ACS OMEGA

http://pubs.acs.org/journal/acsodf

Article

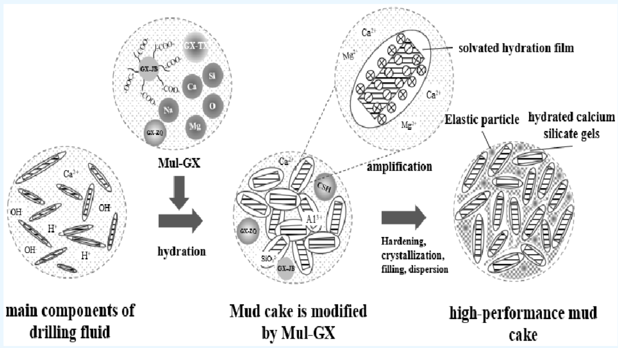
Mud Cake Improver Mul-GX with Lubrication and Interface Enhancement Effect and Its Action Mechanism

Jianwei Zhang, Mengna Liang, Fuping Feng,* Yang Yu, Kun Zhang, and Xu Han

Cite This: *ACS Omega* 2024, 9, 20223−20230

Read Online

ABSTRACT: In view of the problems in which the solid content of drilling fluid increases in the middle and late stages of horizontal well drilling, the lubricity of mud cakes on the borehole wall decreases, and the friction of pipe string increases due to the gradual thickening of mud cakes, which leads to the sticking and the obvious decrease of cementing strength at the second interface, a mud cake improver Mul-GX with lubrication and interface enhancement effect was studied in this paper. Based on the hydration and filling mechanism, the lubricity of the mud cake was improved, its thickness was reduced, and its strength was improved through synergistic effects of solvated water film lubrication and buffering, hardening and crystallization of gelled substances, and filling and dispersion of elastic particles. The mud cake improver Mul-GX is composed of the metasilicate GX-ZQ, polymer copolymer GX-JB, and polymer GX-TX, and the mass ratio of each component was GX-ZQ: GX-JB: GX-TX = 15:1:0.5. The effect of Mul-GX was evaluated through the performance determination of the mud cake and interface cementing simulation experiments. In addition, the microscopic characterization by SEM and XRD were carried out to analyze the mechanism of Mul-GX. The experimental results showed that when Mul-GX was added to the water-based drilling fluid with the 1.0%−1.5% adding quantity, the mud cake lubricity improved by more than 60%, its thickness reduced by 53.9% on average, and its strength increased by 54.3% on average. At the same adding quantity, the interfacial bonding strength was 4.4 times more than the data before adding Mul-GX. All of the results showed that Mul-GX has obvious mud cake lubrication effect and interface enhancement effect.

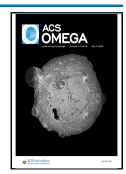


1. INTRODUCTION

Horizontal well technology is a key technology in drilling and completion engineering, which has great advantages in improving single well production and economic benefits, and has gradually become the main development direction in the field of oil and gas development.[1,2] When horizontal wells are drilled to the middle and late stages, the solid-phase content in drilling fluid gradually increases, causing an increase in the thickness and a decline in the lubricity of wellbore mud cake resulting in a significant increase in horizontal friction, which is prone to problems such as sticking.[3−7] Also, the increase in thickness of wellbore mud cake highlights the phenomenon of weak cementing interfaces, leading to a decrease in cementing strength at the second interface, seriously affecting the sealing performance of the wellbore and, more seriously, can cause oil and gas channeling, threatening the lifespan and environmental safety of oil and gas wells.[8−13] Therefore, the problems of increased friction and poor cementing quality caused by the decline in lubricity and the increase in thickness of mud cake have seriously restricted the development of horizontal well technology, which cannot be ignored in the application of horizontal well technology.[14]

Lubricants are often added to the drilling fluid in order to ease the problem of pipe string friction caused by the reduced lubricity of mud cakes in the borehole walls. Lubricants commonly used include asphalt- and oil-based liquid-phase lubricants. In the initial exploiting stage of the horizontal section, the lubrication effect of the above-mentioned lubricants is obvious, usually making the viscosity coefficient of the mud cake less than 0.2. But in the middle and late stages of drilling, as the in solid-phase content in the drilling fluid increases, the effect of asphalt and oil-based liquid-phase lubricants is not significant, and the wellbore mud cake appears weaker as a result of using excessive oil-based liquid-phase lubricants, which can easily cause stuck drilling.[15,16] Meanwhile, traditional liquid lubricants are prone to foam, have poor stability, have fluorescence effects, and even affect the rheology

Received: January 17, 2024
Revised: March 27, 2024
Accepted: April 9, 2024
Published: April 25, 2024



of the drilling fluid, while solid lubricants are generally difficult to degrade and are prone to environmental contamination and reservoir damage, thus limiting their use in horizontal wells.[16−19] In addition, when the solid content of drilling fluid is high, adding liquid lubricants thickens the outer oil film of solid particles, reducing the stacking density of solid particles on the wellbore wall, thickening the wellbore mud cake, reducing its strength, increasing the difficulty of flushing, causing serious weak interface phenomena in cementing, and resulting in a decrease in the quality of interface bonding. In order to solve the problem of the poor quality of mud cake leading to weak cementing interface, mud cake removal method[20] and mud cake modification method are mainly developed.[21] At present, technologies such as MTC,[22,23] MTA,[24] and MCS[25] have been developed to improve cementing quality based on the mud cake modification method, the essence of which is to add improvers to the drilling fluid to improve the quality of mud cake, thus improving the cementing strength of the second interface of cementing.[26,27] However, there have been no reports on improving the lubrication of wellbore mud cakes. In summary, the existing technology of adding liquid lubricants to improve wellbore lubrication is only considered from the perspective of reducing wellbore friction, ignoring the problem that the lubricant deteriorates the quality of the shaft lining mud cake. It cannot effectively improve the lubrication of wellbore mud cakes in the middle and later stages of horizontal wells nor does it effectively solve the problem of wellbore seal failure caused by weak cementing interfaces.

Therefore, in order to improve the drilling efficiency and cementing strength of weak interfaces, a versatile mud cake improver, Mul-GX, is developed in this article, which can improve mud cake lubricity, reduce its thickness, and improve its strength. The viscosity coefficient of mud cake is measured, laboratory interface cementation simulation experiments, drilling fluid compatibility, and temperature adaptability experiments are carried out, the use effect and applicable conditions of the improver are evaluated, and the action mechanism of the mud cake improver Mul-GX is analyzed by combining SEM and XRD microcharacterization.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. Experimental Materials and Instruments. *2.1.1. Experimental Materials.* (1) Composition of mud cake improver Mul-GX: Mul-GX is composed of the metasilicate GX-ZQ with aciculate mineral chain, the polymer copolymer GX-JB with a variety of alkenyl monomers, and the polymer GX-TX with long carbon chain (detailed names of the components are related to intellectual property protection). Mul-GX is a white powder with a particle size of 1200−2000 mesh. The raw materials of Mul-GX are mainly derived from petroleum industry derivatives or from similar geological resources, which are environmentally friendly and nontoxic.

(2) Composition of the water-based drilling fluid: the main components are 6% bentonite, 1% sodium carbonate, 2% polyacrylonitrile-polyacrylamide composite ammonium salt for drilling fluid, 1% potassium polyacrylate KPA, 2% filtrate reducer polyaluminum JS-2, 3% emulsified asphalt YK-H, and 3% low fluorescence wellbore stabilizer HQ-1. The density is 1.3 g cm^{-3}. The water-based drilling fluid is provided by the Jilin Oilfield. It is prepared according to GB/T 29170-2012 Laboratory Testing of Drilling Fluids for the Petroleum and Natural Gas Industry.

(3) Composition of cement slurry: the main components were G grade cement and quartz sand with the proportion of 670:330, 1% retarder GH-9, 4% fluid loss reducer G306, 1.0% drag reduction agent USZ-1, 4% fleeing proof agent G403, 2% silica fume, 0.05% defoaming agent XP-1, and 3% expanding agent G401. All of the above are provided by Jilin Oilfield.

(4) Other lubricants: modified graphite GD-2, nonfluorescent liquid lubricant RH-3, which are provided by Jilin Oilfield.

2.1.2. Experimental Instruments. NZ-3A mud cake viscosity coefficient tester and HTD19941 mud cake properties tester were obtained from Qingdao Haitongda Special Instrument Co., Ltd.; Interface bonding experimental mold was self-made; pH test paper was obtained from Hangzhou Shisan Technology Co., Ltd.; MN-4 Marconi funnel viscometer, GGS-42 high temperature and high pressure filter tester, ZNN-D6B six-speed rotary viscometer were procured from Qingdao Hengtaida Mechanical and Electrical Equipment Co., Ltd.; RGM-300 tensile tester was obtained from Shenzhen Rigg Instrument Co., Ltd.; ΣIGMA thermal field emission electron microscope was obtained from German ZEISS; SmartLab SE X-ray diffractometer was procured from Japan Rigaku.

2.2. Experimental Method. *2.2.1. The Method of Making Mud Cake.* The drilling fluid was taken and fully stirred in a high-speed mixer for 15 min, and it was loaded into a high-temperature and high-pressure static filtration instrument and was filtrated for 30 min at 3.5 MPa and 90 °C (temperature selection depends on the wellbore depth) to prepare mud cake.

2.2.2. Determination of Mud Cake Properties. The thickness and strength of the mud cake were measured with a mud cake performance tester. Its viscosity coefficient was measured by a NZ-3A mud cake viscosity coefficient tester.

2.2.3. Drilling Fluid Performance Measurement. The viscosity, filtration loss, pH, rheological parameters of the drilling fluid, and its extreme pressure coefficient were, respectively, determined by using the MN-4 Mallet funnel viscometer, the GGS-42 high-temperature and high-pressure filter tester, the pH test paper, and the ZNN-D6B six-speed rotating viscometer.

2.2.4. Measurement of Interface Bond Strength. In order to test the effect of a mud cake improver on interfacial bonding strength, a simulation experimental device for cementing interfacial bonding was designed (Figure 1). First, the drill-core (diameter 2.5 cm, height 10.0 cm) was immersed in the

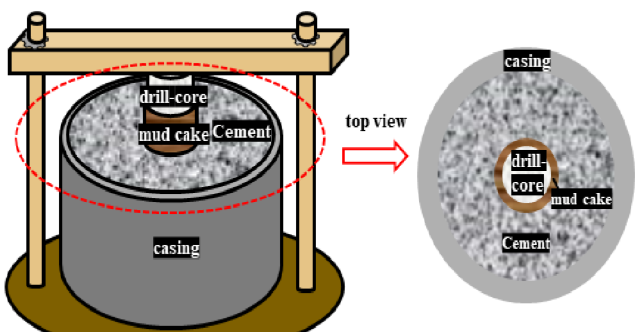


Figure 1. Cementing interface cementation simulation experimental device.

https://doi.org/10.1021/acsomega.4c00462
ACS Omega 2024, 9, 20223−20230

Table 1. Performance Parameters of Mud Cake at Different Compositions of Mul-GX[a]

no.	Mul-GX composition GX-ZQ	GX-JB	GX-TX	viscosity coefficient f/1 min	viscosity coefficient f/10 min	mud cake strength g	mud cake thickness mm
1	0.50%	0.05%	0.05%	0.0741	0.1645	213.8	2.71
2	0.50%	0.10%	0.10%	0.0734	0.1623	237.6	2.73
3	0.50%	0.15%	0.15%	0.0795	0.1691	267.9	2.76
4	1.00%	0.05%	0.10%	0.0532	0.0921	298.7	2.11
5	1.00%	0.10%	0.15%	0.0511	0.0911	287.5	2.15
6	1.00%	0.15%	0.05%	0.0537	0.0927	276.3	2.16
7	1.50%	0.05%	0.15%	0.0442	0.0876	297.5	2.18
8	1.50%	0.10%	0.05%	0.0439	0.0874	285.7	2.19
9	1.50%	0.15%	0.10%	0.0521	0.0913	263.6	2.2
f/1 min k1	0.0757	0.0572	0.0572				
f/1 min k2	0.0527	0.0561	0.1440				
f/1 min k3	0.0467	0.0618	0.0583				
the optimal scheme	A3	B2	C1				
f/10 min k1	0.1653	0.1147	0.1149				
f/10 min k2	0.0920	0.1136	0.1152				
f/10 min k3	0.0888	0.1177	0.1159				
the optimal scheme	A3	B2	C1				

[a]Mud cake strength was the maximum loading mass of the mud cake before it was ruptured. Measuring units of mud cake strength in grams.

drilling fluid, and then soaked at 90 °C for 3 h. After the mud cake with a certain thickness was formed on the outer wall of the drill-core, it was taken out and soaked in water at 45 °C for 10 min to remove the false filter cake. Then, it was placed in the center of the mold and fixed firmly. The prepared cement slurry was injected into the annular space of the mold that simulated the second cementing interface (cement slurry was prepared according to GB/T 19139-2012 Test Methods for Oil Well Cement). After the mold was left at room temperature for 24 h to fully solidify, it was placed in a constant temperature water bath at 120 °C for solidification. After curing, the interfacial bonding strength was measured by the RGM-300 tensile tester.

2.2.5. Sample Microscopic Characterization. The samples of mud cake or interface were chosen and analyzed as follows: the sample structure was analyzed by ΣIGMA thermal field emission electron microscopy (SEM, German ZEISS) in the high vacuum mode. The compositions of the samples were analyzed by a SmartLab SE X-ray diffractometer (XRD, Japan Rigaku).

According to the changes in the microstructure and composition of the samples before and after the addition of the mud cake improver to the drilling fluid, the mechanism of the improver was studied.

3. RESULTS AND DISCUSSION

3.1. Optimization of the Component Proportion of Mul-GX. Mul-GX is composed of the metasilicate GX-ZQ, polymer copolymer GX-JB, and polymer GX-TX. The proportions of these components added into the drilling fluid were adjusted to prepare different types of mud cakes. The viscosity coefficient, thickness, and strength of mud cake were measured at last. The results are listed in Table 1.

According to the analysis of the orthogonal experimental results (Table 1), the optimal component proportion of Mul-GX is GX-ZQ: GX-JB: GX-TX = 15:1:0.5, where the proportion is the mass proportion. When Mul-GX was added to the drilling fluid with the above component proportion, the mud cake lubrication performance increased by 64%-67%, its strength increased by 51.7%, and its thickness decreased to 52.9%. Mul-GX has the ability to lubricate, enhance, and reduce.

3.2. Influence of the Amount of Mul-GX on the Lubricity of Mud Cake. Mud cakes were prepared by adding the Mul-GX mud cake improver to the drilling fluid in varying amounts. The viscosity coefficient of the mud cake was measured to evaluate the lubrication effect of the multifunctional mud cake improver Mul-GX, as shown in Table 2. As can be seen from this table, lubrication is the best when the additive amount of Mul-GX is 1.5%, at which the mud cake lubricity improvement ratio exceeds 64%.

Table 2. Effect of Mul-GX on Mud Cake Lubrication[a]

wt %	f/1 min	improvement ratio/1 min	f/10 min	improvement ratio/10 min
0.0	0.1228	-	0.2680	-
0.5	0.0787	35.9%	0.1763	34.2%
1.0	0.0524	57.3%	0.0963	64.1%
1.5	0.0437	64.4%	0.0875	67.4%
2.0	0.0524	57.3%	0.0875	67.4%

[a]f is the viscosity coefficient of the mud cake.

In order to compare the effect of the mud cake improver Mul-GX with other common lubricants, Mul-GX, common solid lubricant modified graphite GD-2, and nonfluorescent liquid lubricant RH-3 were added to the drilling fluid at the additive amounts of 1.5%, 3.0%, and 6.0%, respectively. The additive amounts of GD-2 and RH-3 were the actual addition of the oil field. Then the mud cakes were prepared in API medium pressure filtration apparatus, and their viscosity coefficients were tested by NZ-3A mud cake viscosity coefficient tester. The experimental results are shown in Figure 2. It can be seen that the lubricity improvement effect of Mul-GX is about 1.8−4.5 times that of the modified graphite GD-2 and nonfluorescent liquid lubricant RH-3, and also the Mul-GX additive amount is the lowest. That is to say, Mul-GX

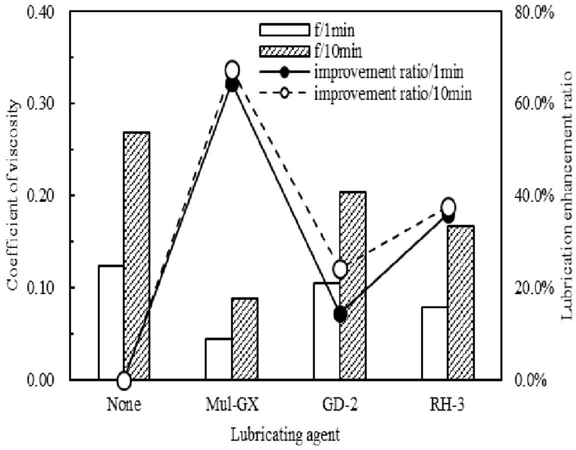


Figure 2. Comparison of lubricants effects.

can provide the best lubrication effect at the lowest additive amount.

3.3. Influence of the Amount of Mud Cake Improver on the Thickness and Strength of Mud Cakes. Mud cakes were prepared by drilling fluid and adding different dosages of Mul-GX, and then the thickness (mm) and the maximum loading mass (g) of the mud cake before it was ruptured were measured, as shown in Table 3, in order to evaluate the effects of Mul-GX on the thickness (H) and strength (T) of mud cakes.

Table 3. Effect of Improver Mul-GX Dosage on Thickness and Strength of Mud Cake[a]

wt %	mud cake thickness mm	improvement ratio (H)	mud cake strength g	improvement ratio (T)
0.0	4.65	0%	188.3	0%
0.5	2.74	41.1%	245.4	30.3%
1.0	2.13	54.2%	292.7	55.4%
1.5	2.16	53.5%	288.3	53.1%
2.0	2.18	53.1%	267.1	41.8%

[a]H is the mud cake thickness; T is the loading mass of the mud cake before it was ruptured.

As can be seen from Table 3, the thickness of the mud cake decreases obviously and the strength of the mud cake increases when the dosage of Mul-GX increases, but when the dosage of Mul-GX is higher than 1.5%, the thinning and strengthening effects of the mud cake are weaker. When the dosage of Mul-GX is 1.0%, the thickness of the mud cake is 2.13 mm, which decreases by 54.2% than before adding Mul-GX, and the maximum loading mass of the mud cake is 292.7 g, compared with the blank mud cake without Mul-GX. (The maximum loading mass (g) of the mud cake before it was ruptured is 188.3 g.) All of the above analysis show that the proper dosage of Mul-GX is 1.0%−1.5% from the point of improvement effect of mud cake thickness and strength.

3.4. Influence of the Amount of Mud Cake Improver on the Lubricity of Mud Cakes. Mud cakes were prepared by adding versatile mud cake improver Mul-GX to the drilling fluid in varying amounts. The viscosity coefficient of the mud cake was measured to evaluate the lubrication effect of the multifunctional mud cake improver Mul-GX. As can be seen from Table 4, lubrication is the best when the additive amount of lubricant is 1.0%, and the maximum increase in lubrication

Table 4. Effect of Improver Mul-GX on lubricity of Mud Cake of Drilling Fluid[a]

wt %	f/1 min	improvement ratio/ 1 min	f/10 min	improvement ratio/ 10 min
0.0	0.1228	–	0.2680	–
0.5	0.0787	35.9%	0.1763	34.2%
1.0	0.0437	64.4%	0.0875	67.4%
1.5	0.0524	57.3%	0.0963	64.1%
2.0	0.0524	57.3%	0.0875	67.4%

[a]f is the viscosity coefficient of the mud cake.

ratio exceeds 60%. This is because Mul-GX, by absorbing water, forms a lubricating buffer in the clay that promotes the solvation of the water film, and the mud cake lubricity becomes better. At the same time, its long carbon chain polymer GX-TX can form a "fishing net" effect, filling between clay particles and improving the deformation ability of the mud cake.

Mul-GX, common solid lubricant modified graphite GD-2, and nonfluorescent liquid lubricant RH-3 in the market were added to the field pulp at the additive amounts of 1.0%, 3.0%, and 2.0%, respectively. The experimental results are listed in Figure 3. The results showed that adding 1.0% improver was

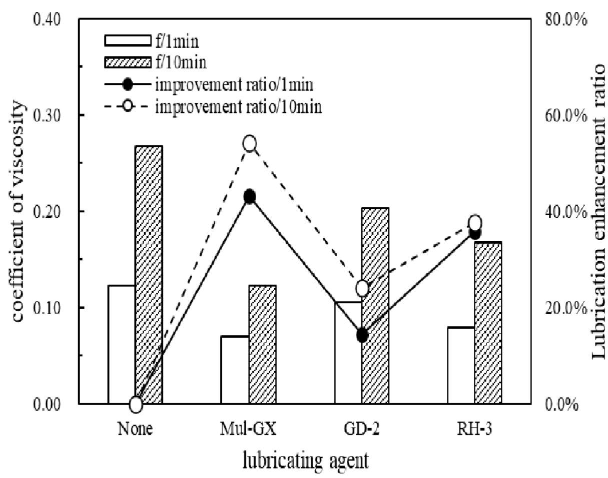


Figure 3. Comparison of lubricant effects.

significantly better than adding 3.0% modified graphite and 2% RH-3, indicating that the improver had better mud cake lubrication than the modified graphite and nonfluorescent liquid lubricant RH-3.

3.5. Interface Enhancement Effect of Mul-GX. In order to research the interface strengthening effect of Mul-GX, an indoor cementing interface bonding simulation experiment was carried out by the method that was mentioned in Section 1.2.5. In the experiment, Mul-GX dosage was 1.5% and the mold was cured in water bath at 90 °C for 7−28 days, and the interface bond strength was tested at last, as shown in Figure 4. The interfacial bonding strength increases with the curing time slowly and does not change after 14 days when the drilling fluid is without Mul-GX. However, when Mul-GX is added into the drilling fluid, the interfacial bonding strength increases with the curing time obviously and is greater than 0.3 MPa after 7 days. After the mud cake is modified by Mul-GX, the interfacial bonding strength increased to 4.38 times maximally, indicating that Mul-GX could effectively improve the interface bond strength.

https://doi.org/10.1021/acsomega.4c00462
ACS Omega 2024, 9, 20223−20230

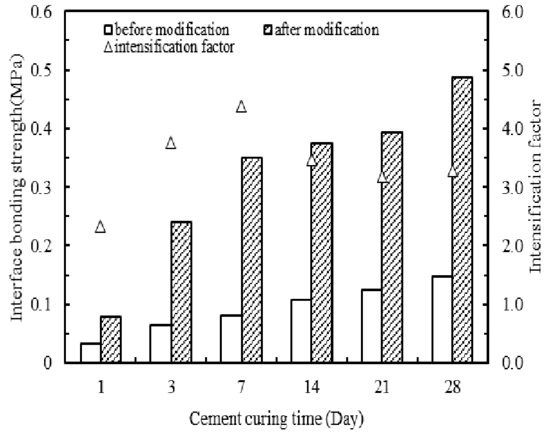


Figure 4. Interface bond strength before and after the action of Mul-GX.

In order to compare the enhanced effect of Mul-GX with the other common lubricants, Mul-GX, common solid lubricant modified graphite GD-2, and nonfluorescent liquid lubricant RH-3 were added to the drilling fluid at the additive amounts of 1.5%, 3.0%, and 6.0%, respectively, and then the cementing interface bonding simulation experiment was carried out at 90 °Cand 7 days. The results are shown in Figure 5.

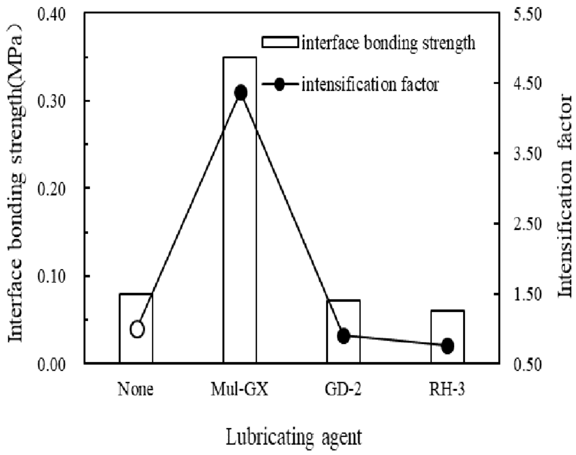


Figure 5. Interface bond strength before and after the action of different lubricants.

As can be seen from Figure 5, modified graphite GD-2 and nonfluorescent liquid lubricant RH-3 decrease the interface bond strength, which means they do not possess the enhancement effect. Contrary to GD-2 and RH-3, Mul-GX shows excellent enhancement effect that could increase the interface bond strength to 4.38 times compared with the value without any lubricant. Combined with the research results of 2.2 and 2.3, it can be seen that Mul-GX has dual effects of mud cake lubrication and interface enhancement.

3.6. Compatibility of Mul-GX with Drilling Fluid. To further investigate the compatibility of Mul-GX with the drilling fluid, different dosages of Mul-GX were added to the drilling fluid, and the rheological parameters of the drilling fluid were measured as shown in Table 5.

Clearly, Mul-GX makes the viscosity, shear force, and filtration loss of drilling fluid to slightly decrease, and the YP/PV is significantly improved compared with that before modification. The other parameters, such as the density and pH, do not change. The results indicate that Mul-GX is effective at improving the rheological properties of the drilling fluid and has good compatibility with the drilling fluid.

Table 5. Effects of Mul-GX on Drilling Fluid Performance Parameters[a]

Mul-GX, wt %	ρ, g·cm^{-3}	FV, s	AV, mPa·s	PV, mPa·s	YP, Pa	YP/PV Pa/(mPa·s)	FL ml	pH
0.0	1.4	54	35	25	9.5	0.38	5.4	9
1.0	1.4	52	36	24	11.5	0.48	4.8	9
1.5	1.4	51	36	24	11.3	0.47	4.8	9

[a] ρ is the density, g·cm^{-3}; FV is the funnel viscosity, s; AV is the apparent viscosity, mPa s; PV is the plastic viscosity, mPa s; YP is the yield value, Pa; YP/PV is the ratio of yield value and plastic viscosity, Pa/(mPa·s); FL is the HTHP fluid loss, mL.

3.7. Temperature Adaptability of Mul-GX. The down-hole temperature varies with the depth of the well, so it is necessary to investigate the effect of Mul-GX in different temperature environments. The performance parameters of the drilling fluid were measured by adding 1.5% Mul-GX was added to the drilling fluid and was aging for 16h at different temperature. Then the mud cake was prepared at 120 °C by using the high temperature and high pressure filtration instrument, and the performance parameters (thickness, strength, and viscosity coefficient) of mud cake were measured. The results are shown in Table 6.

Table 6. Temperature Sensitivity Test Results of Mul-GX

temperature	H/mm	T/g	f/1 min	f/10 min
before modification	4.65	188.3	0.1228	0.268
after modification, 30 °C	2.13	287.9	0.0434	0.0871
after modification, 60 °C	2.15	287.6	0.0435	0.0873
after modification, 90 °C	2.16	287.3	0.0437	0.0875
after modification, 120 °C	2.19	283.1	0.0552	0.0912
after modification, 150 °C	4.71	170.5	0.1405	0.1944

As can be seen from Table 6, when the rolling temperature is lower than 120 °C, the thickness of mud cake is 2.13−2.19 mm, its maximum loading mass is 283−288 g, its viscosity coefficient is 0.04−0.09, where all the parameters nearly not change and also the performance of mud cake are still better than before modification. When the rolling temperature increases to 150 °C, the thickness and viscosity coefficient of mud cake greatly increase and the maximum loading mass greatly decrease, which means the mud cake performance is seriously deteriorated. So the results showed that Mul-GX could maintain good modification effect at temperatures of not more than 120 °C.

3.8. Action Mechanism and Modification Effect. Mul-GX was added into the drilling fluid with1.5% dosage, and then the mud cake sample and the mud cake−cement interface sample were prepared through interface bonding simulation experiment. All of the above samples were analyzed by SEM scanning and XRD diffraction to research the changes of micromorphology and mineral composition before and after adding Mul-GX, the results of which are shown in Figures 6,7. The untreated mud cake by Mul-GX was disordered by solid particles of different particle sizes, and the mud cake was loose and porous (Figure 6a). A large number of microgaps were generated at the mud cake−cement interface, resulting in a

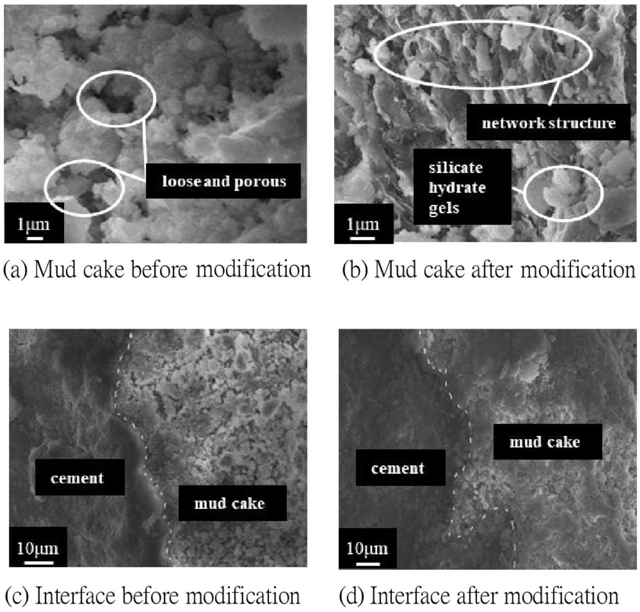


Figure 6. SEM images of the mud cake and mud cake−cement interface: (a) mud cake before modification; (b) mud cake after modification; (c) interface before modification; (d) interface after modification.

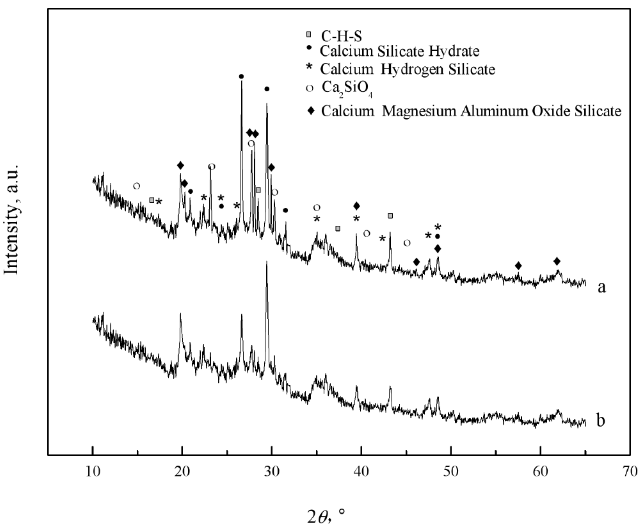


Figure 7. XRD patterns of the mud cake.

decline in interface bonding quality. But a large number of lamellar and winglike gels appear in the mud cake treated with Mul-GX, filling the internal holes in the mud cake and making it more dense and well-integrated (Figure 6b). Thus, the mud cake becomes more smooth and compacter. Besides there are fewer gaps between mud cake and cement at the bonding interface (Figure 6d), indicating good interface bonding quality. Combined with the XRD diffraction pattern (Figure 7), it can be seen that the lamellar and winglike gels formed inside the mud cake are silicate hydrate gels. These gels are attached to the surface of the mud cake and filled between solid particles, which inhibit or eliminate the porous transition zone near the interface to a certain extent, and effectively improve the sealing ability of the bonding interface.

Combined with the above analysis and the molecular structure and physicochemical properties of Mul-GX, the action mechanism of Mul-GX is concluded as follows (action mechanism diagram of Mul-GX is shown in Figure 8).

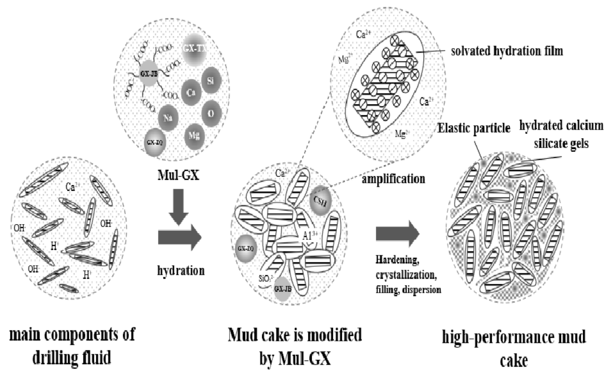


Figure 8. Action mechanism diagram of the mud cake improver Mul-GX.

The metasilicate GX-ZQ with aciculate mineral chain in Mul-GX has excellent adsorbability that can absorb a large number of cations (Ca^{2+}, Mg^{2+}) to aggregate on the surface of solid particles, and then under the action of a large amount of OH^- from cement filtrate a chemical reaction occurs in the hydration film[28,29] to form hydrated calcium silicate gel, which is filled between the pores of solid particles in the mud cake. After solidification, hardening, and crystallization, the hardened layer is formed, which effectively improves the density and strength of mud cake benefiting the excellent interface bonding.

The polymer copolymer GX-JB with a variety of alkenyl monomers in Mul-GX contains a large number of carboxylic groups (−COOH) and hydroxyl groups (−OH) with strong hydrophilicity, which are easily adsorbed on the surface of solid particles through hydrogen bonding and increase the repulsion force between solid particles through electrostatic repulsion and steric-hinerance effect, effectively reducing the thickness of mud cakes. At the same time, the polymer copolymer GX-JB has low cation price and strong hydration ability, causing large hydration film thickness. The thicker hydration film increases the fluidity and lubricity of solid particles, which improves the lubricity of mud cakes and reduces its thickness.

The polymer GX-TX with a long carbon chain in Mul-GX is derived from semicrystalline thermoplastic material with stable chemical properties. Due to its long carbon chain, it has super deformation ability and toughness. This molecular structure can form a “fishing net” filling between solid particles that disperses the solid particles inside the mud cake and increases its deformation ability, thus improving its lubricity.

In summary, the mud cake improver Mul-GX improves the lubricity of mud cake and reduces its thickness by increasing the hydration film thickness outside of solid particles through electrostatic repulsion and steric-hinerance effect based on the physicochemical coupling effect. The hydrated calcium silicate gel generated by the hydration reaction can enhance the strength of the mud cake. The deformability of elastic particles with long polymer chains makes the solid particles in drilling fluid to disperse evenly, and the toughness of the mud cake is improved simultaneously, thus naturally improving its compactness and lubricity.

https://doi.org/10.1021/acsomega.4c00462
ACS Omega 2024, 9, 20223−20230

4. CONCLUSION

In order to effectively solve the problems of high wall friction and lower interface cementation quality in the middle and late periods of horizontal wells, a multifunctional mud cake improver Mul-GX with lubrication and interface enhancement effects was studied. The performance evaluation and action mechanism were also researched, and the detailed conclusions are as follows:

(1) In this paper, a multifunctional mud cake improver Mul-GX with lubrication and interface enhancement effect is provided that is composed of the metasilicate GX-ZQ, polymer copolymer GX-JB, and polymer GX-TX, and the mass ratio of each component was GX-ZQ: GX-JB: GX-TX = 15:1:0.5. Mul-GX is a white powder with a particle size of 1200−2000 mesh, which can be directly added to drilling fluid and has good compatibility with drilling fluid.

(2) When Mul-GX was added to the water-based drilling fluid with 1.0%−1.5% dosage, the mud cake lubricity was improved by more than 60%, its thickness was reduced to 53.9% on average, and its strength increased to 54.3% on average. And with the same adding quantity, the interfacial bonding strength was 4.38 times more than the data before adding Mul-GX. Mul-GX shows significant mud cake lubrication, and the interface enhancement effect at the temperature is not more than 120 °C.

(3) The action mechanism of Mul-GX is summarized as follows: Increasing the hydration film thickness outside of the solid particles in drilling fluid through electrostatic repulsion and steric-hinerance effect improves the lubricity of the mud cake and reduces its thickness. Hardening, crystallization, and filling of hydrated calcium silicate gels by the hydration reaction enhance the strength of the mud cake. Filling, dispersing, and shape changing of the elastic particles with long polymer chains improve the compactness and lubricity of the mud cake. Based on the physicochemical coupling effects described above, the mud cake performance in terms of lubrication, strength, and thickness is improved effectively.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.4c00462.

Brief introduction of the provincial and ministerial level laboratories that this project laboratory relies on, and pictures of the experimental instruments involved in the experiment (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Fuping Feng − *Key Laboratory of Ministry of Education of China on Enhanced Oil and Gas Recovery, Northeast Petroleum University, Daqing, Heilongjiang 163318, China; Key Laboratory of Reservoir Stimulation, China National Petroleum Corporation, Daqing, Heilongjiang 163311, China;* orcid.org/0009-0000-9077-1009; Email: 1451269334@qq.com

Authors

Jianwei Zhang − *Key Laboratory of Ministry of Education of China on Enhanced Oil and Gas Recovery, Northeast Petroleum University, Daqing, Heilongjiang 163318, China*

Mengna Liang − *Key Laboratory of Ministry of Education of China on Enhanced Oil and Gas Recovery, Northeast Petroleum University, Daqing, Heilongjiang 163318, China;* orcid.org/0009-0006-6848-6678

Yang Yu − *PetroChina Jilin Oilfield Company, China National Petroleum Corporation, Songyuan, Jilin 138000, China*

Kun Zhang − *Drilling Engineering Technology Research Institute, Daqing Oilfield Drilling Engineering Company, Daqing, Heilongjiang 163413, China*

Xu Han − *Key Laboratory of Ministry of Education of China on Enhanced Oil and Gas Recovery, Northeast Petroleum University, Daqing, Heilongjiang 163318, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.4c00462

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by Heilongjiang Provincial Natural Science Foundation of China (LH2022E026).

■ REFERENCES

(1) Qun, L.; Yun, X.; Bo, C.; Baoshan, G.; Xin, W.; Guoqiang, B.; Hui, L.; Shuai, L. I.; Bin, D.; Haifeng, F.; Zheng, T.; Tao, L.; Haoyu, Z. Progress and prospects of horizontal well fracturing technology for shale oil and gas reservoirs. *Pet. Explor. Dev.* **2022**, *49* (1), 191−199.

(2) Nie, S.; Li, H.; Hu, Z.; Wen, M.; Gao, S.; Zhang, H.; Luo, H.; Zhang, L. A review of the research status and development prospects for gravel packing sand control in horizontal wells. *Geoenergy Sci. Eng.* **2023**, *229*, 212152.

(3) Li, X. M.; Fan, Y.; Li, J.; Su, X.; Zhan, S.; Hu, G.; He, Y.; Zhang, M. Research on the Influence of a Cuttings Bed on Drill String Friction Torque in Horizontal Well Sections. *Processes* **2022**, *10* (10), 2061.

(4) Pakdaman, E.; Osfouri, S.; Azin, R.; Niknam, K.; Roohi, A. Improving the rheology, lubricity, and differential sticking properties of water-based drilling muds at high temperatures using hydrophilic Gilsonite nanoparticles. *Colloids Surf., A* **2019**, *582*, 123930.

(5) Yan, L.; Congjun, L.; Zhang, Z.; Wang, J.; Xianguang, X.; Sun, J.; Yinao, S. Successful Application of Unique High-Density Water-Based Drilling Fluid Used in Zhaotong Shale Gas Horizontal Wells. In *Paper presented at the SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition*; OnePetro: Nusa Dua, Bali, Indonesia, 2015;pp 176428. DOI: .

(6) Isambourg, P.; Ottesen, S.; Benaissa, S.; Marti, J.Down-Hole Simulation Cell for Measurement of Lubricity and Differential Pressure Sticking. In *Paper presented at the SPE/IADC Drilling Conference*; OnePetro: Amsterdam, Netherlands, 1999; pp 52816. DOI: .

(7) Khalil, A. A.; Sadeq Adnan, M.; Asad, M. S.; Alfarge, D. Decreasing the stick-slip vibration during drilling wells using water and polymer drilling mud modified with NanoSiO2 particles. *Kuwait J. Sci.* **2024**, *51* (2), 100178.

(8) Zhao, C. J.; Li, J.; Liu, G.; Zhang, X. Analysis of the influence of cement sheath failure on sustained casing pressure in shale gas wells. *J. Nat. Gas Sci. Eng.* **2019**, *66*, 244−254.

(9) Zhu, H. Y.; Deng, J. G.; Zhao, J.; Zhao, H.; Liu, H. L.; Wang, T. Cementing failure of the casing-cement-rock interfaces during hydraulic fracturing. *Computers Concrete* **2014**, *14* (1), 91−107.

(10) Jing, W. Exploration of Key Technologies for Cementing Large Displacement Wells. *Western Exploration Engineering* **2019**, *31* (10), 107−108.

(11) Jindong, W. Research on Cementing Quality of High Permeability and Low Pressure Layers in Zone 3/7 of South Sudan. *Western Exploration Engineering* **2019**, *31* (3), 59−61.

(12) Jianwei, Z.; Jian, W.; Xin, L.; Qingming, M.; Baodong, Z. Mud cake quality improvers and their impact on cementing quality. *Silicate Bulletin* **2016**, *35* (2), 623−627.

(13) Zhiqiang, W.; Jianliang, Z.; Yong, J.; Hongsheng, Z. Analysis of Difficulties and Technical Countermeasures for Gas Layer Sealing in Shale Gas Horizontal Wells. *Petroleum Drilling Prod. Technol.* **2012**, *34* (S1), 26−29.

(14) Qin, G.; Xu, M.; He, M.; Chen, K.; et al. Synergistic Effect of Polyaspartate and Polyethylene Glycol on Lubrication Performance of the Water-Based Drilling Mud. *ACS Omega* **2021**, *6* (21), 13817−13830.

(15) Shuming, Y.; Qiang, L.; Huaizhen, Z. Research on High Temperature and High Density Drilling Fluid Lubrication Technology. *Chem. Ind. Eng. Technol.* **2019**, No. 3, 40.

(16) Zhou, S.-S.; Song, J.-J.; Xu, P.; He, M.; Xu, M.-B.; You, F.-C. A review on tribology, characterization and lubricants for water-based drilling fluids. *Geoenergy Sci. Eng.* **2023**, *229*, 212074.

(17) Sönmez, A.; Kok, M. V.; Özel, R. Performance analysis of drilling fluid liquid lubricants. *J. Pet. Sci. Eng.* **2013**, *108*, 64−73.

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

(19) Bukhawwah, M.; Alrammah, S.Laboratory Evaluation Comparison Study Between the Performance of Fatty Acid Solid Lubricant and Liquid Lubricant. In *Paper presented at the International Petroleum Technology Conference*; OnePetro: Riyadh, Saudi Arabia, 2022. DOI: .

(20) Zain, Z. M.; Sharma, M. M. Mechanisms of Mudcake Removal During Flowback. *SPE Drill. Completion* **2001**, *16* (4), 214−220.

(21) Tao, N.; Xiaodong, B.; Xuepeng, Z.; Xuepeng, Z.; Yuqian, X.; Xuemei, Y.; Yuemei, L.; Song, Z. Solidification technology and mechanism analysis of improving the interface cementation quality of mud cake and rock. *Chem. Ind. Oil Gas* **2020**, *49* (5), 76−81+86.

(22) Liu, X. Y.; Nair, S.; Aughenbaugh, K.; van Oort, E. Mud-to-cement conversion of non-aqueous drilling fluids using alkali-activated fly ash. *J. Pet. Sci. Eng.* **2019**, *182*, 106242.

(23) Jinying, Y. Research on the treatment process of oilfield drilling waste mud. *Petrochem. Technol.* **2022**, *29* (5), 233−234.

(24) Jun, G.; Yaxin, Y.; Pengwei, Z.; Pengwei, Z.; Yutang, G.; Yanwei, L.; Sanyue, Y. Principle of Anti-Channeling Cementing Technology with MTA Method and Field Applications in Daqing/Shengli/Henan Oilfields. *Pet. Drill. Tech.* **2012**, *40* (1), 17−21.

(25) Xiong, Y.; Wang, J.; Zhongxian, L.; YijunYang, J. H.; Jun, G. Haiyang Hao. Mud Cake Solidification Reaction at Cement-Formation Interface. *J. Oilfield Chem.* **2015**, *32* (4), 485−489.

(26) Zhang, Y.; Xu, P.; Xu, M.; Pu, L.; Wang, X. Properties of Bentonite Slurry Drilling Fluid in Shallow Formations of Deepwater Wells and the Optimization of Its Wellbore Strengthening Ability While Drilling. *ACS Omega* **2022**, *7* (44), 39860−39874.

(27) Zhang, J.; Wang, D.; Su, H.; Zhu, B.; Meng, Q.; et al. A cement interface enhancer and its action mechanism. *Arab J. Geosci.* **2015**, *8* (10), 7869−7877.

(28) Yang, Y.; Kumar Narayanan Nair, A.; Sun, S.; et al. Layer Charge Effects on Adsorption and Diffusion of Water and Ions in Interlayers and on External Surfaces of Montmorillonite. *ACS Earth Space Chem.* **2019**, *3* (11), 2635−2645.

(29) Chen, W. L.; Chen, W. L.; Grabowski, R. C.; Grabowski, R. C.; Goel, S.; Goel, S. Clay Swelling: Role of Cations in Stabilizing/Destabilizing Mechanisms. *ACS Omega* **2022**, *7* (4), 3185−3191.

https://doi.org/10.1021/acsomega.4c00462
ACS Omega 2024, 9, 20223−20230