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Study on Rheological Property Control Method of "Three High" Water Based Drilling Fluid

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ABSTRACT

The rheological regulation of the "three high" (high temperature, high density and high salinity) water-based drilling fluid is a worldwide problem due to the combined influence of temperature, solid content and salinity. This paper investigates the factors and regulation methods about rheological property of "three high" water based drilling fluid, and the effects of clay, salinity and weighting materials on the drilling fluid rheology. The experimental results show that base mud compound bentonite with attapulgite had good salt resistance and temperature resistance. The clay content should be kept close to 2% in high density mud (ρ=2.0g/cm^3), to control drilling fluid rheology. The sequence of rheological parameters of the "three high" water-based drilling fluid with same density was: manganese oxide> micronized barite> barite> ilmenite powder. When barite compounded with ilmenite powder or micronized barite in the ratio of 1:1 to weight drilling fluid respectively, the rheology and filtration of the "three high" water-based drilling fluid performed well. Based on the optimization of a series of mud additives including fluid loss additive, thinner, anti-collapse filtration reducing agent, lubricant with salt and calcium resistance, a formula of the "three high" water-based drilling fluid system was prepared which had excellent rheology, filtration and sedimentation stability property with the density of 2.2g/cm^3 (180℃). The expansion rate of the drilling fluid was 1.84%, shale recovery rate was 85.73%, lubrication coefficient was 0.122, and resistanced to pollution of 1% $CaCl_2$ and 10% poor clay. It also had excellent reservoir protection and plugging performance.

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1. INTRODUCTION

Salt strata, salt mud composite salt layer and high-pressure salt water layer restrictes the exploitation of oil and gas reservoir [1]. When drilling in complex salt layer, it is easy to cause downhole complex conditions such as borehole instability, lost circulation, sticking, etc. Drilling and completion fluid technology faces many challenges [2-4]. Applied "three high" water-based drilling fluid technology, to a certain extent, it solves the complex problems in the drilling process. But its rheological property control exists high temperature, high salinity, high density, and weighting difficulties, etc unresolved issues [5-10]. Boul synthesized a high-performance salt water tackifier which was based on the multi-molecular structure unit. Horton et al. [11] and Boul [12] prepared a high-density salt water system with temperature resistance of 162℃ and density of 2.3g/cm^3. Al-Ansari used potassium formate/ manganous-manganic oxide to increase the density of drilling fluid to 2.1g/cm^3, with temperature resistance of 155℃, which it was first used in Saudi Arabia [13]. Jin Chengping constructed ultra-high density (2.48g/cm^3) saturated salt water drilling fluid. This drilling fluid had excellent performance in lubricity, inhibitory, high temperature stability, and anti-pollution capacity [14]. Therefore, it has important theoretical and technical value to establish "three high" water-based drilling fluid rheological property control method and provide technical support for deep oil and gas drilling fluid under complex

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conditions. In this paper, the effects of salinity and various factors on the rheological properties of the composite base mud are investigated by optimizing the materials to resist salt and calcium. The influence factors and mechanism of the rheological properties and stability of the "three high" water-based drilling fluid are studied. A new rheological control method of "three high" is formed to build the "three high" water-based drilling fluid system.

2. EXPERIMENTAL

2. 1. Basic Performance Test of Drilling Fluid Drilling fluid property tests were conducted according to American Petroleum Institute (API) specifications. The API filtrate volume (FL) of the mud was determined at pressure of 0.69 MPa for 30 min, using a ZNS-5A type medium-pressure filtration apparatus made by Qingdao Hai Tongda Special Instruments CO., Ltd., China. The viscosity of the mud was reflected by the rotary viscometer torque reading at a rotation speed of 600 rpm, 300 rpm, 200 rpm, 100 rpm, 6 rpm, 2 rpm through a ZNN-D6 type rotating viscometer (Qingdao Hai Tongda Special Instruments CO., Ltd., China). The high temperature and high pressure filtration under 150℃ and 3.5MPa were measured using a GGS 71 filter instrument from FANN Company, U.S.A.

2. 2. Inhibitory Test Linear swelling and hot-rolling dispersion tests were performed to evaluate the inhibition properties of drilling fluid. For the hot-rolling dispersion test, shale recovery assessments were conducted at a low temperature of 77 ℃ to investigate the durability of inhibition.

2. 3. Particle Size Distribution Test The particle size distribution of sample was assessed using a Bettersize2000 laser particle size tester (Dandong Bettersize Instrument Co., Ltd., China) to investigate the influence of factors on the size distribution of slurry particles.

2. 4. VSST Settlement Stability Test In this study, VVST settlement test method was used for dynamic settlement measurement. The required instruments includes: FANN35 viscometer, API drilling fluid rheometer measuring cup, heating jacket, 10mL syringe, and settlement shoes. Among them, the FANN35 viscometerprovides dynamic conditions for the measurement, the measuring cup is the drilling fluid holding container, the heating jacket is used for heating and temperature control, and the syringe is used to draw the drilling fluid sample from the bottom of the heating cup.

The specific operating procedure is: place the settling shoes in the measuring cup of the API drilling fluid rheometer, pour the drilling fluid to be measured, adjust the rotation speed of the rotary viscometer to 600 rpm, when the temperature of the drilling fluid is stable at 50 ℃, use a syringe collect the drilling fluid sample in the hole and measure its density as ρ_1. Then adjust the rotational speed of the rotary viscometer to 100 rpm, and control the temperature to 50 ℃. After 30 minutes, collects sample again in the collection hole and measures the density as ρ_2. Before and after calculation, measure the density difference of the drilling fluid in the collection hole. It is the dynamic density difference of drilling fluid.

2. 5. Plugging Performance Test Through the sand bed filtration test, use quartz sand with different meshes to simulate different permeability conditions of the reservoir, and evaluate the plugging performance of the experimental mud.

3. RESULTS AND DISCUSSION

3. 1. Performance Optimization of Base Mud

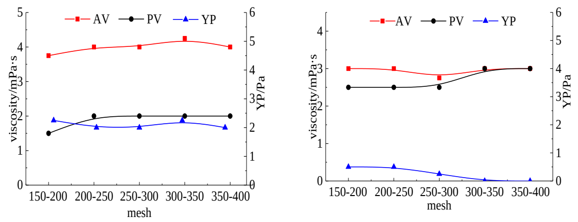
3. 1. 1. Optimizing Proportion of Attapulgite/Bentonite The bentonite and attapulgite were mixed into 4% base mud according to different proportion, and 5% NaCl was added, respectively. Then tested the rheological property and loss property of experimental mud before and after aging at 150℃/16h. According to Table 1, with the decrease of bentonite content, the filtration gradually increased before and after aging; poor quality of attapulgite mud cake resulted in increased filtration; The cutting force and filtration of #4 and #5 mud were larger after aging than before; # 1and #2 mud had good well building property, but low viscosity and shear force; #3 mud was selected as the base mud for the next experiment due to its moderate viscosity, shear force, and filtration.

3. 1. 2. Factors Affecting the Properties of Mixed Base Mud

3. 1. 2. 1. Particle Size of Clay Using attapulgite of different particle sizes prepared 4% base mud (bentonite: attapulgite ratio of 1:1). Then tested the rheology and fluid loss of each base mud at room temperature. According to Figure 1, bentonite played an important role in the rheology and loss property of mixed fresh water base mud, while attapulgite particle size had little effect. The fuller the attapulgite particles were ground, the lower the strength of network structure resulted in insignificant effect on the composite base mud.

TABLE 1. Effect of the different mixture ratio on rheology of base mud

The mixed proportion (bentonite: attapulgite)	condition	AV/mPa·s	PV/mPa·s	YP/Pa	Gel/Pa/Pa	FL/mL	pH
1# (3:1)	Before aging	6.25	2	4.3	2.25/2.5	94	9
	After aging	4.25	2	2.3	3.75/9	170	7
2# (2:1)	Before aging	6.25	2	4.3	2.25/2.75	106	9
	After aging	4	2.5	1.5	3.25/7.75	184	7
3# (1:1)	Before aging	6.75	1.5	5.3	2.5/3.25	122	9
	After aging	4.25	2	2.3	4.75/10	220	7
4# (1:2)	Before aging	8	1.5	6.5	3/4.25	146	9
	After aging	4.5	1	3.5	5.75/18.5	244	7
5# (1:3)	Before aging	8.75	2.5	6.3	3/4	145	9
	After aging	4.5	1	3.5	5/17	268	7



(a) Before aging (b) After aging

Figure 1. Effect of particle size of attapulgite on rheology of mixed mud

3. 1. 2. 2. Aging Temperature The base mud was aged for 16h at different temperatures, then tested their rheological property and loss property. According to Figure 2, with an increase in aging temperature, the viscosity of the mixed base mud increased, and the yield value (YP) decreased to gentle. API filtration increased linearly with aging temperature, indicating that attapulgite can improve the temperature resistance of the base mud.

3. 1. 2. 3. pH Value Regulated pH value of drilling fluid system, tested their rheological property and loss property after aging at 150℃/16h. According to Figure 3, when pH > 9 before aging or pH > 8.5 after aging, the

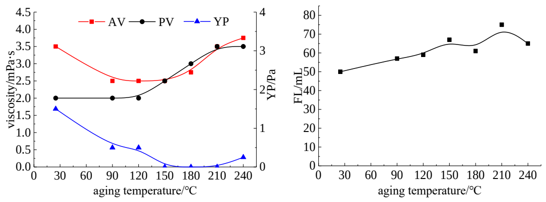


Figure 2. Effect of aging temperature on rheology of mixed mud

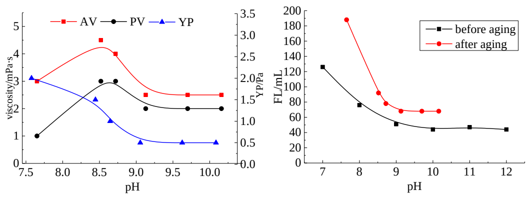


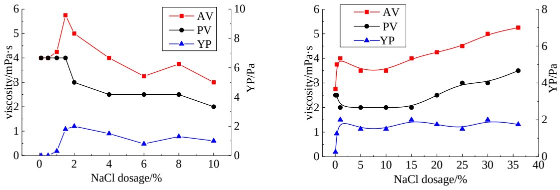
Figure 3. Effect of pH on rheology of mixed mud

surface charge number of attapulgite particles increased with an increase in pH value, and the electrostatic repulsion force was strengthened, which made the viscosity and YP of fresh water base mud to decrease. At the same time, bentonite was easy to be passivated at high temperature under strong alkali environment, which has resulted in a decrease in viscosity and YP of the mixed base mud. The API filtration was the lowest at pH=9, and then it was stable. Therefore, the drilling fluid prepared by mixed fresh water base mud the pH should be greater than 9; or higher as far as possible.

3. 1. 2. 4. Salt

(1) NaCl Rheology tests of compound base mud were carried out at room temperature under different dosage of NaCl. The experimental results are shown in Figure 4. The viscosity and YP of the base mud were ascending in first and descending at last. When attapulgite was added, the viscosity and YP of the mud did not decrease, but kept stable and slightly increased. The results showed that attapulgite can improve the salt resistance of the mud.

(2) $CaCl_2$ The rheology test of compound base mud were carried out at room temperature under different dosage of $CaCl_2$. The effect of $CaCl_2$ addition on the viscosity, filtration, and pH of the mixed base mud is shown in Figure 5. When the amount of $CaCl_2$ was less than 0.15%,



(a) Bentonite mud **(b) Mixed mud**

Figure 4. Effect of NaCl content on rheology of mixed mud

the bentonite flocculated moderately and the viscosity of the mixed mud increased. When the amount of $CaCl_2$ was more than 0.15%, the conversion degree of Na montmorillonite to Ca montmorillonite increased, and the dispersion degree of the system decreased. The viscosity and YP of the mixed mud slightly decreased, which indicated that mixed mud had certain calcium resistance performance.

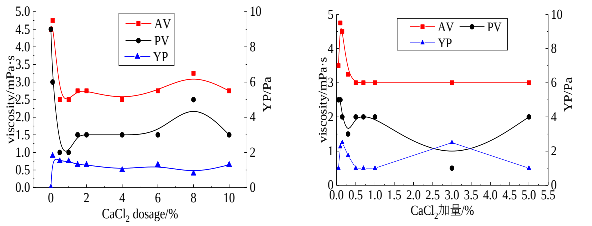
3. 2. Influence of Weighting Materials on the Performance of High Salinity Drilling Fluid The physical parameters of weighting materials used in the experiment are summarized in Table 2.

3. 2. 1. Different Kinds of Weighting Agent Examined the effects of 4 weighting materials on the rheological property of drilling fluid with aging at 150℃/16h. The formula of drilling fluid was 2% mixed mud + 1% PMHA-Ⅱ+ 3% SD-101+ 3% SPNH+ 3% ZDGF+ 3% white oil+ 0.2%Span-80+ 10% NaCl+ 1% SMT+ weighting agent (#3-1). According to Figure 6, the viscosity, YP and API filtration of the after aging mud increased as the density increases. When density increased to 1.8-1.9 g/cm^3, these properties changed greatly. At the same density, the viscosity and YP of the supermicro barite weighted mud were higher than which weighted by ilmenite powder, and this phenomenon was more significant with the increase of density. When $\rho >$ 1.9 g/cm^3, the manganese oxide weighted mud became tick and the rheological property of the mud get worse.

3. 2. 2. Mix Weighting Agents Mixed barite with ilmenite powder, and barite with supermicro barite by different mass ratio to weight high density drilling fluid #3-1, then tested their performance after aging at 150℃/16h. According to Figure 7, when the mass ratio of barite and ilmenite powder was 1:1, the viscosity and YP of high-density brine drilling fluid were low, and the filtration was moderate. When the mass ratio of barite and supermicro barite was 1:1, the viscosity, YP and API filtration were low, and then the rheological property was optimal. The physical parameters of weighting materials used in the experiment are summarized in Table 2.

3. 2. 3. Influence of Weighting Materials on the Sedimentary Stability of Drilling Fluid Used different weighting materials to weighting drilling fluid #3-1 to different density. Tested the density difference ($\Delta\rho$) of the upper and lower layers after aging and standing 24 hours of each system. Learning from Figure 8, with an increase in weighting density, the density difference of each system decreased gradually and the sedimentary stability became better. With the same density, the sedimentary stability of supermicro barite and manganous oxide was the best, followed by barite, while ilmenite powder was the worst.

By studying the effects of mortar soil, salinity and weighted materials on the rheology and settlement stability of the "three high" water-based drilling fluid and its mechanism, it was found that the base mud performance was better after the combination of attapulgite and bentonite (1:1), and the weighting material should not be used alone, it should be mixed and weighted in a certain proportion to have a better improvement effect on the rheology of the "three high" water-based drilling fluid.



(a) bentonite mud (b) mixed mud

Figure 5. Effect of $CaCl_2$ content on rheology of mixed mud

TABLE 2. The physical parameters of weighting materials

Weighting materials	density/(g/cm^3)	Structural shape	rigidity	D_{50}/μm
Common barite	4.2	lump	3.1	18.49
Supermicro barite	4.3	sphere	3.8	2.101
Ilmenite powder	4.5	Irregular grain	6.0	23.74
manganese oxide	5.0	sphere	5.5	1.572

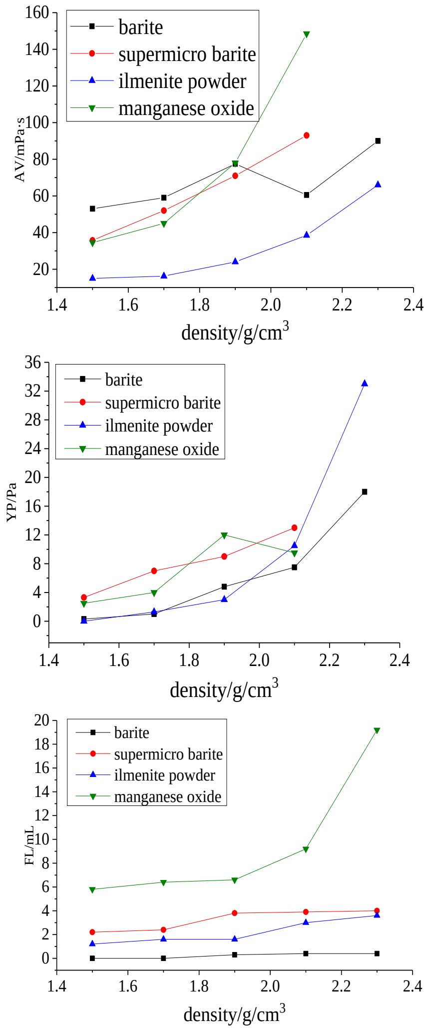


Figure 6. The effect of weighting materials on drilling fluid

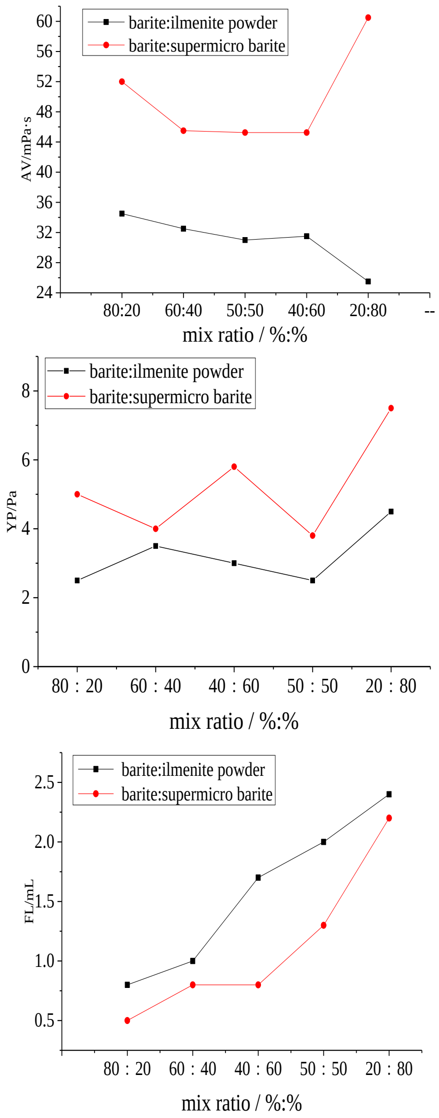


Figure 7. Effect of mixture materials on drilling fluid

3. 3. Build of the 'three high' Water-based Drilling Fluid System

3. 3. 1. Optimization of Drilling Fluid System Filter loss reducer used polymer anti-salt calcium and temperature resistance ZDP-1, resin filter loss reducer SMP-3, lignite filter loss reducer SPNH; viscosity reducer SDJN and SF-260 with good properties; ZDGF and sulfonated asphalt PLH are used as blocking. Also, anti-sagging agents; solid lubricants GRA and white oil were used as lubricants. After 28 groups of formula optimization, the best performance formula was obtained. The aging conditions were 150 °C/16h, ρ= 2.2g/cm^3, and the formula was: 2.5% base mud+ 0.4% NaOH+ 0.1% ZDP-1+ 8% SMP-3+ 2% SPNH+ 3% ZDF-1+ 2% ZDGF+ 30% NaCl+ 0.3% CaO+ 1.5% CaCO3 (2800 mesh)+ 4% white oil+ 0.4% Span-80+ barite + 1.5% SF260 (HSHD-3).

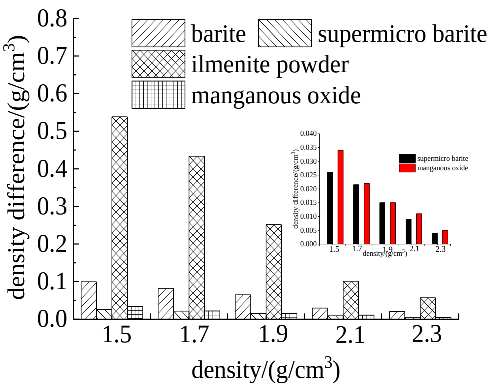


Figure 8. Effect of weighting material and density on sedimentation stability of drilling fluid

TABLE 3. Results of drilling fluid optimation experiment

Formula	Condition	AV/mPa·s	PV/mPa·s	YP/Pa	Gel/Pa/Pa	FL/mL	pH	HTHP/mL	Coefficient of lubrication
HSHD-3	Before aging	105	81	24.0	4/47.5	0	9	11	0.122
	After aging	79	64	15.0	3.75/27	0.4	9		

3. 3. 2. Evaluation of Drilling Fluid System

3. 3. 2. 1. Temperature Resistance and Temperature Stability It is known from Table 4 that the drilling fluid performance was stable after aging at 150°C/64h, which indicated that the formula had good temperature resistance and high temperature stability. After 180°C/16h aging, the filtration loss of the drilling fluid was only 1 mL, the viscosity and shear force change were relatively small, and the drilling fluid performance was stable, indicating that the formula can withstand high temperatures of 180°C.

3. 3. 2. 2. Anti-pollution Performance Prepare sieve inferior soil with 100 meshes of argillaceous siltstone from the Bashkirchik Formation. According to Table 5, after adding 1% $CaCl_2$ and 10% inferior soil, tested rheology and fluid loss at room temperature, the formula HSHD-3 had little change in viscosity, shear force and filtration loss after aging, indicating that it had better resistance to Ca^{2+} pollution and can reach inferior soil 10%.

3. 3. 2. 3. Settlement Stability The HSHD-3 formula after aging at 150℃/16h was stirred at high speed for 30min, and kept at rest for 24h. The density difference between the upper and lower sides was measured. The density difference measured by the static sedimentation method was only 0.032g/cm^3 (Table 6, Figure 9). The density difference measured by the

TABLE 4. Evaluation results on anti-temperature of drilling fluid

Experimental Conditions	Condition	AV/mPa·s	PV/mPa·s	YP/Pa	Gel/Pa/Pa	FL/mL	pH
150℃/16h	Before aging	105	81	24.0	4/47.5	0	9
	After aging	79	64	15.0	3.75/27	0.4	9
150℃/32h	Before aging	108	81	27.0	4.5/47	0	9
	After aging	81.5	67	14.5	3.25/16.5	0	9
150℃/48h	Before aging	107.5	80	27.5	5/55	0	9
	After aging	68	47	21.0	3/20.5	0.8	9
150℃/64h	Before aging	109.5	83	26.5	4.5/54	0.8	9
	After aging	61.5	53	8.5	3.5/18	0	9
160℃/16h	Before aging	111	82	29.0	6.5/6	1	9
	After aging	55	46	9.0	3.25/14.5	0.4	9
170℃/16h	Before aging	92.5	79	13.5	2.25/15	1	9
	After aging	48.5	41	7.5	3.75/20	0.6	9
180℃/16h	Before aging	101	77	24.0	6/55.5	0	9
	After aging	70.5	32	38.5	10/29	1	9

TABLE 5. Evaluation results on resisting pollution performance of drilling fluid

Experimental conditions	Condition	AV/mPa·s	PV/mPa·s	YP/Pa	Gel/Pa/Pa	FL/mL	pH
1%$CaCl_2$	Before aging	87.5	55	32.5	26.5/36.5	3	9
	After aging	61	52	9.0	1.75/9	0	9
10%Inferior soil	Before aging	140.5	101	39.5	8.5/74	0.1	9
	After aging	104	82	22.0	6/29.5	1	9

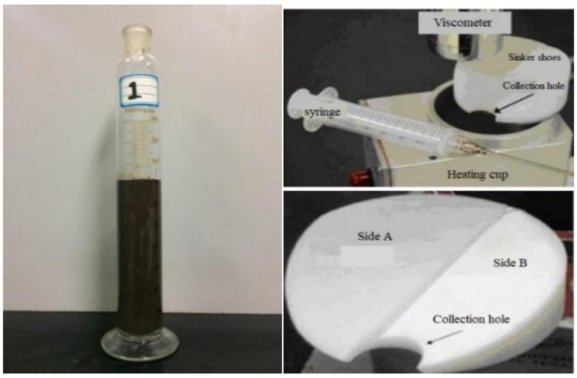
TABLE 6. Evaluation results on sedimentation stability of drilling fluid

Method	**Position**	**Density /g/cm³**	**Density difference /g/cm³**
Dynamic settlement method	upper layer	2.185	0.042
	Lower layer	2.227	
Static settlement method	upper layer	2.22	0.032
	Lower layer	2.252	

sedimentation method (VSST) was 0.042g/cm^3. Two methods showed that HSHD-3 had good sedimentation stability.

3. 3. 2.4. Inhibitory Selected mud shale of Bashkichik Formation (6-10 mesh), the shale recovery rate of the HSHD-3 formula was evaluated by rolling dispersion of mud shale, and compared with the polysulfonate drilling fluid system used in the Bashkichik formation. It can be seen from Figure 10 that the expansion rate of calcareous cores in clear water was 31.42%, the expansion rate of polysulfide drilling fluid was 15.21%, the expansion rate of HSHD-3 was only 1.84%; the recovery rate of clear water was 12.97%, and the recovery rate of polysulfonate drilling fluid used on site was 34.50%, and the recovery rate of the HSHD-3 formula was 85.73%, which indicated that the HSHD-3 formula had a strong inhibitory effect.

3. 3. 2. 5. Plugging Performance Test the "three high" water-based drilling fluid system optimized formula to penetrate the sand bed depth after aging at 150°C/16h. From Table 8, it can be seen that the sand bed penetration depth of optimized formula was very small, and the depth of 40-60 mesh medium pressure sand bed filtrate intrusion into the sand bed was 2.3 cm, indicating that the optimized formula had excellent plugging.



(a) Static settlement method (b) Dynamic settlement method

Figure 9. Measuring method of sedimentation stability

TABLE 7. Results of drilling fluid arrest to shales decentralization

Hashtag	**Well section**	**Sample**	**Initial/ g**	**Finally/ g**	**Recovery rate /%**
BZ-102	6728-6799m	Shimizu	30	3.89	12.97
		Polysulfide system for field use	30	10.35	34.50
		HSHD-3 Experimental pulp	30	25.75	85.83

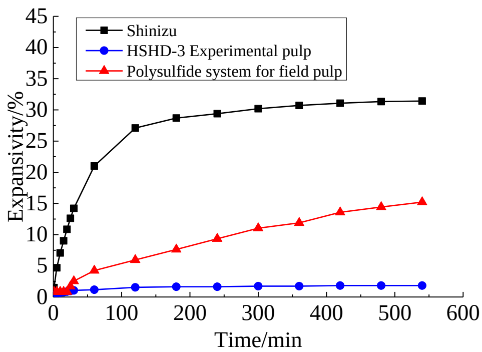
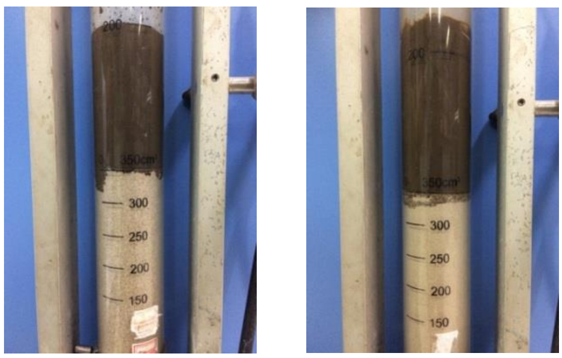


Figure 10. Results of drilling fluid arrest to shale swelling



(a) 40-60 mesh (b) 80-120mesh

Figure 11. The experimental results of sand bed filtration

TABLE 8. The experimental results of sand bed filtration

Formula	Sand mesh	Sand particle size /mm	Intrusion sand bed depth/cm
HSHD-3	40-60	0.425-0.250	2.3
	80-120	0.180-0.125	1.2

Based on this, the "three high" water-based drilling fluid formulation, with a temperature resistance of 180°C, provides new research ideas for deep high-temperature and high-pressure oil and gas production. Combined with the increasingly stringent environmental protection requirements, the environmental protection indicators of the system should also be regarded as key research.

4. CONCLUSION

(1) The suitable ratio of attapulgite to bentonite is 1: 1. The compound base mud has good resistance to salt and calcium and temperature. The bentonite plays a major role in the rheology and filtration of the compound base mud. When the mortar content is about 2%, the “three high” drilling fluid (ρ = 2.0g/cm^3) has better rheology.
(2) When we used four kinds of weighting materials alone, the viscosity, shear force, and API filtration loss of “three high” drilling fluids increased with increasing weighting density. With high-density conditions, the viscosity, shear force, and API filtration loss of ultrafine barite and trimanganese tetroxide are difficult to control; then, use of ultrafine barite and trimanganese tetroxide are not suitable for individually weighting the "three high" drilling fluids. When the barite, ilmenite powder, and ultrafine barite are respectively mixed at a ratio of 1: 1, the "three high" drilling fluid had good rheology and filtration loss; settlement stability: ultrafine barite> trimanganese tetroxide> barite> ilmenite powder. It can be seen that the use of compound weighting and optimization of the compounding ratio can well meet the rheological control requirements of the "three high" drilling fluids, which has a good guiding significance for the selection and use of drilling fluid weighting materials in the future.
(3) The "three high" water-based drilling fluid formula with a density of 2.2 g/cm^3 (180°C) has good rheology and lubricity, the expansion rate of calcareous cores is only 1.84%, resistance to pollution of 1% $CaCl_2$ and 10% poor clay, with good reservoir protection and plugging performance. It can be better applied to the drilling and production of high temperature and high pressure oil and gas reservoirs, and has a good industrial application prospect.

5. ACKNOWLEDGMENTS

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Persian Abstract

چکیده

تنظیم رئولوژیکی سیال حفاری مبتنی بر آب "سه حد بالا" (درجه حرارت بالا ، چگالی بالا و شوری زیاد) یک مشکل جهانی است که به دلیل ترکیبی دما ، محتوای مواد جامد و شوری است. در این مقاله به بررسی فاکتورها و روشهای تنظیم در مورد خاصیت رئولوژیکی سیال حفاری مبتنی بر آب "سه حد بالا" و تأثیر رس ، شوری و وزن مواد در رئولوژی مایعات حفاری می پردازیم. نتایج تجربی نشان می دهد که بنتونیت ترکیب گل و لای پایه با آتوپلولیت مقاومت خوبی در برابر نمک و دما دارد. محتوای گل رس را باید نزدیک ۲٪ در گلهای با چگالی بالا ($\rho = 2.0g / cm^3$) نگه داشت تا بتوانید رئولوژی گل حفاری را کنترل کنید. توالی پارامترهای رئولوژیکی "سیال حفاری مبتنی بر آب" سه حد بالا "با چگالی یکسان بود: اکسید منگنز> باریت میکرونیزه> باریت> پودر ایلمنیت. هنگامی که باریت به ترتیب با پودر ایلمنیت یا باریت میکرونیزه در نسبت مایع حفاری وزنی ۱: ۱ به وزن ترکیب می شود ، رئولوژی و تصفیه مایعات حفاری مبتنی بر آب "سه حد بالا" به خوبی انجام می شود. بر اساس بهینه سازی یک سری مواد افزودنی گلی از جمله افزودنی برای از بین رفتن مایعات ، نازک تر و ضد ریزش تصفیه کننده ضد آب ، روان کننده با نمک و مقاوم به کلسیم ، فرمول سیستم سیال حفاری مبتنی بر آب "سه حد بالا " تهیه شده است. خصوصیات رئولوژی ، فیلتراسیون و رسوب گذاری با چگالی ۲.۲g / cm^3 (180°C). میزان انبساط مایع حفاری ۱.۸٤٪ ، سرعت بازیابی شیل ۸۵.۷۳٪ ، ضریب روانکاری ۰/۱۲۲ و مقاومت در برابر آلودگی ۱٪ $CaCl_2$ و ۱۰٪ خاک رس ضعیف بود. همچنین از حفاظت و مخزن بسیار عالی از مخزن برخوردار بود.