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Biodegradable Lubricant with High-Temperature and Ionic-Contamination Resistance: Deep Eutectic Solvent ChCl-PEG

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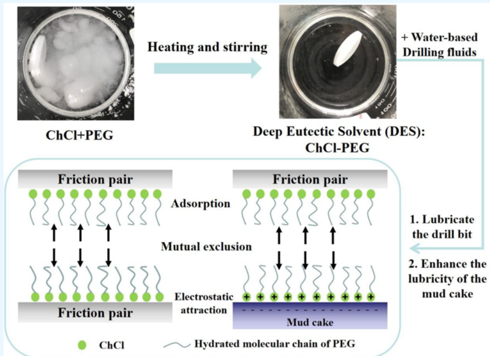
ABSTRACT: Drilling fluid lubricants guarantee safe and fast drilling. When drilling high-temperature or $NaCl/CaCl_2$-containing formations, there is an urgent need to develop environmentally friendly lubricants that are resistant to high temperature and ionic contamination. In this study, a deep eutectic solvent (DES) ChCl-PEG lubricant for a water-based drilling fluid was designed and prepared. ChCl-PEG is a kind of biodegradable material with high thermal stability formed by hydrogen bonding between choline chloride (ChCl) and polyethylene glycol (PEG). Within 240 °C, ChCl-PEG significantly improved the lubricating properties of drilling fluids and mud cakes. The lubrication coefficient (K) was controlled within 0.2, and the reduction rate of the adhesion coefficient (Δf) was higher than 40%. The salt and calcium resistances of ChCl-PEG at high temperature (150 °C) are as high as 36% NaCl and 20% $CaCl_2$. Under these conditions, ChCl-PEG maintains a low value of K: 0.097−0.157 (5−36% NaCl) and 0.145−0.162 (5−20% $CaCl_2$), respectively. Also, it maintains higher values of Δf, which can reach up to 51.6% and 80%. The lubricating mechanism of ChCl-PEG can be summarized as the adsorption of ChCl and the formation of a large number of hydrated molecules.



1. INTRODUCTION

In the process of high-temperature deep drilling, with an increase in the depth of well, the lifting and rotation drag of the drill string increases greatly. When drilling into a formation with strong abrasiveness and poor drillability, the drilling tool seriously wears. Adding a high-quality lubricant to drilling fluid to reduce friction and torque and protect drilling tools is a guarantee of safe and rapid drilling.[1,2] Lubricants for drilling fluids include solid and liquid types. Solid lubricants are mainly spherical inert materials, which reduce friction by converting sliding friction into rolling friction, such as glass beads,[3] carbon pellets,[4] elastic graphite,[5] etc. Solid lubricants are easily removed by solid control equipment and are easily damaged and deformed by the extrusion of the drill pipe; thus, they are subject to certain restrictions.[6]

Traditional liquid lubricants are mineral oils, surfactants, vegetable oils, polyol lubricants, etc.[7,8] Mineral oils contain harmful substances such as aromatic hydrocarbons and long-chain alkanes. With the increasingly strict environmental regulations, it has been gradually replaced by environmentally friendly lubricants.[1] Surfactant lubricants are mostly anionic type surfactants containing sulfonic acid groups, which will demulsify or fail under high cation conditions. Also, they are thermally decomposed at high temperatures and generate sulfur dioxide.[9] In contrast, vegetable oil lubricants are environmentally friendly and nontoxic and have good lubricity. Researchers have modified vegetable oils through amidation and transesterification[10,11] or compounded them with extreme-pressure elements (N, P, B, etc.), polyols, surfactants, etc. to further improve their lubricating performance.[12,13]

Hao et al. reacted modified vegetable oil with polyhydroxy-amine and then compounded it with anionic surfactants to obtain RY-838. RY-838 is a low-fluorescence lubricant with a temperature resistance of 160 °C, and the reduction rate of the lubrication coefficient in water-based drilling fluids can reach 86%.[14] Modified vegetable oil was obtained through the aminolysis of the vegetable oil and reaction with a low carbonic acid, and the temperature resistance reached 170 °C.[15] However, vegetable oil lubricants are easily crystallized at low temperatures and have fluorescence, which will interfere with the well logging. With an increase in drilling depth and bottom hole temperature, scholars have gradually developed polyol lubricants with higher temperature resistance. Lv et al. obtained the polyether polyol lubricant SYT-2 through the copolymerization of ethylene oxide and propylene oxide. SYT-2 is an environmentally friendly material with no fluorescence,

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no biotoxicity, and easy biodegradation. The reduction rate of the lubrication coefficient exceeds 80%, but its temperature resistance is low (≤120 °C).[16] Qian et al. synthesized the environmentally friendly water-based lubricant SMLUB-E by using natural fatty acids and polyols. The temperature resistance of SMLUB-E was up to 160 °C.[17] Li et al. synthesized the polyol lubricant SDL-1 by using a long-chain fatty acid, a small-molecule polyol, and an extreme pressure agent containing sulfur. SDL-1 provided a low shear resistance interface by forming an adsorption film on the contact surface, which greatly reduced friction and had high-temperature resistance and salt resistance (180 °C, 30% NaCl and 30% $CaCl_2$).[18] The nontoxic, low-fluorescence lubricant NH-JZ was developed by using long-chain polyol amines and various active elements. As reported, the temperature resistance of NH-JZ can reach up to 200 °C, and it has good compatibility with various water-based drilling fluid systems.[19]

The environmental properties and temperature resistance of traditional lubricants have been continuously improved and innovated; however, lubricants with high-temperature resistance (>200 °C), salt resistance, calcium resistance, environmental protection, nontoxicity, and nonfluorescence are still in short supply. Therefore, the development of new materials with lubricating properties is still challenging work.

At present, the lubricating properties of novel nanomaterials,[20−22] ionic liquids (ILs),[23−27] and deep eutectic solvents (DESs) have attracted much attention. Among them, a DES is a novel nontoxic and biodegradable solvent, which was first discovered by Professor Abbott at the University of Leicester in 2003. Researchers noted an abnormally deep melting point depression at the eutectic composition of certain hydrogen bond donors (HBDs) and acceptors (HBAs).[28] It reportedly melts to a transparent and uniform liquid at a low enough temperature so as to make the novel liquids economically accessible as solvents and/or electrolytes for new and existing chemistries, which shows good prospects in many fields, such as extraction and separation, electrodeposition, synthetic catalysis, material preparation, etc.[29−31]

A wide selection of raw materials makes DESs designable, and products that meet specific needs can be obtained by optimizing raw materials and ratios. The majority of DESs that have been reported thus far are traditionally classified as type I, which combines a quaternary ammonium salt and a metal chloride, type II, consisting of a quaternary ammonium salt and a metal chloride hydrate, type III, consisting of a quaternary ammonium salt and an HBD (typically an organic molecular component such as a carboxylic acid, amino acid, polyol, etc.), type IV, consisting of a metal chloride hydrate and HBD, and type V, which is a relatively new class composed of only nonionic, molecular HBAs and HBDs. Among them, most studies tend to favor type III.[28,32,33] In this study, a DES was designed with the main goal of improving the lubricity of the drilling fluid. Choline chloride (ChCl) is a low-cost, environmentally friendly, and nontoxic small-molecule organic ammonium salt, and it is also the earliest material used to prepare a DES with crystalline urea.[29,34] Also, ChCl as an HBA can provide a large amount of positive charge, which is expected to play an adsorption role. Polyethylene glycol (PEG) was chosen as the HBD. Jiang et al. used PEG to form PEGylated DES in 2017.[35] In addition, PEG exhibits low friction properties in aqueous environments.[36] The deep eutectic solvent ChCl-PEG was prepared and characterized. Then, its lubricating properties in water-based drilling fluids under high-temperature, high-salt, and high-calcium conditions were comprehensively evaluated. The lubricating mechanism of ChCl-PEG is discussed.

2. MATERIALS AND METHODS

2.1. Materials. Choline chloride (ChCl, AR, 98%) was a commercial product from Shanghai Aladdin Biochemical Technology Co., Ltd. (Shanghai, China). Polyethylene glycol with a molecular weight of 200 (PEG, CP) was purchased from Sinopharm Chemical Reagent Co., Ltd. EST is a self-made modified starch polymer with high-temperature resistance, and its detailed synthesis method is given in the previous literature.[37] Bentonite for preparing base mud was purchased from Weifang Boda Bentonite Co., Ltd.

2.2. Methods. *2.2.1. Preparation of ChCl-PEG.* The most common preparation method for a DES is heating and stirring until a homogeneous liquid is formed. Other methods include vacuum evaporation, grinding, and freeze-drying. During the process, no additional solvent is needed, and no reaction in the traditional sense occurs. Consequently, no purification steps are required.[28]

ChCl was mixed with PEG in a mass ratio of 7:20, stirred, and heated at 60 °C for 2 h. Then, as shown in Figure 1, a clear and homogeneous liquid product was formed and named ChCl-PEG. It is worth noting that the proportion of ChCl and PEG is not random. The research of Jiang et al. provided a range of ratios for DES synthesis.[38] The ratio used in this study was optimized according to the lubrication properties of the product.

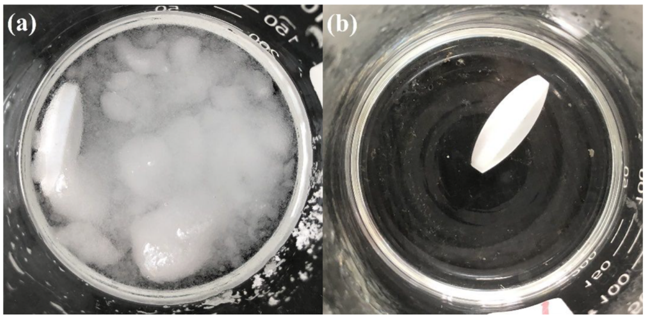

Figure 1. Preparation of ChCl-PEG: (a) before reaction; (b) after reaction.

2.2.2. FT-IR and ^1H NMR. ChCl, PEG, and ChCl-PEG were characterized by Fourier infrared spectroscopy (FT-IR) and hydrogen nuclear magnetic resonance spectroscopy (^1H NMR). The sample was directly put into an infrared spectrometer (Model Bruker vertex70) for the FT-IR test, without a potassium bromide tablet pressing method. The scanning wavenumber range was 4000−600 cm^{-1}. The sample (2 mg) was dissolved in deuterated chloroform ($CDCl_3$) and tested in a hydrogen nuclear magnetic resonance spectrometer (JNM-ECA600v).

2.2.3. Thermogravimetric Analysis (TGA). A differential thermal thermogravimetric analyzer (Model TGA Q5000) was used to investigate the thermal stabilities of ChCl, PEG, ChCl-PEG under a nitrogen atmosphere at a heating rate of 10 °C min^{-1} with a temperature range of 30−380 °C.

2.2.4. Biodegradability. According to the Chinese Standard "SY/T 6788−2020 Evaluation method for environmental protection technology of water-based oilfield chemicals", the

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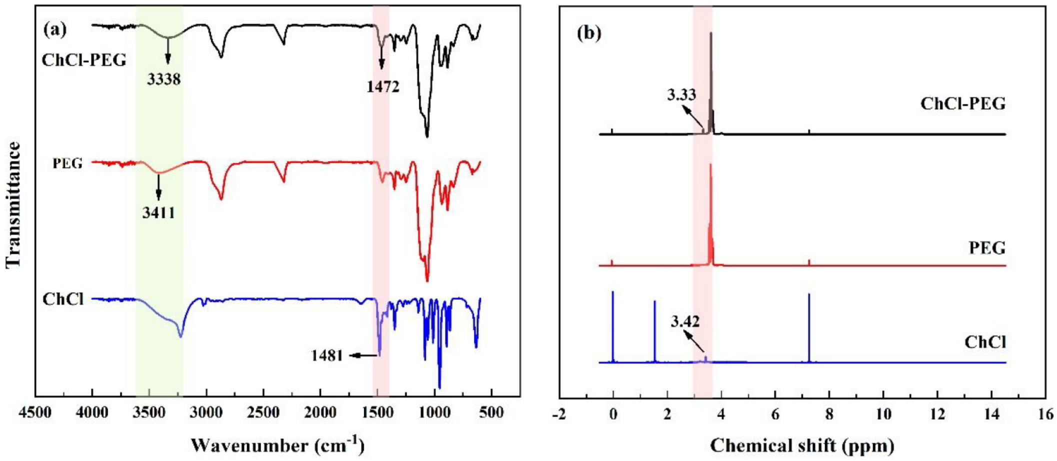

Figure 2. FT-IR and ^{1}H NMR spectra of ChCl-PEG: (a) FT-IR; (b) ^{1}H NMR.

biodegradability of CHCl-PEG was tested by the BOD_5/COD ratio method. BOD refers to the total amount of dissolved oxygen consumed by the oxidation and decomposition of organic matter in the biochemical action of microorganisms to make it gaseous or inorganic. In this study, a dilution inoculation method was used to test the BOD_5 value (oxygen consumption 95%) of the sample for 5 days. A chemical oxidant (dichromate) was used to oxidatively decompose the oxidizable substances in the water, and the chemical oxygen demand (COD) was calculated according to the content of the residual oxidant.

2.2.5. Lubricity Test. The lubrication performance of drilling fluid includes the lubricity of the fluid and the lubricity of the mud cake. The extreme pressure lubrication coefficient and mud cake adhesion coefficient are two main technical indexes to evaluate the lubricity of drilling fluid, which were evaluated by an extreme pressure lubricator (Model EP) and a mud cake adhesion coefficient instrument (Model NF-2), respectively.

In the extreme pressure lubricator test method, the instrument was turned on, the speed was adjusted to 60 rpm, and the idled for 5 min. First, distilled water was poured into the sample cup, and the lubrication coefficient was 29.0; thus, the correction coefficient of the device was 1.1724. Then, the distilled water was replaced with the test sample, and the friction block and the friction ring were completely immersed. A torque wrench was adjusted to a pressure of 150 psi, and the friction coefficient (M) after the instrument ran for 5 min was recorded

$$\text{friction coefficient } (M) = \text{friction coefficient reading}/100 \tag{1}$$

$$\text{lubrication coefficient } (K) = 1.1724 \times M \tag{2}$$

$$\text{reduction rate of lubrication coefficient } (\Delta K) = (K_0 - K_1) \times 100\%/K_0 \tag{3}$$

where K_0 is the K value of the drilling fluid without lubricant and K_1 is the K value of the drilling fluid with lubricant added.

The sample was poured into an adhesion coefficient instrument and nitrogen gas was injected to make the difference pressure 3.5 MPa. After the drilling fluid was filtered for 30 min, a complete mud cake could be obtained on the filter screen of the equipment. Then, a pressure rod was used to make sure the sticking plate and the mud cake were fully stocked. Finally, the maximum torque value (N) when the mud cake started to slide was recorded

$$\text{adhesion coefficient } (f) = \text{maximum torque } (N) \times 0.845/100 \tag{4}$$

$$\text{reduction rate of adhesion coefficient } (\Delta f) = (f_0 - f_1) \times 100\%/f_0 \tag{5}$$

where f_0 is the f value of the drilling fluid without lubricant and f_1 is the f value of the drilling fluid with lubricant added.

The relevant parameters were calculated according to eqs 1–5.

3. RESULTS AND DISCUSSION

3.1. Characterization of ChCl-PEG. *3.1.1. FT-IR and ^{1}H NMR.* The FT-IR and ^{1}H NMR spectra of CHCl-PEG were compared with those of PEG and CHCl, and the interaction between PEG and CHCl was analyzed. As shown in Figure 2a, after the synthesis of CHCl-PEG, the characteristic peak of hydroxyl (−OH) in PEG shifted from 3411 cm^{-1} to the lower wavenumber 3338 cm^{-1}. The bending vibration absorption peak of methylene ($-CH_2-$) in CHCl shifted from 1481 to 1472 cm^{-1}. Figure 2b shows that the chemical shift of CHCl shifted from 3.42 ppm to a lower value of 3.33 ppm in the ChCl-PEG spectrum. All of these results prove that the deep eutectic solvent CHCl-PEG has been successfully prepared by using CHCl and PEG through hydrogen bond interactions.[39,40]

3.1.2. Thermogravimetric Analysis. As shown in Figure 3a, almost no thermal decomposition occurred in ChCl within 260 °C, and the sample retention rate wasis higher than 97%. At 260−320 °C, strong decomposition occurred to generate CO_2, H_2O, HCl, and other products, and the sample weight was greatly reduced. The sample retention rate was less than 3% at 320 °C. PEG has poor thermal stability. When the heating temperature was higher than 160 °C, severe chain fragmentation and pyrolysis occurred, resulting in a sudden decrease in sample quality. The sample retention rates at 160, 200, and 240 °C were 90.2%, 68.2%, and 20.6%, respectively.

As reported, DESs generally first decompose to HBDs and HBAs at high temperatures through a weakening of the hydrogen bond interactions. Subsequently, HBDs with relatively low boiling points or poor stabilities undergo

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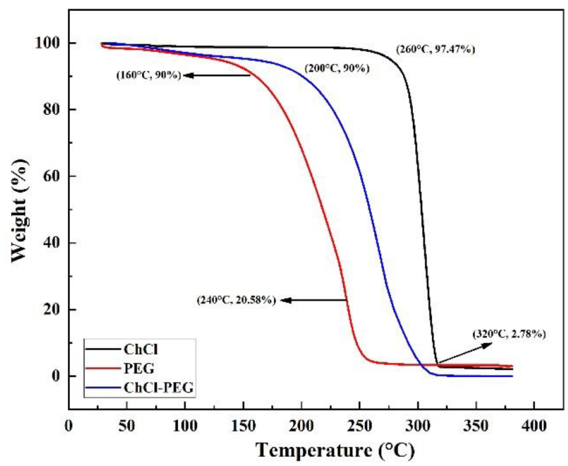

Figure 3. TGA curves of ChCl, PEG, and ChCl-PEG.

volatilization or decomposition. This conclusion also could be drawn from an investigation of ChCl-PEG.[41] The thermal stability of ChCl-PEG is between those of ChCl and PEG. The formation of hydrogen bonds significantly improves the thermal stability of the raw material PEG. The product ChCl-PEG can maintain high thermal stability within 200 °C, and the retention rate of ChCl-PEG at 200 °C was 90.0%. At 200−240 °C, although partial hydrogen bond fracture and thermal decomposition of PEG occurred, ChCl-PEG still maintained a high sample retention rate, which was 71.2% at 240 °C. When the temperature was increased above 260 °C, the raw material ChCl began to decompose violently. At the end of the test (380 °C), the sample almost completely decomposed, and the retention rate was close to 0.

The onset temperature of the TGA curve is often used to define the thermal stability of materials. However, previous studies found that the onset temperature may lead to an overestimation of the upper operation limit.[41−43] That is to say, DESs may degrade at a temperature significantly lower than the onset temperature within a long period. Consequently, it is necessary to investigate the long-term thermal stability of DESs, especially for industrial applications. In this study, the temperature resistance of CHCl-PEG was investigated by aging at high temperature for 16 h.

3.1.3. Biodegradability. The biodegradability evaluation index (Y) was calculated by eq 6. If $Y < 5.0$, the material is difficult to degrade, if $5.0 \leq Y < 25.0$, the material is degradable, and if $Y \geq 25.0$, the material is easily degradable.[44] As Table 1 shows, the Y value of CHCl-PEG is 34.81, higher than 25. Therefore, CHCl-PEG is a biodegradable material.

$$Y = (BOD_5/COD) \times 100 \quad (6)$$

Table 1. Biodegradability of ChCl-PEG

sample	BOD_5	COD	Y
ChCl-PEG	99.2	285	34.81

3.2. Lubricity Evaluation of ChCl-PEG. *3.2.1. High-Temperature Resistance.* The control group was prepared with 3% bentonite mud and 3% EST. Then 1−5% ChCl-PEG was added to the control group for the experimental groups. After the drilling fluid was agedat 120−240 °C for 16 h and taken out, the lubrication coefficient (K) and the adhesion coefficient (f) were tested. The reduction rates of the lubrication coefficient (ΔK) and that of the adhesion coefficient (Δf) were calculated according to eqs 3 and 5.[45,46]

Figure 4 shows the changes in the K value and the ΔK value of the drilling fluid after aging at different temperatures with the dosage of ChCl-PEG. At 120−240 °C, ChCl-PEG effectively reduced the K value of the drilling fluid, with ΔK ranging from 9.00% to 40.61%. It can be seen from Figure 4a that the K value of the control group at high temperature is much higher (0.18−0.26). After 1% ChCl-PEG was added, the K value significantly decreased to 0.16−0.21. With an increase in ChCl-PEG, the K value continuously decreased and the ΔK value increased. When the concentration of ChCl-PEG was 3%, the K value of drilling fluid could be controlled to be 0.17 at 200 °C and lower than 0.19 at 240 °C; when the dosage of ChCl-PEG was increased to 5%, the K value of the drilling fluid was less than 0.18 at 240 °C. To sum up, ChCl-PEG had a lubricating effect in an aging temperature range of at least 240 °C, which significantly reduced the extreme pressure lubrication coefficient of the drilling fluid and made it meet the lubricity requirements of water-based drilling fluids ($K < 0.2$).[47]

As shown in Figure 5, compared with the control group, the addition of ChCl-PEG significantly reduced the f value of the mud and had a high value of Δf. At 120−240 °C, the f value of the drilling fluid decreased from 0.06−0.19 to 0.04−0.11 after adding 1% ChCl-PEG, and the value of Δf was higher than 40%. When the concentration of ChCl-PEG was increased to 2%, the f value of the drilling fluid was lower than 0.10, and the Δf value was higher than 50%. When the dosage of ChCl-PEG was ≥3%, the drilling fluid had a low f value ($f < 0.08$) at 240 °C, and the Δf value was between 54.48% and 65.71%.

According to the Chinese standard "Q/SY 17088−2016 Technical Specifications for Liquid Lubricants for Drilling Fluids",[48] a lubricant that reduces the value of the adhesion coefficient by more than 50% meets the standard. Therefore, ChCl-PEG is a liquid lubricant for a water-based drilling fluid that can be used in a wide high-temperature range (at least 240 °C). When the aging temperature is at 200 °C, the amount of ChCl-PEG should be ≥2%. At 200−240 °C, the dosage of ChCl-PEG should be ≥3%.

3.2.2. Ca^{2+}/Na^+ Contamination Tolerance. The control group was prepared by adding 5%, 10%, 15%, 20%, 25%, 30%, or 36% NaCl or 5%, 10%, 15%, or 20% $CaCl_2$ to the base mud containing 3% EST. The experimental group was prepared by adding 3% ChCl-PEG to the control group. Then the lubricity of the prepared mud was tested after aging at 150 °C for 16 h.

Figure 6a shows the variation of the K value with the concentration of NaCl. It can be seen that, with the increase of NaCl concentration, the K value of the control group gradually increased and the lubricity of the polymer-containing base mud decreased. For the experimental group, on the one hand, the addition of NaCl reduced the lubricity of the polymer. Thus, when the concentration of NaCl was less than 20%, the K value slightly increased with an increase in NaCl. On the other hand, ChCl-PEG has a synergistic effect with NaCl. When the concentration of NaCl was higher than 20%, the synergistic effect between NaCl and ChCl-PEG was more prominent than the inhibitory effect of NaCl on the polymer. At this time, the K value of the experimental group increased. When the concentration of NaCl was higher than 25%, the K value was lower than 0.1. As shown in Figure 6b, the K value of the experimental group containing 3% ChCl-PEG was always

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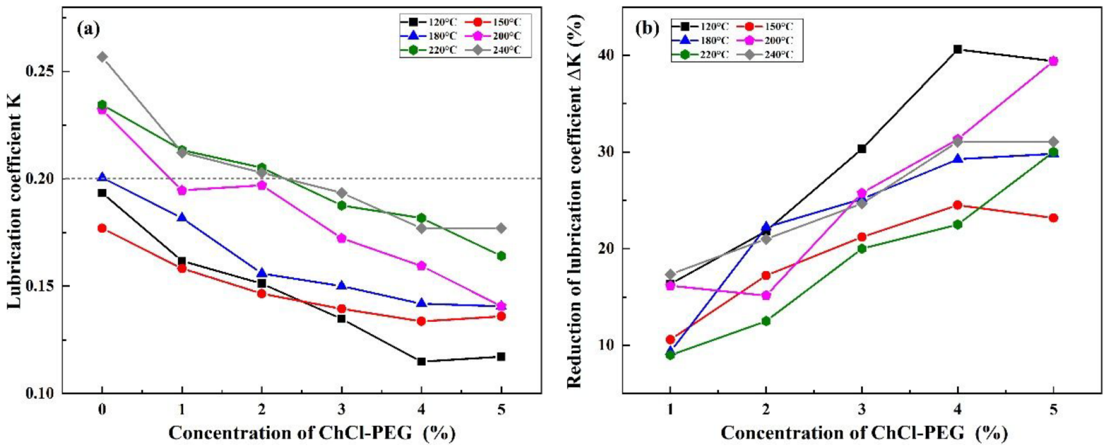

Figure 4. Changes of K and ΔK values with the addition of ChCl-PEG at different temperatures: (a) lubrication coefficient K; (b) reduction rate of lubrication coefficient ΔK.

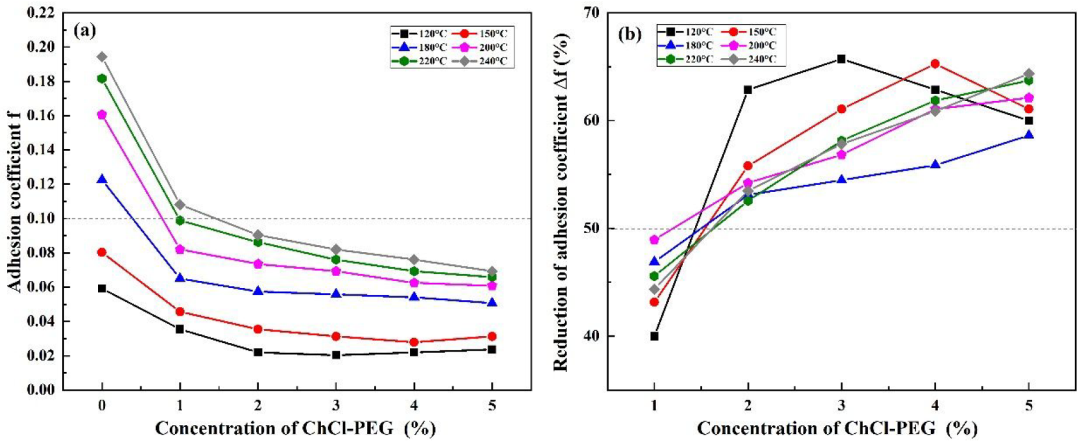

Figure 5. Changes of f and Δf values with the addition of ChCl-PEG at different temperatures: (a) adhesion coefficient f; (b) reduction rate of adhesion coefficient Δf.

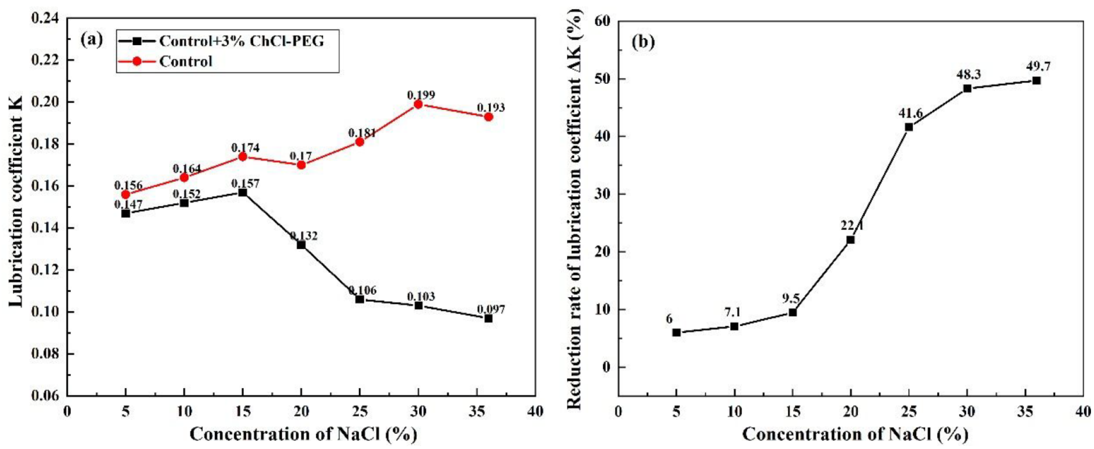

Figure 6. Changes of K and ΔK values of drilling fluid without/with 3% ChCl-PEG after aging at 150 °C with the concentration of NaCl: (a) K; (b) ΔK.

lower than that of the control group, and the reduction rate of the lubrication coefficient (ΔK) increased significantly from 6.0% to 49.7% with the increase of NaCl concentration.

Figure 7a shows that the K value of the control group increased with an increase in $CaCl_2$ concentration, and the K value of the mud containing $CaCl_2$ (0.18−0.25) was higher than that of the NaCl-containing system (0.16−0.19). Therefore, $CaCl_2$ has a more significant inhibitory effect on the lubricity of the control group. The extreme pressure lubricity of the drilling fluid was significantly improved in the experimental group, and ChCl-PEG also showed a synergistic effect with $CaCl_2$. As the concentration of $CaCl_2$ was increased from 5% to 20%, the K value fluctuated between 0.145 and

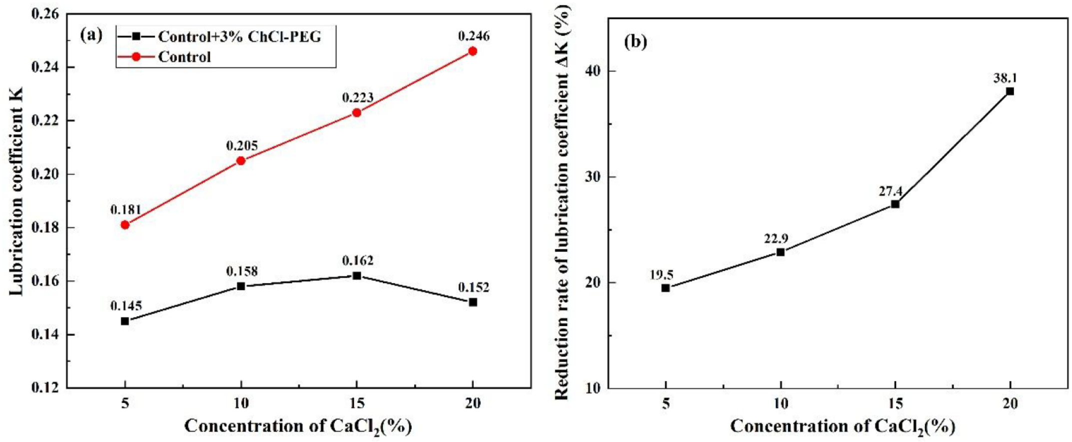

Figure 7. Changes of K and ΔK values of drilling fluid without/with 3% ChCl-PEG after aging at 150 °C with the concentration of $CaCl_2$: (a) K; (b) ΔK.

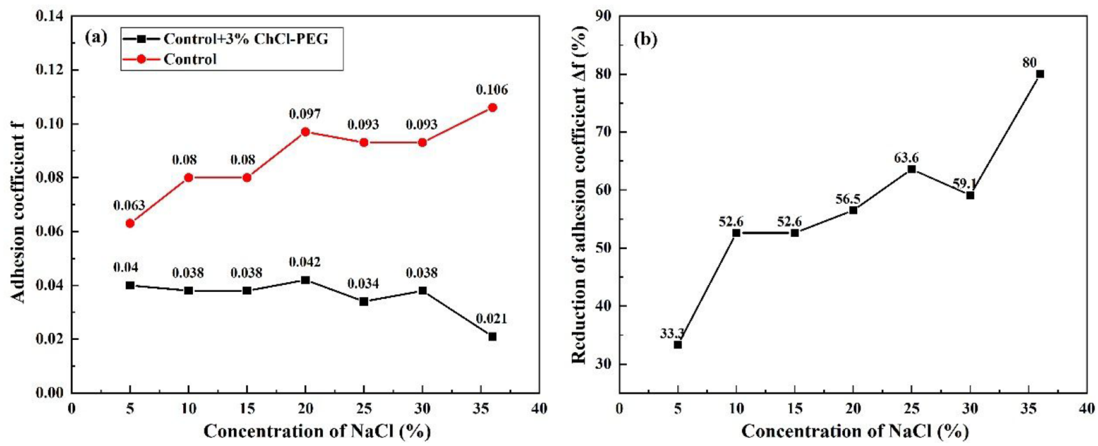

Figure 8. Changes of f and Δf values of drilling fluid without/with 3% ChCl-PEG after aging at 150 °C with the concentration of NaCl: (a) f; (b) Δf.

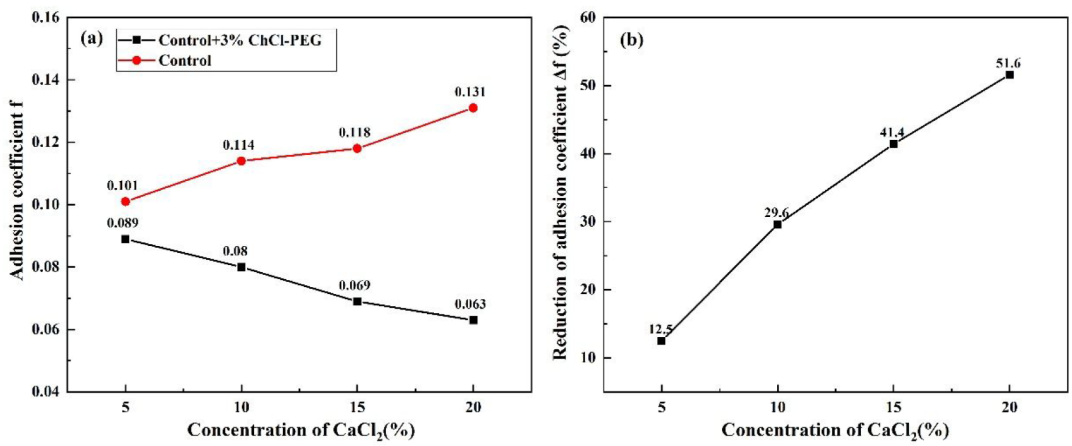

Figure 9. Changes of f and Δf values of drilling fluid without/with 3% ChCl-PEG after aging at 150 °C with the concentration of $CaCl_2$: (a) f; (b) Δf.

0.162. Compared with the control group, ΔK increased from 19.5% to 38.1%.

Figures 8a and 9a show the changes of the f value with the concentration of NaCl/$CaCl_2$, respectively. It can be seen that with an increase in the concentration of NaCl/$CaCl_2$, the f value of the control group showed an upward trend, while the f value of the experimental group containing 3% ChCl-PEG gradually decreased. In other words, NaCl/$CaCl_2$ reduced the lubricity of the mud cake of the control group. After 3% ChCl-PEG was added, the lubricity of mud cakes improved.

Figures 8b and 9b show that the Δf value of the experimental group at high temperature and concentration of NaCl/$CaCl_2$ was positive: that is, the lubricity of the mud cake in the experimental group was always higher than that of the

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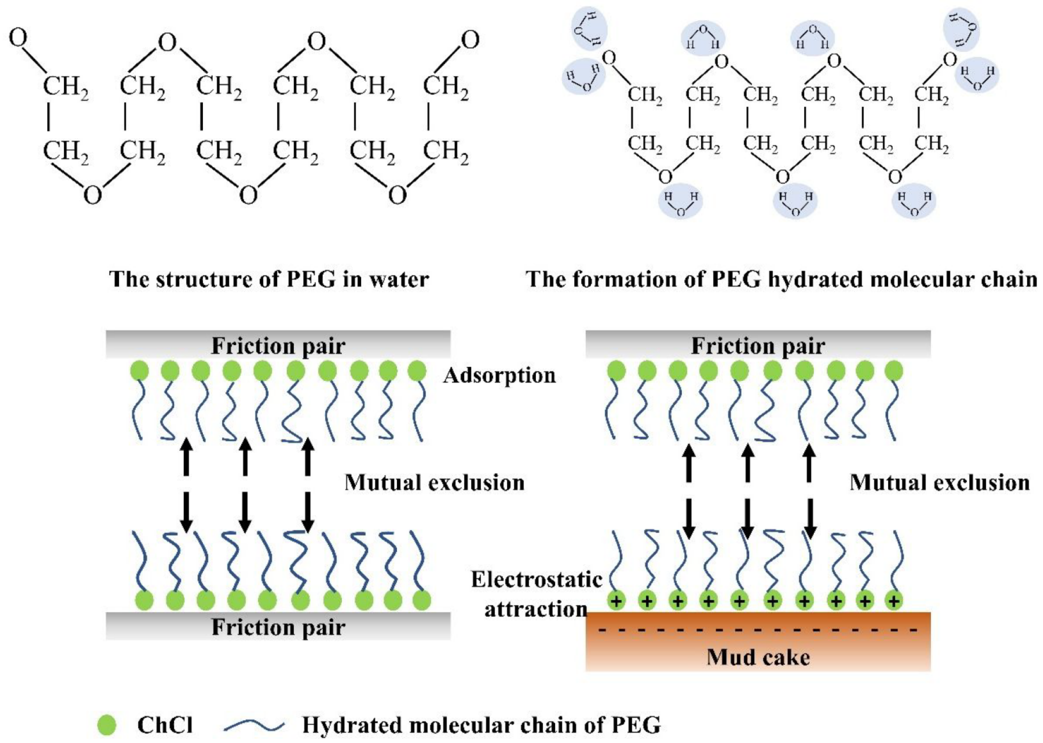

Figure 10. Schematic diagram of the lubrication mechanism of ChCl-PEG.

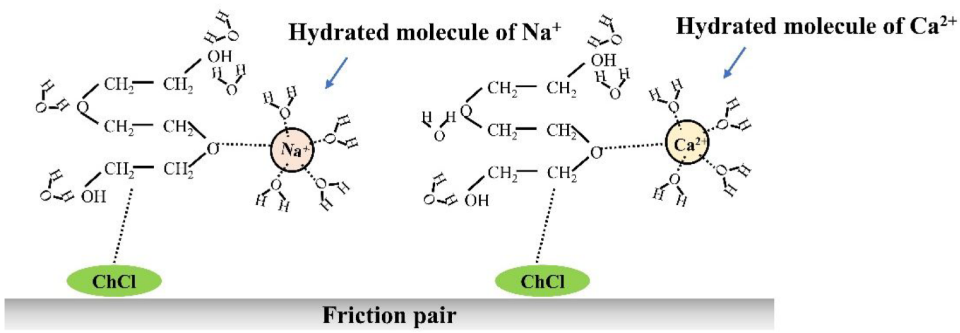

Figure 11. Schematic diagram of the synergistic mechanism of ChCl-PEG and $NaCl/CaCl_2$.

control. With an increased concentration of $NaCl/CaCl_2$, the Δf value gradually increased, which further indicated that ChCl-PEG had a synergistic effect with $NaCl/CaCl_2$.

In short, both NaCl and $CaCl_2$ have inhibitory effects on the lubricity of the polymer-containing base mud, and the effect of $CaCl_2$ is more significant than that of NaCl. ChCl-PEG significantly improves the lubricity of the polymer-based slurry system. The values of K and f at high temperature and s high concentration of $NaCl/CaCl_2$ were effectively reduced. Also, ChCl-PEG exhibited a synergistic effect with $NaCl/CaCl_2$. The values of ΔK and Δf both increased gradually with an increase in $NaCl/CaCl_2$.

3.3. Discussion on the Mechanism of Lubrication.

Figure 10 is a schematic diagram of the lubrication principle of the deep eutectic solvent ChCl-PEG. On one end of ChCl-PEG, CHCl has a large number of positive charges and can be adsorbed on the metal surface.[49,50] The main clay mineral forming the mud cake is montmorillonite. Montmorillonite has a layered crystal structure composed of two Si−O tetrahedra and one Al−O octahedron, in which Al^{3+} will undergo lattice substitution with Mg^{2+}, resulting in residual negative charges. Thus, ChCl will also be adsorbed on the surface of negatively charged clay particles through an electrostatic interaction. On the other end of ChCl-PEG, PEG contains hydrophilic groups (hydroxyl and ether bonds), which can combine with water molecules to form a hydrated molecular chain and extend to form a "bottle brush".[51] When the friction pairs (spindles and sliders, mud cake and adhesive disk) are close to each other, the polymer hydrated molecular chains will first contact and repel each other. Thereby a good boundary lubrication effect is achieved and the friction coefficient is effectively reduced.

The results show that ChCl-PEG has a good lubricating effect in high-temperature, high-salt, and high-calcium environments, improving the lubricity of the drilling fluid system and mud cake. What is more, ChCl-PEG has a synergistic effect with a high concentration of Na^+/Ca^{2+}. The lubricating effect of ChCl-PEG is enhanced with an increase in cation concentration. As shown in Figure 11, Na^+/Ca^{2+} in the solution can combine with water molecules to form hydrated molecules and interact with PEG hydrated molecular chains to enhance the stability of the hydrated molecular layer.[51] In addition, there are microscopic troughs on the surface of the friction pair, especially the mud cake, which can store the hydrated molecules formed by ChCl-PEG/Na^+/Ca^{2+}. As the concentration of NaCl/$CaCl_2$ increases, the number of hydrated molecules in the interlayer and the valleys increase. Molecular layers are constantly destroyed and replenished, thus exerting good lubrication and synergistic effects.[52]

4. CONCLUSION

In this paper, ChCl-PEG was shown to be a biodegradable lubricant for a water-based drilling fluid and has a resistance to high temperature (≤240 °C), salt (150 °C aged, 0−36% NaCl), and calcium (150 °C aged, 0−20% $CaCl_2$). Under the above conditions, the lubrication coefficient (K) of ChCl-PEG-containing drilling fluids was effectively controlled within 0.2, and the Δf value of the mud cake exceeded 12.5%. The lubrication mechanism of ChCl-PEG is attributed to the adsorption of ChCl and the formation of a large number of hydrated molecules. In summary, ChCl-PEG is an environmentally friendly water-based lubricant, which has good application potential in deep complex oil/gas or high-temperature geothermal drilling engineering.

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Notes

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