Synergistic Effect of Polyaspartate and Polyethylene Glycol on Lubrication Performance of the Water-Based Drilling Mud

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ABSTRACT: The poor lubrication performance of water-based drilling mud hinders its application in the drilling process of extended, reach horizontal wells. To overcome this shortcoming, polyaspartate (PA) and poly(ethylene glycol) (PEG) were used to improve the lubrication performance of the water-based drilling mud. The conventional performances, lubrication performance, and micro-image of antiewear steel balls of the modified water-based drilling mud were analyzed. The results show that the coefficient of friction (COF) of the water-based drilling mud mixed with 10% PA and 5% PEG was the lowest, reaching 0.094, the reduction rate of COF was 63.1%, and the drilling mud cake stuck factor was also the lowest. The addition of PA and PEG had no effect on the rheological properties of water-based drilling mud and also can significantly reduce the filtrate volume; the reduction rate of the filtrate volume reached 43.5%. All of these result from the synergistic effect of PA and PEG; they are adsorbed on the metal surface and the mud cake to form a lubricating film. At the same time, the lubricants also changed the appearance of the solid particles in the mud cake, which reduced the friction between the mud cake and the drilling tool. Moreover, effects of the influence of drilling mud properties on lubricants (alkali metal ions, pH, temperature, and drilling mud density) were examined. The water-based drilling fluid with the synergistic effect of PEG and PA shows similar lubrication performance as the oil-based drilling fluid and can meet the technical requirements of corresponding horizontal wells.

1. INTRODUCTION

In recent years, drilling engineering has gradually developed to directional wells, extended-reach wells, cluster wells, deep wells, and ultra-deep wells. These different wellbore structures increase the torque and friction force in the drilling process, which is easy to accelerate the wear of drilling tools, increase the power consumption of the drilling equipment, and even lead to drilling safety accidents such as broken drilling and sticking.1,2 The oil-based drilling mud has strong inhibition and high lubricity, which can effectively prevent sloughing and sticking. However, environmental pollution, affecting logging quality, and high cost are also its disadvantages. The water-based drilling mud does not have these problems, but the poor lubrication performance and high friction have restricted its development. Therefore, improving the lubrication performance of the water drilling mud has great significance in solving the above problems.3−5 Adding high-quality lubricating oil into water-based drilling mud to reduce downhole friction is one of the main technical means to prevent and solve drilling safety problems at present.6,7 The research and development of water-based drilling mud systems and corresponding lubrication treatment agents are of great significance to the wide application of water-based drilling muds in the future.

PEG is a polyol, and the diversity of its molecular structure determines the diversity of products. It not only has good shale inhibition performance but also has a good lubricating effect, making it widely useful in petroleum drilling.8−11 In addition, it has been widely used in artificial joint materials, biopharma-
novel metal working fluid, which is used as a lubricant in the process of cutting, bending, grinding, and forming ferrous and nonferrous metals. At the same time, the “extreme pressure four-ball test” was carried out to test the relative bearing capacity of the lubricant under constant conditions, and the result shows that it has good lubrication performance. Based on the good lubrication performance of PA in metal cutting fluids, it also can be used in water-based drilling mud. Both PA and PEG are environmentally friendly and degradable treatment agents, which fully conform to the development concept of water-based drilling mud. Many studies on improving the lubricity of water-based drilling mud with a single material have been well proved, but the application of composite materials in water-based drilling mud has not been well reported. To develop high-quality water-based drilling mud suitable for drilling technology, PEG and PA composite materials are used in the water-based drilling mud, and the relationship between their synergistic effect and their representative functions is studied. The research results provide a reference for the development of high-performance water-based drilling mud.

2. RESULTS AND DISCUSSION

To understand the influence of various additives on the performances of water-based drilling mud more intuitively, effects of PA and PEG on the rheological properties, filtrate volume at high temperature and high pressure, coefficient of friction, and the mud cake stuck factor were studied. The control sample (excluding PEG and PA) was plotted as “WBM”.

2.1. Effect of PA on the Performance of Water-Based Drilling Mud

2.1.1. Effect of PA on the Rheological Property of Water-Based Drilling Mud. The rheological property is one of the basic properties of drilling mud, which plays an important role in solving the following drilling problems: (1) carrying cuttings to ensure the cleanliness of bottom hole and well suit; (2) suspending cuttings and barite; (3) improving the mechanical drilling speed; and (4) maintaining borehole stability and ensuring downhole safety. Therefore, the rheology of drilling mud directly affects the performance of these functions.

Figure 1 shows the effect of PA content on the plastic viscosity (PV) and yield point (YP) of water-based drilling mud. Data were collected at a standard temperature of 50 °C. With the increase of the PA content, the PV and YP of the water-based drilling mud, respectively, increased by 2 cP and 2.1 lb/100 ft², but the changes in these values are almost negligible. Therefore, PA has no effect on the rheological property of water-based drilling mud.

Figure 2 shows the effect of PA content on the gel strength (g) of water-based drilling mud. It exhibits an increase of gel strength at an increased PA concentration, following the trend for YP. The increase of the PA content, the PV and YP of the water-based drilling mud, respectively, increased by 2 cP and 2.1 lb/100 ft², but the changes in these values are almost negligible. Therefore, PA has no effect on the rheological property of water-based drilling mud. Figure 2 shows the effect of PA content on the gel strength of water-based drilling mud. It exhibits an increase of gel strength at an increased PA concentration, following the trend for YP. Moreover, the change at 10 s and 10 min is not obvious at the same concentration. This phenomenon shows that PA can slightly improve the suspending ability of cuttings under static conditions.
2.1.2. Effect of PA on the Lubrication Performance of Water-Based Drilling Mud. The lubrication performance of drilling mud usually includes two aspects: the lubrication performance of drilling mud and the mud cake stuck factor. These two indexes are the main technical indicators for evaluating the lubrication performance of drilling muds. PA has good lubricity and antiwear property in metal cutting fluids, so it can be used as the base fluid of water-based drilling mud to improve the lubrication performance of water-based drilling mud.\(^{23}\)

The relationship among the content of PA, the coefficient of friction of water-based drilling mud, and the mud cake stuck factor was studied, and the results are clearly shown in Figure 3. With the increase of the PA content, the coefficient of friction of the water-based drilling mud shows a decreasing trend, but it is not obvious. After 20% PA treatment, the coefficient of friction of water-based drilling mud decreases to 0.175, merely.

PA had a very low coefficient of friction, but when it was added to water-based drilling mud, it did not show a positive effect on the lubrication performance. Moreover, it was found that when sodium hydroxide was added into the PA pure agent, it was difficult to dissolve sodium hydroxide in PA due to the low water activity and poor solubility of PA, which made PA molecules unable to fully diffuse in solution.

The mud cake stuck factor increased with the growth of PA, which was not favorable. This is because PA has high adhesion, forms chelates with various ions (such as calcium, magnesium, copper, and iron), and adheres to the metal surface.\(^ {24}\) Therefore, the metal block was blocked when it started to slide.

2.1.3. Effect of PA on the Filtrate Volume of Water-Based Drilling Mud. Filtration and wall building performance are important performances of drilling mud, which have very important impact on the stability of the wellbores of loose, broken, and unstable formation. The filtrate volume of drilling mud is the most intuitive response to its filtration and wall building performance.\(^ {25}\)

As shown in Figure 4, with the increase of PA content, the volume of the filtrate of water-based drilling mud at high temperature and pressure gradually decreases. When the PA content reaches 10%, the volume of the filtrate decreases to a peak value of 1.6 mL. After that, the PA content continues to increase, and the volume of the filtrate no longer decreases, but increases again. The reason for the decrease in the filtration volume of drilling mud is that PA is a long-chain polymer molecule with polar groups (such as amino and carboxyl groups) at the end of the chain. So, the PA molecules have adsorption and cross-linking with mud cake, which can plug pores and achieve a certain filtration reduction effect.\(^ {19}\)

In summary, PA had little effect on the rheological property of water-based drilling mud and could reduce the filtrate volume, but its performance as a lubricant was not outstanding, which needs to be studied.

2.2. Effect of PEG on the Performance of Water-Based Drilling Mud. 2.2.1. Effect of PEG Content on Rheological Properties of Water-Based Drilling Mud. It is found that the
The rheological properties of drilling mud do not change with the molecular weight of PEG. Therefore, we chose one of the molecular weight PEG to study the effect of its content on the rheological properties of drilling fluid.

Figure 5 illustrates the effect of PEG content on the rheological properties. With the increase in the content of PEG, the PV and YP values of the water-based drilling mud slightly increased, but it is not obvious. The PV increased by 3 cP and the YP increased by 2.1 lb/100 ft². These changes can be ignored.

Figure 6 shows the effect of PEG content on the gel strength of water-based drilling mud. As the PA concentration increases, the gel strength increases. Under the same concentration, the changes at 10 s and 10 min are not obvious. This also shows that PEG can slightly increase the slurry’s ability to suspend rock cuttings under static conditions. It can be seen that the effect of PEG on the rheological properties of water-based drilling mud is not very significant.

2.2.2. Effect of Molecular Weight of PEGs on the Lubricating Performance of Drilling Muds. PEG has the advantages of strong inhibition, high lubricity, and miscibility with water in any ratio, which is suitable for the development of water-based drilling mud suitable for strong water-sensitive formation. Therefore, the influence of PEGs on the lubrication performance of water-based drilling mud was studied.

The influence of PEGs with different molecular weights on the lubrication performance of water-based drilling mud is shown in Figure 7. With the increase of the content, the COF of the
drilling mud shows a decreasing trend, with the highest reduction rate being 19.6% and the lowest being 13.0%. PEG can improve the lubrication performance of water-based drilling mud, but it is not as expected. When drilling extended, reach horizontal wells, the formation can be drilled smoothly only when the COF of drilling mud is generally lower than 0.10.27

Obviously, PEG does not meet the requirements.

2.2.3. Effect of PEG Content on Filtrate Volume of Water-Based Drilling Mud. Figure 8 exhibits the change in the fluid loss volume of water-based drilling mud with different molecular weights and different concentrations of PEG. As the concentration of PEG increases, the fluid loss volume shows a decreasing trend. Also, as the molecular weight of PEG increases, the fluid loss volume gradually decreases. This result shows that PEG can reduce the filtrate volume of water-based drilling mud to a certain extent. This is because PEG is a long-chain molecule with polar groups (hydroxyl group) at the end chain. The hydroxyl groups were adsorbed on the surface of the clay and barite of mud cake, which can effectively block the micropores and achieve the effect of reducing the filtrate volume. Small molecular-weight PEG can only block smaller pores, while larger molecular-weight PEG can also block larger micropores through cross-linking adsorption.

2.3. Synergistic Effect of PA and PEG on the Performances of Water-Based Drilling Mud. In view of the limitations of PA and PEG in improving the lubrication performance of water-based drilling mud, PA and PEG were considered to be mixed into the water-based drilling mud, with an expectation that the synergistic effect could exhibit good lubrication performance.

However, when PEG and PA were mixed into the water-based drilling mud, and the amount of PA reached 15%, insoluble particles appeared in the drilling mud, as shown in Figure 9b. Even when the amount of PA reached 20%, the insoluble particles in the drilling mud increased and became more obvious, as shown in Figure 9c. In addition, as shown in Figure 10, with the increase of PA content, the filtrate volume of water-based drilling mud is significantly reduced, but when the amount of PA is more than 10%, the filtration gradually increases. Therefore, the black particles in the drilling mud should be the water-loss additive SPNH or LSF. With the increase of the PA content, the solubility of these solid particles in water-based drilling mud also decreased. This also explains why the filtrate volume of water-based drilling mud tended to increase with the increase of PA content. Therefore, the final dosage of PA was chosen as 10%.

2.3.1. Synergistic Effect of PA and PEG on Lubrication Performance of Water-Based Drilling Mud. In view of the facts discussed in Sections 2.1 and 2.2, the performances in improving the lubricity of water-based drilling mud were not very satisfactory when PA and PEGs were used alone. The most suitable additive and proportion can be selected by adding PEG with different molecular weights and contents in the water-based drilling mud and using it in combination with PA.

The effect of different molecular weights and contents of PEGs on the COF of WBM + 10% PA is illustrated in Figure 11. With the increase of molecular weight and content of PEGs, the COF decreases; when the molecular weight of PEG is 6000, the COF reaches the lowest value. Compared with 0.23 of WBM + 10% PA, the COF of WBM + 10% PA + 5% PEG-6000 decreases to 0.094, and the reduction rate of COF reached 59.1%. However, when the molecular weight of PEG was 8000, the COF increased.

It can be seen from Figure 11 that when the concentration of PEG reaches 5%, the COF reaches the lowest value, and the COF of PEG-6000 is the lowest. Therefore, PEG-6000 is selected as the additive of water-based drilling mud, and its addition amount is 5%, which can improve the lubricity of drilling mud.

PEG is a nonionic polymer with hydroxyl groups at both ends. Due to the coud point effect, poly(ethylene glycol) in drilling mud had “phase separation” and became an oil-soluble substance.28 The hydroxyl groups on the molecular chain adsorbed on the surface of the mud cake and metal to form a lubricating film. Moreover, with the increase of the molecular weight of PEG, the lubricating film gradually thickens and the lubricating performance of the drilling mud decreases. However, with the increase of the molecular weight of PEG, the hydroxyl value also decreased.29 PEGs with different molecular weights have different hydroxyl values, i.e., the amount of hydroxyl groups in unit mass sample, as shown in Table 6. When the molecular weight reached 8000, the hydroxyl groups on the
molecular chain were relatively less to be effectively adsorbed on the mud cake and metal surface, thus increasing the COF.

The control sample (excluding PEG and PA) was plotted as WBM. Figure 12 shows the comparison of COF, which includes WBM, WBM + 10% PA, WBM + 5% PEG, and WBM + 5% PEG + 10% PA; 10% PA and 5% PEG reduce the COF of water-based drilling mud by 12.2 and 19.6%, respectively. These two ratios are selected because they have the most significant effect on water-based drilling mud. However, when they all were added to the water-based drilling mud together, the COF of the water-based mud is only 0.094 and the COF decreases by 63.1%. The oil-based mud is equipped indoors for lubrication performance test, and the composition is presented in Table 1. The results show that the COF of oil-based mud is generally between 0.070 and 0.080. Therefore, it can be considered that the lubricating performance of WBM + 5% PEG + 10% PA is close to that of the oil-based mud.

The reasons for the low COF of 10% PA + 5% PEG water-based drilling mud are as follows: the polar group formed by hydrolysis of PA adsorbed on the metal through chelation and formed firm lubrication on the metal surface. Then, the hydrophilic group of the ether bond and the terminal hydroxyl group of PEG molecules through hydrogen bond form a second layer of lubricating film outside the PA lubricating film. The synergistic effect of the two layers of lubricating films reduced the contact friction between friction surfaces, improved the

Table 1. Oil-Based Mud Composition

| components   | function                  | concentration (g) |
|--------------|---------------------------|-------------------|
| water        | base fluid                | 80                |
| diesel oil   | base fluid                | 270               |
| HIEMUL-B     | emulsifier                | 12                |
| HICOAT-B     | emulsifier                | 2.4               |
| CaO          | adjuvant of emulsifier    | 6.0               |
| MoGel        | viscosifier               | 10.0              |
| HIFLO        | filtration control        | 12.0              |
| HIFLO-L      | filtration control        | 8.0               |
| barite       | weighing agent            | 460               |
extreme pressure and antiwear property of drilling mud, and enhanced the lubricity of water-based drilling mud.

Figure 13 shows the comparison of the mud cake stuck factor of the four water-based drilling muds. Obviously, the synergistic effect of PA and PEG is more effective than that of individual use. Because PA has high adhesion, it can form chelates with various ions (such as calcium, magnesium, copper, and iron) and adhere to the metal surface, so it shows a higher mud cake adhesion coefficient. However, PEG chains combine with water molecules through hydrogen bonding and polarization, and the hydrated PEG chains become more lubricated, more fluid, and thus have lower friction. The lubricating film formed by PEG molecules adsorbed on PA, which blocks the direct contact between the metal slider and mud cake, so PEG and its synergistic effect with PA show a lower mud cake stick factor.

2.3.2. **Synergistic Effect of PA and PEG on Rheological Properties of Water-Based Drilling Mud.** In Sections 2.1 and 2.2, it was found that there was little effect on the rheological properties of water-based drilling mud when it was used alone. However, the rheological properties of water-based drilling mud changed after it was treated with PA and PEG. PEG was added into the water-based drilling mud containing 10% PA, and the synergistic effect of different amounts of PEG and PA on the rheological properties of the water-based drilling mud was observed. The data related to the synergistic effect of PA and PEG on viscosity profiles are presented in Table 2.

The measured shear stress of WBM containing PA and PEG as a function of shear rate and PA or PEG concentration after hot rolling is presented in Figure 14. The result shows that the shear stress of WBM with PA and PEG is higher than that of WBM, and the shear stress increases with the increase of the PEG content. At low shear rates, the increase of shear stress is small. At a higher shear rate, with the increase of PEG content, the increase of shear stress is more obvious. Especially at a shear rate of 1021.8 s⁻¹, the shear stress increases by 45.8%. Therefore, the addition of PEG and PA significantly improved...
the viscosity of water-based drilling mud and increased the pump pressure in drilling engineering.

Figure 15 illustrates the change in the rheological parameters, YP and PV, of WBM + 10% PA for PEG-6000. Theoretically, YP measures the electrochemical force or attraction of a fluid under flowing conditions. YP depends on the surface properties of drilling mud solids, the volume concentration of solids, and the electrochemical environment of these solids. The result shows that with the increase of PEG concentration, YP value only increases from 13.65 to 16.8 lb/100 ft², which can be ignored. Therefore, the addition of PEG has little effect on YP value.

The variation of the rheological parameter PV of WBM + 10% PA as a function of PEG concentration is also shown in Figure 15; the addition of PEG has no effect on PV. The calculated PV range is 20 to 27 cP. In most practical applications, the value of PV is determined by the concentration of drilling mud solids. Moreover, low and stable PV is desirable as excessive PV will increase the pump pressure required to pump the fluid, resulting in an excessive equivalent circulating density (ECD).

Figure 16 shows the effect of PEG content on the gel strength of WBM + 10% PA. It shows that the gel strengths of drilling muds increase with the increase of PEG concentration, and the 10 s and 10 min reached 7.35 lb/100 ft² finally. Generally, this phenomenon suggests that the WBM containing PEG and PA can better suspend cuttings under static conditions.
2.3.3. Synergistic Effect of PA and PEG on Filtrate Volume of Water-Based Drilling Mud. Figure 17 depicts the synergistic effect of PA and PEG on the filtration of water-based drilling mud. When 1% PEG is added to the drilling mud, the filtrate volume decreases significantly. However, with the addition of PEG, the filtrate volume showed a decreasing trend, but it was not particularly obvious. Obviously, PEG and PA can significantly reduce the filtrate volume of water-based drilling mud, which is good for site construction.

Figure 18 shows the comparison of HTHP filtration of WBM, WBM + 10% PA, WBM + 5% PEG, and WBM + 10% PA + 5% PEG. The addition of 10% PA or 5% PEG can reduce the filtrate volume of water-based drilling mud by 12.9% or 21.0%, but once they are all mixed into the water-based drilling mud together, the reduction rate of the filtrate volume reaches 43.5%. Because PA and PEG can be adsorbed on the surface of clay and barite through chelation and hydrogen bonding, microcracks and micropores are prevented, and the volume of the filtrate is reduced.26

2.4. Surface Characteristics. 2.4.1. Micromorphology of Wear Scars on Wear-Resistant Steel Balls. In water-based drilling mud, bentonite particles are hard and can be regarded as abrasives. When the antiterror test was started, these bentonite particles were pressed against the friction pair, which would produce plowing and wear. However, with the addition of lubricants, the lubricant molecules would adsorb on the surface of the friction pair to form a film, which effectively protects the steel surface from the influence of abrasive particles, and the worn surface becomes smooth.12

The wear scar morphology of the wear-resistant steel ball was observed by scanning electron microscopy (SEM). Figure 19 shows a comparison of wear caused by the WBM (excluding PA and PEG), WBM + 10% PA, WBM + 5% PEG, and WBM + 10% PA + 5% PEG.

As shown in Figure 19a, the wear scar of WBM reveals considerable rough river-vein patterned layers, mainly in the direction of sliding. In WBM containing PA or PEG, as shown in Figure 19b,c, there are multiple relatively regular plowed tracks, but there is still polished wear. Figure 19d shows the steel ball wear mark of WBM + 10% PA + 5% PEG. From the low-power observation, it can be found that the surface of the grinding mark is smooth, with no deep plow path. The high-power observation shows that the surface of the steel ball is smooth with some friction marks in the longitudinal direction, but no obvious polishing wear and plowing path. It has the best ability to protect metal surfaces from wear. Compared with the above three kinds of drilling muds, the SEM image of WBM + 10% PA + 5% PEG is more clear and smoother. PA or PEG was adsorbed on the metal surface by chelation, forming a weak film; then, PEG was connected with PA through the hydrogen bond of polar groups, forming a more solid and thick lubricating film on the surface of steel ball, reducing the direct contact between friction pairs, so as to achieve the effect of reducing friction and drag.

Apart from the load applied to the friction testing machine, solids contained in a drilling mud evidently contribute to friction and scar. In this study, each drilling mud consisted of 50% (w/w) solids that might lead to high friction.33

2.4.2. Micromorphology of Mud Cakes. The solid particles in the mud cake structure without a lubricant (Figure 20a) are scattered and full of edges and corners, while in the mud cake with lubricants (Figure 20b), the solid particles are tightly wrapped and round. By observing the microstructure of the mud cakes, it can be found that the lubricants changed the appearance of the solid particles by wrapping the solid particles in the mud cake, transforming the irregular shape into a regular spherical shape. PA and PEG can change the friction between the drilling tool and the mud cake, forming a “ball bearing effect” on the mud cake surface, effectively reducing the friction resistance between the drilling tool and the mud cake.34

2.5. Analysis of Influence of Drilling Mud Properties on Lubricity. 2.5.1. Influence of pH. In drilling operation, salt alkali formation may be encountered, which may change the acid–base property of the drilling mud. Therefore, it is necessary to study the effect of pH on the lubricant and the drilling mud. The influence of pH is tested with the addition of NaOH to the base drilling mud; 10% PA and 5% PEG are used as lubricious additives. The performance of the lubricants and the lubricity of the drilling mud do not change with pH increasing up to 11.5.

2.5.2. Influence of Alkali Metal Ions. A rock salt layer or a salt gypsum layer is often encountered in drilling operation. When salts dissolve into the water-based drilling mud, the performance of the water-based drilling mud becomes unstable. Sodium, potassium, and calcium salts were used to evaluate the salt resistance of the system.35 The influence of alkali metal ions is tested with different qualities have different effects on the lubrication effect of water-based drilling mud. The effect of K+ is higher than that of Na+ in the case that both can reduce the coefficient of friction of the drilling mud. The performance of lubricants and the lubricity of the drilling mud are affected negatively by the increase of Ca2+ content.

2.5.3. Influence of Temperature. The temperature of drilling mud varies with geological conditions and the well depth. In the process of drilling, the circulating drilling mud system is always in an environment of constant temperature change. Different drilling mud systems have their own applicable temperature ranges. To observe the change in system performance with temperature and obtain the temperature range, the temperature...
resistance of the lubricant was evaluated in a laboratory. The temperature resistance performance was evaluated at 70−130 °C, as shown in Table 3, which showed that the lubrication performance was basically unchanged and the temperature resistance was good. The COF was determined with an FANN extreme pressure lubricator.

2.5.4. Influence of Drilling Mud Weight. Mud with different densities is needed for different formation conditions and
reservoir depth. Barite is added to the basic drilling mud and weighed to the densities of 1.6 and 1.8 g/cm³, respectively. The influence of specific gravity of the drilling mud on its quality is tested, as shown in Table 5. However, increasing the drilling mud weight with the addition of 10% PA and 5% PEG lubricants has no effect on lubricity increasing with the barite content. The COF was determined with an FANN extreme pressure lubricator.

3. CONCLUSIONS

In this paper, the conventional and lubrication performances of water-based drilling mud including PA or PEG and their hybrid combination were comparatively examined and the following conclusions were drawn:

(1) The COF of the water-based drilling mud mixed with 10% PA and 5% PEG was the lowest, reaching 0.094, the reduction rate of COF was 63.1%, and the mud cake stuck factor was also the lowest.

(2) The addition of PA and PEG had no significant effect on the PV of the water-based drilling mud, but they increased the YP and gel strength of the drilling mud, which was advantageous. At the same time, they significantly reduced the filtrate volume, the reduction rate of filtrate volume reaching 43.5%.

Table 3. Effect of Temperature and Density on the Lubrication Performance of Drilling Mud

| factor     | COF   |
|------------|-------|
| T (°C)     |       |
| 70         | 0.097 |
| 90         | 0.094 |
| 110        | 0.097 |
| 130        | 0.093 |
| ρ (g cm⁻³) |       |
| 1.4        | 0.094 |
| 1.6        | 0.096 |
| 1.8        | 0.103 |

Figure 20. Micromorphology of the mud cakes of (a) WBM and (b) WBM + PA + PEG.

Figure 21. Effect of different alkali metal ions on the lubrication performance of the system.
(3) Through chelation and hydrogen bonding, PA and PEG formed a tough and thick lubricating film on the surface of the friction pair, which also changed the appearance of solid particles in the mud cake, thereby achieving the purpose of reducing friction.

4. MATERIALS AND METHODS

4.1. Materials. Sodium hydroxide pellets (NaOH, 99.9%) were obtained from Shandong Sun Sheng Chemical Co. Ltd. Wyoming sodium bentonite (Aquagel Gold Seal) was obtained from Shanghai THIOE Mining and Construction Machinery Co., Ltd, China. Polyanionic cellulose (PAC) was obtained from Nanjing Landoil Chemical Co., Ltd. Sodium chloride (NaCl), potassium chloride (KCl), calcium chloride (CaCl2), xanthan gum, lignite resin (SPNH), modified starch (FLOTROL), asphalt resin (LSF), and PA (l) were supplied by Jingzhou Jiahua Technology Co., Ltd. PEG(s) were supplied by Jiangxi Yipu Pharmaceutical Co., Ltd.

4.2. Experimental Procedure. 4.2.1. Drilling Mud Preparation. The drilling mud was prepared by mixing water, PA, NaOH, sodium bentonite, polyanionic cellulose, xanthan gum, modified starch, lignite resin, asphalt resin, and barite, using a high-speed agitator. First, prehydrated bentonite slurry and water were mixed and stirred in proportion for 10 min. Second, xanthan gum was added and stirred for 5 min to increase the viscosity. Third, the filtrate reducers polyanionic cellulose, modified starch, lignite resin, and asphalt resin were added, in turn, and stirred for 20 min. Finally, barite was added to improve the density of the slurry and stirred for 20 min. The drilling mud’s weight was 1.40 g/cm³. Table 4 shows the formulation of WBM used in this study. The basic properties of PA and PEG are shown in Tables 5 and 6, respectively. To simulate the circulation of the drilling mud in the borehole under the actual drilling conditions, all drilling mud samples were aged in a hot rolling oven at 90 °C for 16 h.

4.2.2. Rheological Tests. The rheological properties of the samples were tested using a ZNND 6 rotational viscometer. The hot-rolled drilling mud was stirred at a high speed for 20 min and then heated to 50 °C to determine its rheological properties. The rheological properties including apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) were calculated from the readings of the 600 and 300 rpm dials according to the following formulas obtained by the American Petroleum Institute’s (API) drilling mud evaluation standard procedure.

\[
\begin{align*}
AV (\text{apparent viscosity}) &= 0.5\varphi600, \ (cP) \\
PV (\text{plastic viscosity}) &= \varphi600 - \varphi300, \ (cP) \\
YP (\text{yield point}) &= 0.5(\text{AV} - \text{PV}), \ (lb/100 \text{ ft}^2)
\end{align*}
\]

Gel strength is the shear stress of the drilling mud measured at a low shear rate (3 rpm) after a static period of 10 s and 10 min. 4.2.3. Filtration Testing. 4.2.3.1. API Fluid Loss. The drilling mud was poured into a filter cup, a filter paper was placed on it, and it was covered with a filter cover and pressed tightly. The pressure was quickly pressurized to 100 psi and released into the cup. When the first drop of the filtrate began to appear, the volume of the filtrate was recorded using a stopwatch for 30 min. 4.2.3.2. HTHP Fluid Loss. First, drilling mud was injected into the filter cup, the upper and lower valve stems were closed, and then put into a heating sleeve. Second, the top and bottom regulators were adjusted to 100 psi, respectively. Third, the upper valve stem was opened, the pressure was released into the filter cup, and the pressure was maintained until the required temperature was reached. Finally, when the pressure reached 600 psi, the pressure at the top was increased to 600 psi and the bottom valve was opened simultaneously to start collecting the filtrate for 30 min.

4.2.4. Lubrication Test. The coefficients of friction of drilling mud and mud cake are technical indexes to evaluate the lubrication performance of drilling mud. Friction is related not only to the lubricity of drilling mud and the roughness of the contact surface between the drilling tool and formation but also to the plastic deformation of the contact surface, the size and distribution of the lateral force of the drill string, and the size and rotation speed of the drill string.

The basic principle of most lubricity testers is to measure the sliding coefficient of friction, such as a mud cake stuck factor tester, which is used to measure the “stuck pipe tendency” of the mud cake. Or by measuring the torque between the rotating surface and the stationary surface, such as EP extreme pressure lubricator, it can simulate the torque produced by the wellbore to the rotation of the drill pipe and the resistance to the running in. The lubrication performance test was carried out according to the Chinese standard <Q/SY 17088-2016>.

Lubricity coefficient: The lubricity coefficient was determined with an FANN extreme pressure lubricator. The friction part of the instrument was known as the lubrication ring and slider. During the dynamic friction test, the slider was pressed on a rotating steel ring, and the reading of the coefficient of friction was taken at 150 pounds after 5 min. Since each measurement result did not have the same value, a correction factor of 34 divided by the water reading was used, as shown in eq 4.
Suppose the weight of the slider is \( W \), its component in the inclined plane is \( F_x \), that is friction. Its vertical component is \( P \), that is positive pressure. According to Newton’s law of friction

\[
\begin{align*}
\text{coefficient of friction: } f &= \frac{F_x}{P} = \frac{W \sin \alpha}{W \cos \alpha} = \tan \beta
\end{align*}
\]

It can be seen from the similar triangle relationship that

\[
\angle \alpha = \angle \beta, \text{ then } \tan \alpha = \tan \beta
\]

\( \angle \beta \) is measured by an instrument, and \( \tan \beta \) is the coefficient of friction of the mud cakes; that is, the mud cake stuck factor is measured by the instrument.

4.2.4.2. Antiwear Performances. First, the oil box was filled with water-based drilling mud, and the motor was started to make the bearing rotate and rub against the steel ball. Second, a weight was added every 3 s until the film broke and the bearing locked up. Finally, the motor was turned off, and the steel ball was taken out and kept for the follow-up observation of the wear trace. The antiwear machine is shown in Figure 23.

After the antiwear test, the steel ball was taken off. The wear scar developed on the ball was determined using a microscope to assess the antiwear behavior of the lubricant in the drilling mud.

4.2.5. Microstructural Observations. The wear scar formed on the antiwear steel ball was observed using a scanning electron microscope (SEM) (SU8010, Hitachi, Japan) to evaluate the antiwear performance of the lubricants in the drilling mud. At the same time, mud cakes were characterized using the SEM, which was used to describe the geometry change of solid particles in mud cakes after adding lubricants into the drilling mud, so as to evaluate the effect of lubricants on the lubrication performance of mud cakes.

4.2.6. Drilling Mud Properties. To determine the influence of various property changes of drilling mud on its lubrication performance, density variables, temperature variables, and various alkali metal ion contamination experiments were carried out.

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Notes

The authors declare no competing financial interest. The data used to support the findings of this study are included within the article.

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■ REFERENCES

1. Yeung, J.; Li, J.; Lee, J.; Guo, X. In Evaluation of Lubricants Performance for Coiled Tubing Application in Extended Reach Well, SPE, 2017.

2. Livescu, S.; Craig, S.; Aitken, B. In Coiled Tubing Friction in Extended-Reach Wells, SPE, 2016.
(3) Shen, W. The present situation and consideration of the research on the lubrication performance of drilling mud in extended reach well. *Pet. Drill. Tech.* 2001, 29, 25−28.

(4) Patel, A.; Zhang, J. H.; Ke, M. J.; Panamarithupalyam, B. In Lubricants and Drag Reducers for Oilfield Applications-Chemistry, Performance, and Environmental Impact, SPE, 2013.

(5) Kan, Y. N. Performance evaluation of environmental friendly lubricant for extended reach well. *Oilfield Chem.* 2017, 34, 581−584.

(6) Li, R.; Hou, Y.; Yu, W. Y. Development and evaluation of a cationic synthetic water-based lubricant. *Lubr. Eng.* 2016, 41, 100−104.

(7) Humoooda, M.; Ghamarya, M. H.; et al. Influence of additives on the friction and wear reduction of oil-based drilling mud. *Wear* 2019, 422−423, 151−160.

(8) Guo, B. Y. The influence of the cloud point of polyol on the lubrication and anti sloughing performance of drilling muds. *Pet. Drill. Tech.* 2004, 32, 42−43.

(9) Li, H.; Xiao, H. Z. Application of polyol in drilling muds. *Oilfield Chem.* 2003, 20, 280−284.

(10) Xiao, W. F.; Yue, Q. S.; Xiang, X. J.; Wang, C. J. Study on the mechanism of water-based anti sloughing lubricant. *Deterg. Cosmet.* 2000, 23, 142−145.

(11) Peng, S. P.; Pu, X. L.; Luo, X. S.; Xu, Z. B. Study on the environmental protection performance of PPG drilling muds additive. *Drill. Prod. Technol.* 2004, 27, 94−95.

(12) Ren, S. S.; Lu, H. L. Tribological properties of graphene oxide PEG composites applied on artificial joint. *Acta Mater. Compositae Sin.* 2017, 34, 2598−2604.

(13) Liu, W.; Huang, K.; Rao, X. Y. Study on the composition of leucine and PEG6000. *China J. Chin. Mater. Med.* 2011, 36, 061−2064.

(14) Zhao, W.; Yuan, S.; Yu, P.; Luo, Y. B. Synthesis of the Water Soluble PEG Ester of Phosphate and Its Lubricating Property and Corrosion Behavior. *Lubr. Eng.* 2015, 40, 64−66.

(15) Luo, Y.; Luo, Z. H.; Dang, J. H. Synthesis and performance evaluation of polycarboxylic hydrogel as anti sloughing lubricant for drilling mud. *J. Jpn. Pet. Inst.* 2005, 27, 647−649.

(16) Xu, M. B.; Xu, H. B.; Wang, C. J. Study on a new type of polyol ether lubricant for drilling mud. *Oilfield Chem.* 2002, 19, 301−303+321.

(17) Massey, F. P.; Owen, N. M. Lubricants for Drilling Muds. U.S. Patent US20101590712015.

(18) Alonso-deboltt, M. A.; Bland Ronald, G. Glycol and Glycol Ether Lubricants and Spotting Fluids. U.S. Patent US54953861999.

(19) Kalota, D. J.; Skippy, R. H.; Larry, A. Water Soluble Metal Working Fluids. U.S. Patent US5616541997.

(20) Kalota, D.J.; Spickard, L. A.; Skippy, H. Water Soluble Metal Working Fluids. U.S. Patent US54014281995.

(21) Kalota, D. J.; Chou, Y.; Hirzel, Y.; Timothy, K.; Silverman, D. C. Water Soluble Metal Working Fluids. U.S. Patent US6706702004.

(22) Mao, H. Research on the Technology of Ultra-high Temperature and Ultra-high Density Water Based Drilling mud. *China University of Petroleum* 2017, 16−19.

(23) Xuan, Y.; Qian, X. L.; Lin, Y. X.; et al. Research progress and development trend of water based drilling mud lubricants. *Oilfield Chem.* 2017, 34, 721−726.

(24) Zhao, J. B.; Wei, J.; Tan, T. W. Progress in research and application of Polyspartate hydrogel. *Chem. Ind. Eng. Prog.* 2019, 38, 3355−3364.

(25) Yao, R. G.; Zhang, Z. H. Status Quo of Methods for Evaluating Filtration Performance and Mud Cake Quality of Drilling mud. *Drill. Fluid Completion Fluid* 2016, 33, 1−9.

(26) Zhao, S. L. Study and performance evaluation of glycerol based drilling mud with strong inhibition and high smoothness. *Pet. Drill. Tech.* 2020, 1−9.

(27) Zhao, S. L. Study and performance evaluation of glycerol based drilling mud with strong inhibition and high lubricity. *Pet. Drill. Tech.* 2020, 48, 56−62.

(28) Xiao, H.; Liu, S. H.; Chen, Y.; Han, D. X.; Wang, D. G. Impacts of polypropylene glycol (PPG) additive and pH on tribological properties of water based drilling mud for steel-steel contact. *Tribol. Int.* 2017, 110, 318−325.

(29) Wang, B.; He, Y. W. Study on Synthesis of multifunctional polyethylene glycol. *Chem. Propellants Polym. Mater.* 2010, 8, 46−48.

(30) Müller, M. T.; Yan, X.; Lee, S.; Perry, S. S.; Spencer, N. D. Lubrication properties of a brushlike copolymer as a function of the amount of solvent absorbed within the brush. *Macromolecules* 2005, 38, 5766−5773.

(31) Yunita, P.; Irwan, S.; Kania, D. Evaluation of non-ionic and amionic surfactants as additives for water-based drilling mud. *Am. J. Chem.* 2015, 5, 52−55.

(32) Kania, D.; Yunus, R.; Omar, R.; Rashid, S. A. Nonionic polyol esters as thinner and lubrication performance enhancer for synthetic-based drilling muds. *J. Mol. Liq.* 2018, 266, 846−855.

(33) Saffari, H. R. M.; Soltani, R.; Alaee, M.; Soleymani, M. Tribological properties of water-based drilling muds with borate nanoparticles as lubricant additives. *J. Pet. Sci. Eng.* 2018, 171, 253−259.

(34) Sümeza, A.; Kökb, M. V.; Özel, R. Performance analysis of drilling mud liquid lubricants. *J. Pet. Sci. Eng.* 2013, 106, 64−73.

(35) Wen, S. Z.; Huang, P. *Principle of Tribology*, 3rd ed.; Tsinghua University Press: Beijing, 2008; pp 25−27.

(36) Pan, X. Y. Discussion on testing method of lubricating property of drilling mud. *Drill. Fluid Completion Fluid* 1992, 9, 67−71.