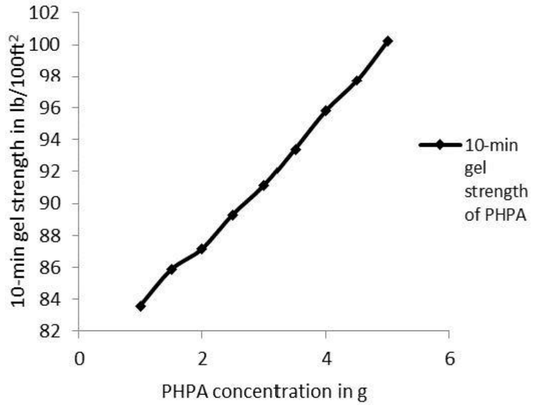

Fig. 14. Variation in 10-min gel strength with increasing PHPA concentration

However, the CMC mud showed a greater initial and 10-min gel strength than the PHPA mud.

3.5. Filtration properties

Variations in the filtration properties, including the filtrate loss and mud cake thickness, are shown in Figures 15–18. Both the filtrate loss [17] and mud cake thickness show the desired decreasing trend as the CMC [22] and PHPA [12] concentrations increase. The PHPA mud shows a greater decrease in mud cake thickness, providing a thin mud cake, which is desirable and essential for a stable wellbore.

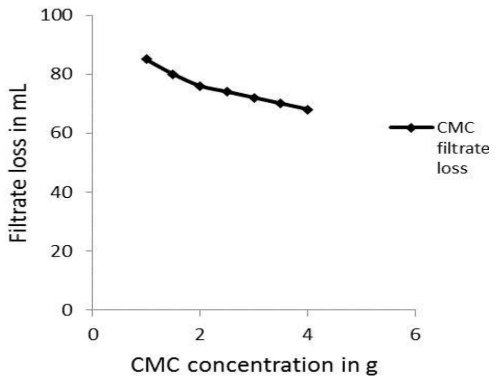

Fig. 15. Variation in filtrate loss with increasing CMC concentration

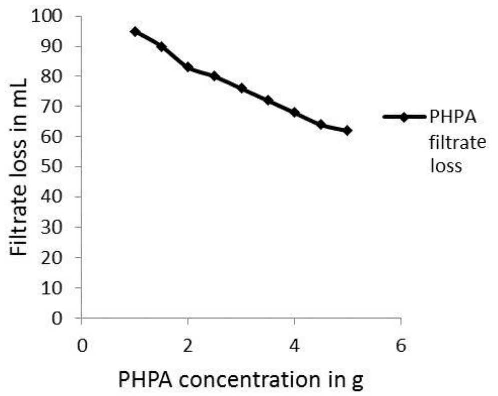

Fig. 16. Variation in filtrate loss with increasing PHPA concentration

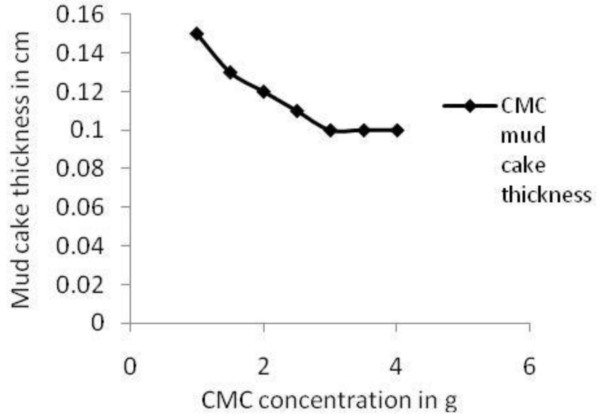

Fig. 17. Variation in mud cake thickness with increasing CMC concentration

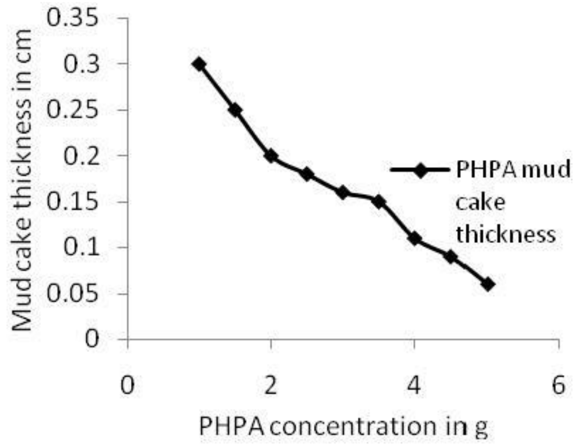

Fig. 18. Variation in mud cake thickness with increasing PHPA concentration

3.6. Rheological model analysis for CMC and PHPA mud

Rheological models for both CMC [9] and PHPA [13] mud were characterized by analyzing the variations in shear stress with shear rate and rotational velocity, as shown in Figures 19–22. The variations in shear stress with shear rate for both CMC [23, 24] and PHPA mud follow a nonNewtonian power law model. Moreover, by using a power law model, the flow behavior index, *n*, was calculated for both muds for all CMC and PHPA concentrations. All values were less than 1, indicating that both muds were Herschel–Bulkley [12] in nature, with yield stress points exceeding zero.

Figures 19 and 20 clearly show that the shear stress increases with increasing shear rate. The shear stress ranges from 70.5 to 80.8 dyne/cm^2 for 1-g CMC mud and from 88.9 to 98.9 dyne/cm^2 for 5-g CMC mud. As the CMC concentration increases, more stress is required to move the mud, and the yield point also increases. The shear stress increases sharply for the initial shear rates and rotational velocities and becomes steadier for higher shear rates and rotational velocities.

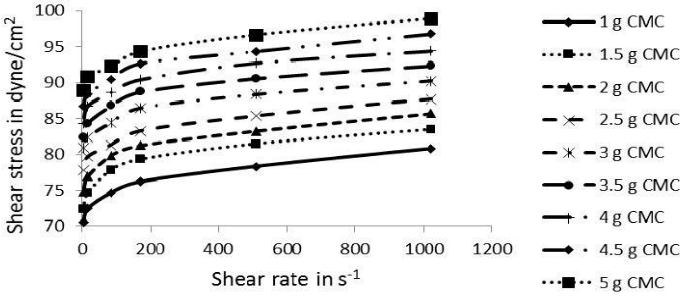

Fig. 19. Variation in shear stress with shear rate for various CMC concentrations

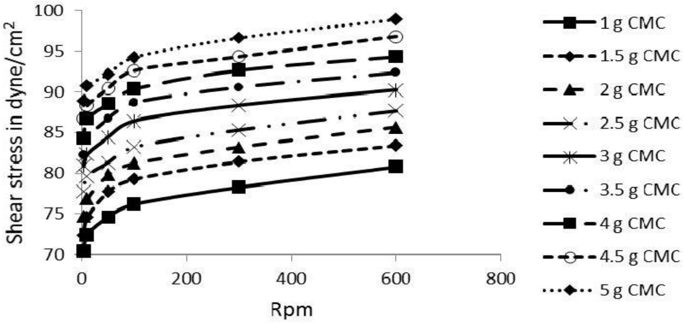

Fig. 20. Variation in shear stress with rotational velocity for various CMC concentrations

Figures 21 and 22 show that the shear stress ranges from 63.7 to 73.9 dyne/cm^2 for 1-g PHPA mud and from 79.6 to 89.0 dyne/cm^2 for 5-g PHPA mud.

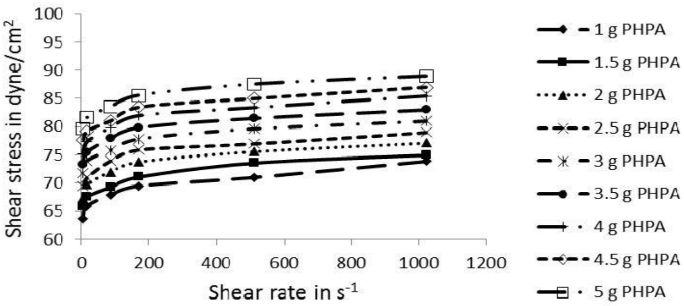

Fig. 21. Variation in shear stress with shear rate for various PHPA concentrations

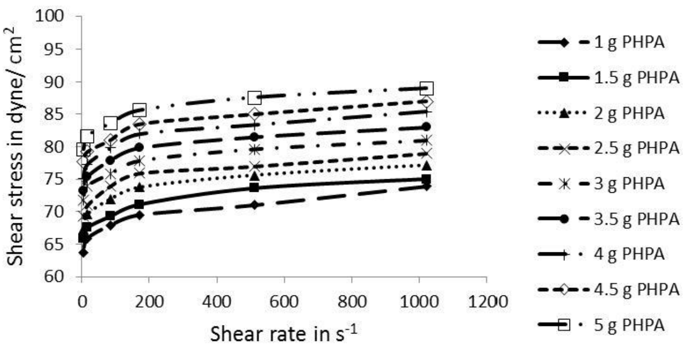

Fig. 22. Variation in shear stress with rotational velocity for various PHPA concentrations

The yield point of the PHPA mud increases with increasing PHPA concentration, and more shear stress is required to move the mud. Comparison shows that more stress is required to shear through CMC mud than through PHPA mud. The viscosity indicates the resistance of a fluid to shear deformation. By comparing the viscosities and shear stresses of CMC and PHPA mud, we found that both polymers act as good viscosifiers; as the concentrations of these polymers increase, the viscosity of the fluid increases as well. For this reason, the shear stress increases for higher concentrations of these polymers. CMC generally acts as a better filtrate-loss-reducing agent, while the PHPA mud exhibits higher viscosity and shear stress for the studied concentrations.

3.7. Effect on shale swelling: a real-world application

The strength of shales acquired from Champhai district, Mizoram, was determined by a shale stability test. This test demonstrated that the bentonite mud system is very weak with respect to shale stability when no polymer is added. Shale swelling occurs rapidly in the bentonite mud system, at a moderate rate in the bentonite–CMC mud system, and much more slowly in the bentonite–PHPA mud system. For powdered shale, much less time is required for the shales to become completely saturated in bentonite mud, while a moderate time is required for the bentonite–CMC mud. For the bentonite–PHPA mud, a long duration is needed for the powdered shales to become completely saturated. Slight swelling of the shales occurs after 8 h in the bentonite mud system, 16 h in the bentonite–CMC mud system, and 24 h in the bentonite–PHPA mud system. The shale swelling behaviors for the three mud systems are shown in Figure 23.

As shown in Figure 23, the shale particles expand over time for all three mud types. In the nonpolymer mud, the shale particles could not be prevented from swelling; thus, shale swelling occurs rapidly in non-optimized mud. In contrast, CMC and PHPA act as a sealing agent in clay chemistry to prevent shales from swelling. Because the shale swelling occurred continuously, we attempted to obtain a uniform graph from the readings. The readings were noted after 2-h intervals, as it was not possible to continuously note the readings for 48 h. The results show that PHPA more efficiently prevents shale swelling than CMC; this result was also theoretically validated, as the same findings were obtained in the static immersion test.

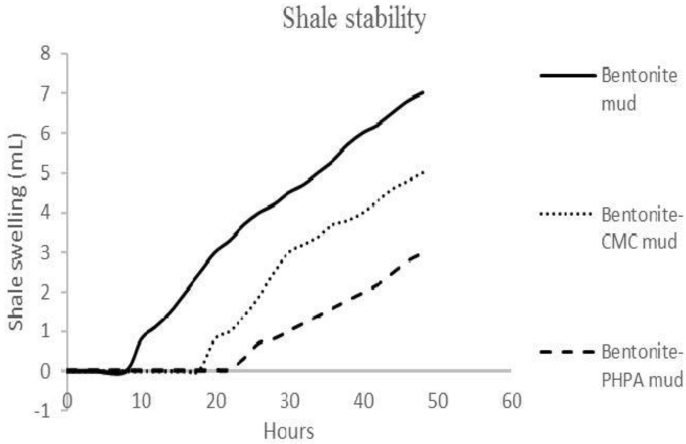

Fig. 23. Shale swelling for different types of drilling mud

4. Conclusion

The addition of both CMC and PHPA resulted in improved properties in drilling fluid. The density remained nearly constant with their addition; however, the rheological and filtration properties were effectively enhanced. PHPA produced greater improvements than CMC. The PHPA mud exhibited a higher effective viscosity, apparent viscosity, and plastic viscosity than the CMC mud; thus, PHPA is a better viscosifier. The PHPA mud also showed higher yield point and gel strength values, indicating that PHPA mud has a better cutting-carrying capacity than CMC mud. Moreover, the PHPA mud exhibited better filtration properties than the CMC mud, demonstrating that PHPA can be used as an active fluid loss-reducing agent and can contribute to the wellbore stability by forming a thin, tough mud cake that prevents pipe sticking. With regard to shale stability, PHPA was superior to CMC, as a lower amount of shale swelling was observed over a longer duration for PHPA compared with CMC.

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