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Preparation and research of intelligent drilling fluid based on temperature-sensitive modified bentonite

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ABSTRACT

The application of intelligent materials in drilling fluids has greatly reduced the investment of human resources and effectively made up for the shortcomings of traditional drilling fluids, such as insufficient directivity, poor adaptive ability and difficult monitoring. Therefore, the research of intelligent drilling fluids is a valuable direction for the future oil and gas industry. In this study, the temperature-sensitive modified bentonite NIPAM-B developed by Pan Yi *et al.* was used as the drilling fluid base slurry, and the drilling fluid additives were optimized to complete the modulation of the intelligent drilling fluid inspection system. In addition, the rheology, filtration, shale wellbore stability and stability of the intelligent drilling fluid inspection system will be evaluated. The results show that the intelligent drilling fluid has good temperature-sensitive thickening performance, and the rheology is not affected by temperature changes, which can realize intelligent heating and thickening. In addition, compared with the original bentonite drilling fluid system, the intelligent drilling fluid has good fluid loss reduction ability and shale borehole wall protection ability, and the shale rolling recovery rate reaches more than 95 %.

Keywords: Bentonite modification; Intelligent drilling fluid; N-isopropyl acrylamide; Temperature sensitive.

1. INTRODUCTION

In order to avoid native bentonite being vulnerable to its defects or functional deficiencies, improve the application space of bentonite, the modification and optimization of bentonite have become the focus of bentonite research. Nowadays, the modification research of bentonite is usually based on physical intercalation and chemical modification [1].

As one of the basic components of drilling fluid, bentonite has a very intuitive impact on drilling fluid performance. The rheological control of drilling fluid is closely related to bentonite. Traditionally, the control methods of drilling fluid rheological include reinforcing phase content, improving the dispersion of clay, adding tackifiers products (tackifiers, high viscosity anti-collapse agents, high viscosity cellulose, etc.). There are many common rheological control methods for drilling fluids. It includes increasing the solid content, improving the dispersion degree of clay, and adding tackifying products (tackifier, high viscosity anti-collapse agent, high viscosity cellulose, etc.). However, the above process operation is more complicated, which not only increases the workload of drilling personnel, affects the drilling speed, but also prolongs the construction period and increases the cost.

Domestic and foreign experts in the petroleum industry, including oil and gas well drilling, oilfield exploitation and oilfield wastewater treatment, have explored the application of temperature-sensitive materials [2]. For example, KAMAL and SULTAN [3] of King Fahd University of Petroleum and Minerals in Saudi Arabia found that the increase of capillary force (capillary force is the main driving force for oil displacement) is due to the increase of viscosity of displacement fluid. The increase of capillary force improves the efficiency of oil and gas exploitation. According to the above principle, KAMAL and SULTAN [3] prepared a new thermosensitive

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water-soluble polymer suitable for high temperature and high shear (HTHS) conditions. Due to thermally sensitive monomers, when the temperature exceeds the lower critical solution temperature (LCST), a physical network will be formed, resulting in an in viscosity, which effectively solves the problems such as the difficulty in exploiting high-temperature and high-salt reservoirs. German BASF Company [4] developed a temperature-sensitive oil displacement product based on hydrophobic modified polyacrylamide (PAM), which can improve oil recovery. The viscosity of the product can change with temperature, and the heating thickening behavior is reversible. During the injection at the surface temperature, the fluid's viscosity is low, which can be quickly injected, and the viscosity increases after entering the formation, so that the oil displacement efficiency is more efficient. Domestic scholars have also done a lot of research on TPS, such as Fan Guoqiang [5] of Tianjin University synthesized N-isopropylacrylamide (NIPAM), potassium persulfate (KPS), and other graft polymerization products PAA-g-P-NIPA and PAA-g-P (NIPA-CO-DMAA) to prepare temperature-sensitive thickener PAA/PNIPA8, which can have high stability on mud performance at high temperature. British Petroleum (BP), Chevron, Nalco and Texaco [6] have jointly developed a new temperature-sensitive microgel oil displacement agent, which has been put into use. Some scholars have studied the epidemic regulation of oilfield working fluid and the working principle modeling of thermosensitive polymer [7, 8]. At present, the thermosensitive polymer products have been used in the domestic Jidong Oilfield [9] and some oilfields in Indonesia, and the thermosensitive performance is good [10].

Modified bentonite has been used in drilling fluid, but the temperature response ability still needs to improvement. In order to solve the problem of drilling fluid rheology caused by increasing temperature and decreasing viscosity, PAN *et al*. [11] grafted silane coupling agent KH570 on the surface of sodium bentonite to synthesize intelligent temperature-sensitive bentonite (NIPAM-B). Based on the intelligent temperature sensitive bentonite (NIPAM-B) prepared by PAN *et al*., the drilling fluid additives were optimized and the intelligent temperature sensitive drilling fluid detection system was determined. The rheology, fluid loss, stability and shale wellbore stability of the above systems were studied.

2. EXPERIMENTAL SECTION

2.1. Materials and instruments

The primary experimental materials in this experiment were intelligent temperature-sensitive bentonite NIPAM-B, guar gum, zwitterionic polymer strong coating agent (FA-367), composite metal zwitterionic polymer tackifier(PMHA), sulfonated phenolic resin (SMP-2), sulfonated lignite resin (SPNH), etc. Amon them, intelligent thermosensitive bentonite NIPAM-B was synthesized by sodium bentonite (Shengheng Mineral Products Co., Ltd., Lingshou County, Hebei Province), N-isopropylacrylamide (Shanghai Macklin Biochemical Technology Co., Ltd.), acrylic acid (Shanghai Macklin Biochemical Technology Co., Ltd.), potassium persulfate (Shanghai Macklin Biochemical Technology Co., Ltd.), silane coupling agent KH570 (Sinopharm Chemical Reagent Co., Ltd.), etc. (other experimental materials of unmarked manufacturers are provided by the oilfield site).

The experimental instruments used in this experiment are: GJD-B12K frequency conversion high-speed mixer (Qingdao Hongxiang Petroleum Machinery Manufacturing Co., Ltd.); zNN-D6B six-speed rotary viscometer (Qingdao Hongxiang Petroleum Machinery Manufacturing Co., Ltd.); gRL-3BX portable roller heating furnace (Qingdao Hongxiang Petroleum Machinery Manufacturing Co., Ltd.); gGS42 high temperature and high pressure filter (Qingdao Hongxiang Petroleum Machinery Manufacturing Co., Ltd.); bSA223S electronic analytical balance (Beijing Sedolis Instrument System Co., Ltd.).

2.2. Synthesis of intelligent thermosensitive bentonite (NIPAM-B)

The steps for synthesizing intelligent thermosensitive bentonite (NIPAM-B) [11] are as follows: (a) 20 g bentonite is dissolved in 90mL of anhydrous ethanol and ultrasonically shaken for 20min. 1.4ml silane coupling agent KH570 was dissolved in 10ml anhydrous ethanol, ultrasonic shock for 20min. Mix the two solutions until they are fully dispersed. (b) Under nitrogen protection, the above solution was transferred into three flasks and reacted at 70 °C for 6 hours. (c) The above solution was centrifuged, washed repeatedly with anhydrous ethanol, and dried at 60 °C. The product was named 'KH570-B'. (d) N-isopropylamide and acrylic acid were dissolved in H_2O/THF (tetrahydrofuran) mixed solvent with a volume ratio of 2:1 in a certain molar ratio, adding 20g KH570-B, ultrasonic dispersion 30min. (e) Under the protection of nitrogen, potassium persulfate (KPS) was added to the above solution, and the system was stirred rapidly to make the system uniform. The product was centrifuged for 3 min, and then the supernatant was removed. The left was washed with anhydrous ethanol for several times (remove the reagent and unreated agent). After vacuum drying at 60 °C for 6 hours, the intelligent temperature-sensitive bentonite NIPAM-B was obtained.

The schematic diagram of intelligent thermosensitive bentonite synthesis is shown in Figure 1.

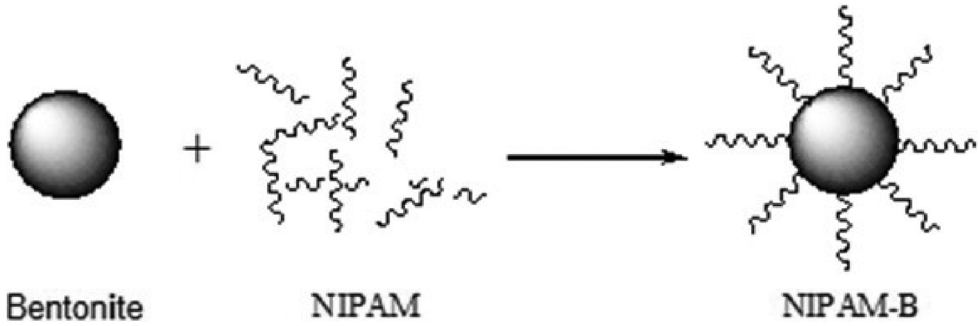

Figure 1: Synthetic schematic diagram of intelligent temperature-sensitive bentonite.

2.3. The applicability of intelligent temperature-sensitive bentonite

In order to test the applicability of the product NIPAM-B in practical engineering, the product was washed many times with anhydrous ethanol (removing impurities), dried in a vacuum at 60 °C, and the apparent morphology was investigated, providing a basis for the storage and transportation of the product.

2.4. Determination of test system and performance test

In this study, the test drilling fluid system [7, 12] includes the intelligent temperature-sensitive bentonite, filtrate reducer, adhesives. According to the national standards and industry standards (GB/T5005-2010 'National Standards of the People's Republic of China-Drilling Fluid Materials Specification' [13], and SY/T5490-2016 'Drilling Fluid Test Soil' [14]), the rheological properties, filtration loss reduction and shale wellbore stability of the drilling fluid inspection system were evaluated. In addition, static settlement tests and dynamic settlement tests are used to determine the stability of drilling fluid [15–18].

3. RESULT AND DISCUSSION

3.1. Preparation of intelligent thermosensitive bentonite

As shown in Figure 2, unmodified bentonite (a) as a whole is a light yellow powder, no granular, fluffy state. The bentonite (b) after surface modification showed yellow-grey flake, slight graininess, reduced fluffy state, low bonding strength and fragile state under dry state without any treatment. The subsequent experiments were conducted using the modified bentonite after drying. It can be concluded that the bentonite modified by intelligent temperature sensitivity is more convenient for storage and transportation in practical application after drying.

The molecular structure of intelligent thermosensitive bentonite is shown in Figure 3 [19].

3.2. Determination of intelligent drilling fluid inspection system

3.2.1. Determination of drilling fluid base-slurry

Eight groups of distilled water with a volume of 400ml were weighed with a measuring cylinder, and the intelligent thermo-sensitive bentonite with a mass ratio of 1%–8 % and distilled water was added respectively. The bentonite was stirred with a high-speed mixer for 1h, and remained for 4h. As shown in Figure 4. The AV

Figure 2: Comparison of temperature-sensitive bentonite before and after modification: orig-inal bentonite (a) and NIPAM-B (b).

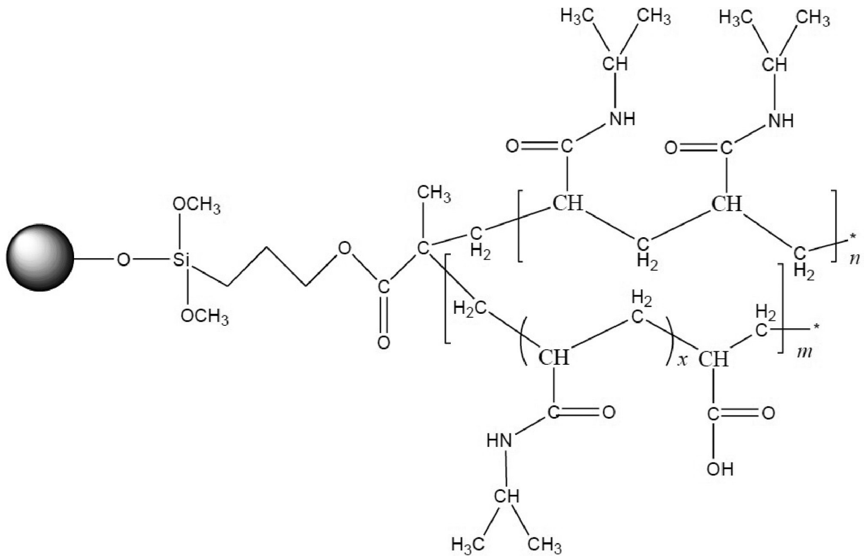

Figure 3: Schematic diagram of intelligent temperature-sensitive bentonite structure (NIPAM-B).

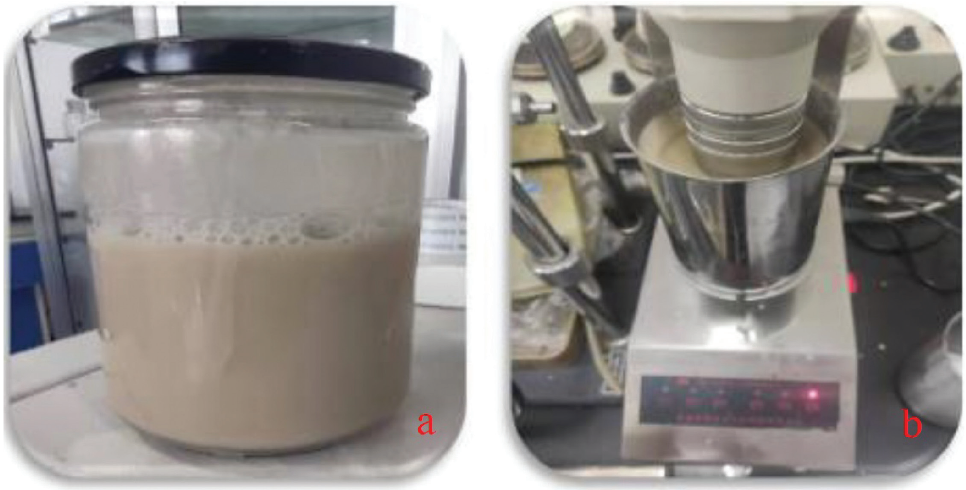

Figure 4: Bentonite base-slurry (a) and its rheological measurement (b).

Table 1: Selection of modified bentonite slurry concentration.

CONCENTRATION (%)	AV	PV	YP	b (DYNAMIC PLASTIC RATIO)
1%	0.75	0.5	0.25	0.5
2%	1	0.5	0.5	1
3%	1.5	1	0.5	0.5
4%	2	1.5	0.5	0.333333
5%	2.5	2	0.5	0.25
6%	3.5	3.5	0	0

(apparent viscosity), PV (plastic viscosity) and YP (static shear force) values of the base-slurry with different dosages were measured by a viscometer after 16 hours of aging in a roller heating furnace, and the filter loss of the base-slurry was measured by a filter. Table 1 is rheological data of modified Bt slurry concentration.

Figure 5 showed light that AV (apparent viscosity) and PV (plastic viscosity) are proportional to the concentration, and both increase steadily in the range of 2 % – 5 % of the whole. The concentration increased over 5 %, and excessive growth was unfavorable to the control of the base-slurry flow pattern, so the base-slurry concentration should be controlled within the range of 2 % – 5 %. In addition, the YP value of intelligent

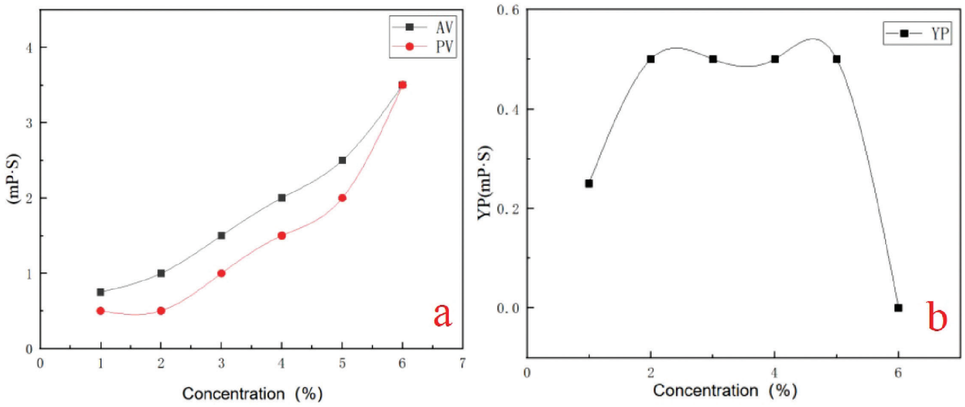

Figure 5: Changes in AV \ PV (a) and YP (b) of intelligent temperature-sensitive bentonite under different concentrations.

thermo-sensitive bentonite is proportional to the attention in the range of 1 % – 2 %, and remains at about 0.5 in the range of 2 % – 5 %. When the concentration increases to 5 %, the YP value decreases, and the rock carrying capacity of the base-slurry decreases when the YP value is too low, which will interfere with the drilling effect of the base-slurry. The selection of bentonite concentration should not only ensure the viscosity and rheological properties of the base-slurry, but also control the AV and YP values within a reasonable range and make them reach the allowable maximum allowable value. Therefore, the concentration of bentonite is 4 %.

3.2.2. Determination of adhesive for drilling fluid

The appropriate viscosity value will make the drilling fluid have the excellent rock carrying capacity to improve drilling efficiency, and the viscosity of the drilling fluid is mainly controlled by two aspects. On the one hand, the viscosity of the drilling fluid is increased by adding bentonite, but it is not continuously added due to the influence of solid content. An excessive proportion of solid-phase will make the flow pattern of the drilling fluid challenging to control and make the reservoir vulnerable to drilling fluid pollution. On the other hand, adding tackifiers to the drilling fluid can improve the viscosity of drilling fluid while keeping solid content unchanged, which plays an vital role in drilling fluid additives. In this experiment, guar gum, FA-367, and PMHA, which are common in drilling sites and have good viscosity enhanceing effects, were selected. With 400 mL distilled water and 4 % NIPAM-B as the original base-slurry, 0.1 % – 0.5 % guar gum, FA-367, and PMHA were added, respectively, and aged at 80 °C for 6 hours. The viscosity was tested after cooling to room temperature. The measurement data of AV (Figure 6 a), PV (Figure 6 b), YP (Figure 7 a), and b (Figure 7 b) (dynamic plastic ratio) of base-slurry are shown in Figure 6 and Figure 7.

It can be seen from Figure 6 and Figure 7 that the apparent viscosity and plastic viscosity of the three kinds of tackifiers increase ijn different degrees with the increase of concentration. Among them, the variation of the guar gum slope is the largest, and the rise of AV and PV is the most obvious. The increase of AV and PV of FA-367 and PMHA is relatively low. The AV, PV, and YP of FA-367 are in a low state, and the tackifying effect is not apparent. The b value of the PMHA base-slurry system changes dramatically, which is easy to causes the instability of base-slurry rheology and is not conducive to the flow pattern control of drilling base-slurry. Due to

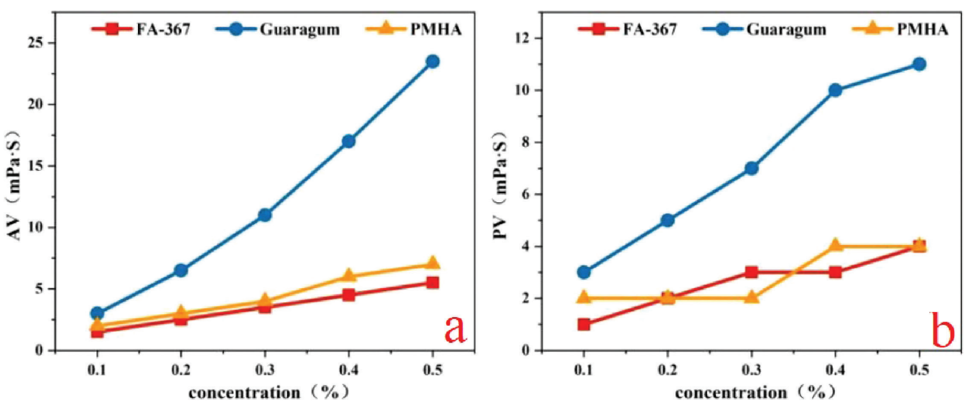

Figure 6: Changes of the thickener AV (a) and PV (b) at different concentrations.

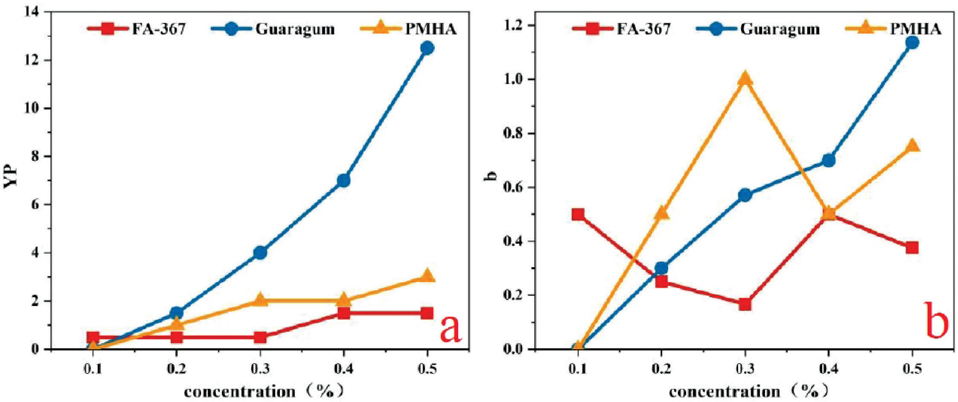

Figure 7: Changes of thickener YP (a) and b (b) under different concentrations.

the relatively low viscosity of NIPAM-B after modification, the most substantial viscosifying effect should be selected to make up for it in the three viscosifiers. Therefore, guar gum is selected as the viscosifier of drilling fluid. The slope of guar gum PV, YP, and b values changes significantly at 0.5 %, indicating that the controllability is difficult at this concentration. However, to ensure that guar gum can play a maximum viscosifying effect, 0.4 % guar gum is selected as the most appropriate viscosifier of drilling fluid.

3.2.3. Determination of filtrate reducer for drilling fluid

When the filtrate loss of drilling fluid is too large, a large amount of water will enter the formation, resulting in water swelling of shale and rapid decrease of structural stability, and finally wellbore collapse. In addition, excessive filtration will also make the formed filter cake relatively loose, the borehole diameter will be greatly reduced, and the torque in the process of drill string movement will be increased. In particular, pressure change and swabbing will occur when the drill is taken off, and there will be accidents such as sticking. Therefore, reasonable drilling fluid filtration value will be the main method to evaluate the drilling fluid quality. In this experiment, two common drilling fluid filtrate reducer SMP-2 (sulfonated phenolic resin) and SPNH (sulfonated lignite resin), were selected as the screening targets of intelligent drilling fluid inspection system. SPNH and SMP-2 were added 0.5 % – 2.5 % in 400 ml distilled water + 4 % NIPAM-B + 0.4 guar gum solution, respectively. As shown in Figure 8, the relevant data are listed in Table 2 and Table 3 for the optimization process diagram of the type and dosage of the filtrate reducer.

Different types of fluid loss additives have different effects on the viscosity and rheology of the base slurry. It can be seen from Table 2 and Table 3 that except for the slight difference in apparent viscosity (AV) and plastic viscosity (PV) of drilling fluid at 0.5 % concentration, the concentration of SPNH and SMP-2 had no effect on AV and PV values, but the addition ratio of SMP-2 had little interference with the rheology of drilling fluid. The static shear force (YP) is almost not affected by the amount of fluid loss agent added. In contrast, SPNH has a more obvious effect on the viscosity (AV, PV) and rheology of the base slurry.

As shown in Figure 9, the filtration loss of drilling fluid and mud cake thickness is inversely proportional to the addition amount of filtrate reducer. The more the addition amount is, the smaller the mud cake thickness and filtration loss are.

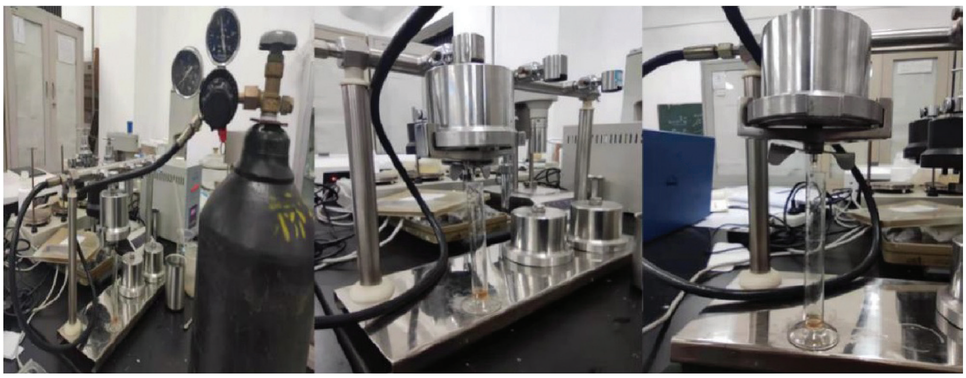

Figure 8: Determination of Filtration Loss of Drilling Fluid.

Table 2: Effect of SPNH on drilling fluid performance under different concentrations.

CONCENTRATION (%)	AV	PV	YP	FL(ml)	FILTER CAKE THICKNESS (mm)
0.50%	10	8	2	17	0.9
1.00%	7.5	6	1.5	16	0.8
1.50%	6	5	1	15	0.8
2.00%	6	5	1	14.6	0.78
2.50%	6	5	1	13.8	0.8

Table 3: The influence of SMP-2 on drilling fluid performance under different concentrations.

CONCENTRATION (%)	AV	PV	YP	FL(ml)	FILTER CAKE THICKNESS (mm)
0.50%	13	9	4	14.4	0.9
1.00%	12.5	9	3.5	11.2	0.7
1.50%	12.5	9	3.5	11	0.6
2.00%	12.5	9	3.5	10.8	0.5
2.50%	16.5	13	3.5	10.8	0.4

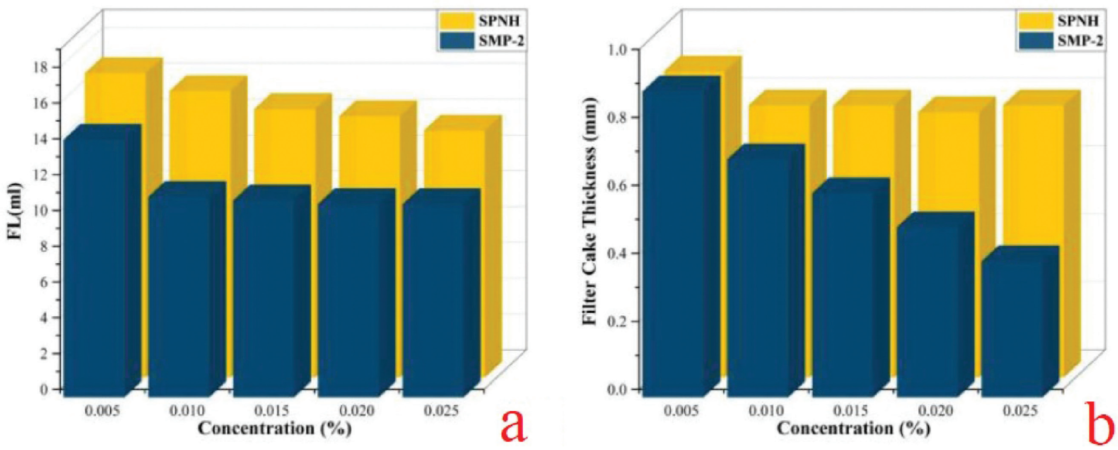

Figure 9: The influence of fluid loss agent concentration on the fluid loss of drilling fluid (a) and the change of filter cake thickness (b).

When the concentration of SPNH and SMP-2 was 2.5 %, the filtration reduction effect reached 18.82 % and 25 %, respectively. SPNH had better wall-forming performance than SMP-2, and the cake thickness was maintained at about 0.8 mm. By consulting the relevant literature that the laboratory mud filtration should be a less than 16 ml, mud cake thickness in 0.5 – 1.5 mm is the most appropriate. Due to the low viscosity of drilling fluid matrix slurry, the types that have less or even higher influence on the viscosity of matrix slurry should be considered in the reducer selection. In addition, the impact of cake thickness, formation quality, and addition cost should be considered. Finally, SPNH with a concentration of 1.5 % was used as the additive amount of filtrate reducer in the intelligent drilling fluid system.

By determining drilling fluid base-slurry concentration and the optimization analysis of additive types and addition amount, the '400ml distilled water + 4 % NIPAM-B + 0.4 % guar gum + 1.5 % SPNH' was finally determined as the intelligent drilling fluid inspection system.

3.3. Performance and results

'400ml distilled water + 4 % NIPAM-B + 0.4 % guar gum + 1.5 % SPNH' was used as intelligent drilling fluid experimental group, and '400ml distilled water + 4 % conventional nano-Na-bentonite + 0.4 % guar gum + 1.5 % SPNH' was used as conventional drilling fluid control group. Two sets of drilling fluids are configured and aged at 80 °C for 16 hours, then cooled to room temperature. Then two groups of drilling fluid rheology, filtration, shale wellbore stability, and drilling fluid stability, were investigated.

3.3.1. Evaluation of drilling fluid rheology

Rheology is the main parameter of drilling fluid temperature-sensitive intelligent inspection. The advantages and disadvantages of rheology will have significant interference on the rock carrying capacity, drilling speed, pump pressure, cuttings suspension and construction progress of drilling fluid, which is directly related to the drilling speed, quality and production cost. In this experiment, the apparent viscosity and plastic viscosity rheological properties of intelligent drilling fluid and conventional drilling fluid were tested. The results are shown in Figure 10 and Figure 11.

In the range of 15 – 80 °C, the rheological test is also carried out with 5 °C as the unit threshold. The relevant data are shown in Figure 10 and Figure 11, respectively, the rheological data (mainly AV and PV) of conventional drilling fluid and intelligent drilling fluid at different temperatures. As shown in Figure 7, AV of traditional fluid of drilling decreases with temperature increase , and AV reduces by nearly 50 % between 20 °C and 80 °C. Although PV fluctuates slightly, it is inversely proportional to temperature on the whole, and PV decreases by 40 %, especially in the range of 15 – 25 °C. This is due to the expansion of temperature resulting in the rapid increase of active bentonite particles in drilling fluid, and the mutual movement between solid particles is more effortless, resulting in changes in drilling fluid rheology. As shown in Figure 8, AV and PV values of intelligent drilling fluid are inversely proportional to temperature changes in the range of 15 – 45 °C. With 45 °C as a turning point, AV and PV values increase significantly in the range of 45 – 60 °C, remaining stable after 60 °C. This is because, at 45 °C, intelligent temperature-sensitive bentonite reached the lowest critical solution

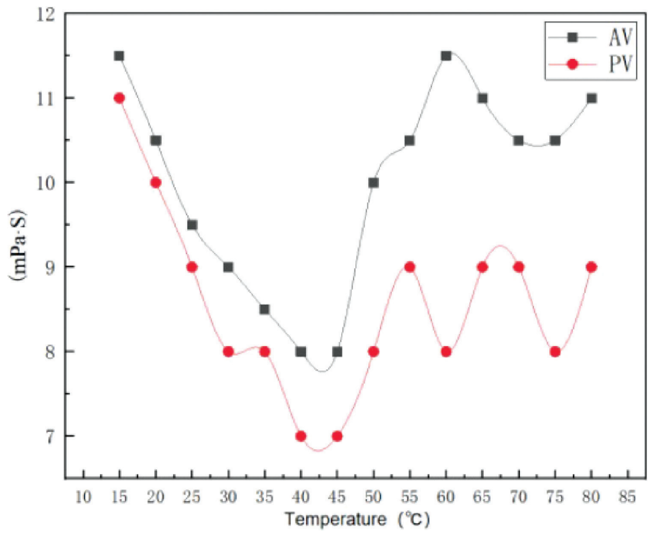

Figure 10: Rheological data of conventional drilling fluid.

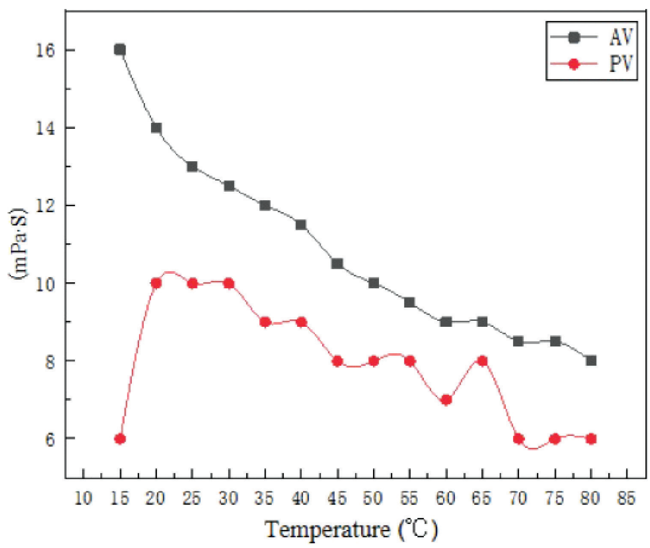

Figure 11: Rheological data of intelligent drilling fluid.

temperature. At this time, the long chain of poly (N-isopropylacrylamide) on intelligent thermosensitive bentonite turns into a dense cluster line, and begins to play a role. After 60 °C, the long chain of temperature-sensitive molecules reaches a dense colloidal state, resulting in increased rheological properties of drilling fluids [20, 21]. As shown in Figure 12. It can be seen that intelligent temperature-sensitive drilling fluid has good temperature sensitivity and viscosity increasing performance, which can ensure the stability of the drilling fluid flow pattern.

3.3.2. Evaluation of drilling fluid filtration

The filtration ability t drilling fluid is mainly manifested in the compactness of mud cake composition quality and the size of filtration loss. In the drilling process, the water in the drilling fluid will be filtered through the borehole wall and then infiltrated into the reservoir, resulting in the collapse of shale caused by water expansion. Finally, the borehole stability is reduced, resulting in drilling accidents. As shown in Figure 13, the filtration tests of the two groups of drilling fluids were carried out in this experiment, and the relevant data are shown in Table 4.

Table 4 shows that the filtration and cake thickness of bentonite drilling fluid is lower than that of intelligent drilling fluid. The FL value of bentonite drilling fluid is 20 ml, while the intelligent drilling fluid is only 11 ml. It can be seen from Figure 14 that the filter cake formed by bentonite drilling fluid is thick and loose (a), and the thickness reaches 1.3 mm. The filter cake has apparent cracks, which is easy to cause the filter cake to fall off from the wellbore, resulting in a substantial increase in the solid content of the bottom hole or the contact

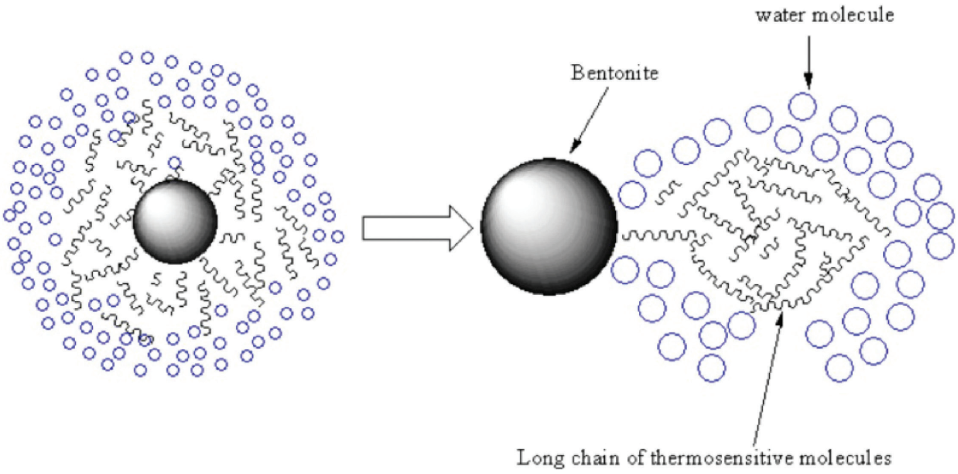

Figure 12: Schematic diagram of the temperature-sensitive long-chain response on the surface of the intelligent temperature-sensitive bentonite.

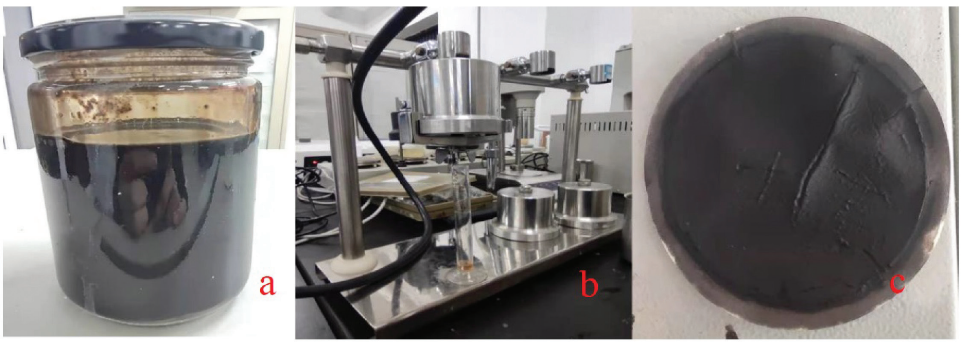

Figure 13: Determination of fluid loss of drilling fluid (a: intelligent temperature-sensitive drilling fluid; b: fluid loss instrument for drilling fluid; c: mud cake).

Table 4: Comparison of fluid loss reduction performance of different drilling fluids.

TYPE OF DRILLING FLUID	FILTRATION LOSS (ml)	FILTER CAKE THICKNESS (mm)
Bentonite Drilling Fluid	20	1.3
Intelligent Drilling Fluid	11	0.6

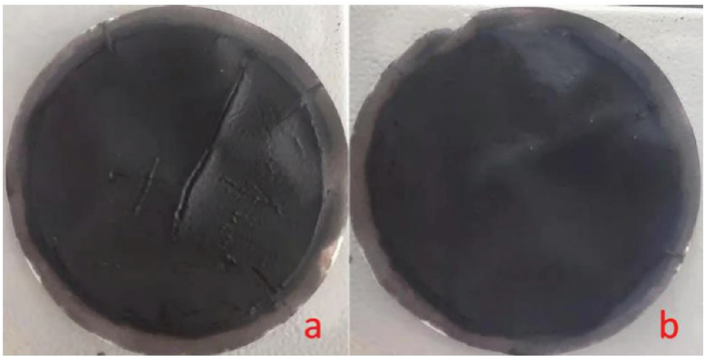

Figure 14: Drilling fluid filter cake (a: bentonite original soil drilling fluid; b: smart drilling fluid filter cake).

point between the drill string and the wellbore, and ultimately the emergence of solid mud wrapped around the drilling tool, thus seriously affecting the drilling speed. The filter cake (b) formed by the intelligent drilling fluid is dense, and the thickness is only 46.15 % of the former, which can effectively seal the wellbore and resist the change of wellbore pressure within a certain range.

3.3.3. Evaluation of wellbore stability of drilling fluid shale

When the drilling fluid enters the shale bottom, it is easy to cause problems such as wellbore shedding. With the continuous development of the oil and gas mining industry and the deepening of drilling strata, shale formations are often drilled. In addition, shale oil and gas development has become an essential supplement to conventional oil and gas resources. Since shale is formed by dehydration and condensation of various clay minerals, hydration expansion is caused by water, and the stability is significantly reduced. When drilling fluid enters shale formation, it is easy to cause wellbore shedding, mud pack, borehole diameter expansion, and diameter shrinkage. The rolling recovery rate of shale is tested to provide a reference for drilling fluid performance evaluation. Shale rolling recovery test as an important method for wellbore stability measurement can provide reference for drilling fluid performance evaluation. In this experiment, water, conventional bentonite drilling fluid, and intelligent temperature-sensitive drilling fluid were tested, and the relevant data were recorded as shown in Table 5.

It can be seen from Table 5 that the recovery amount and recovery rate of bentonite drilling fluid and intelligent drilling fluid are significantly higher than those of fresh water, in which the intelligent drilling fluid has reached 95.58 %, 4.2 times that of fresh water. The bentonite drilling fluid has also acquired 90.66 %, 4.01 times fresh water. It can be seen that the intelligent drilling fluid system has better shale wellbore protection ability than the clean water and bentonite drilling fluid system.

3.3.4. Evaluation of stability of drilling fluid inspection system

The stability of drilling fluid plays a vital role in the evaluating drilling fluid performance, which has a direct or indirect impact on the rheology, suspension capacity, and maintenance cost of drilling fluid. In this experiment, the static settlement test and dynamic settlement test were used to observe the settlement of bentonite drilling fluid and intelligent drilling fluid, and then the stability of the two drilling fluids was compared.

The static settlement test data are shown in Table 6.

Table 5: Shale rolling recovery rate data.

TYPE OF DRILLING FLUID	RECOVERY QUANTITY (g)	RECOVERY RATE (%)
Fresh Water	11.3	22.60%
Bentonite Drilling Fluid	45.332	90.66%
Intelligent Drilling Fluid	47.79	95.58%

Table 6: Test data of drilling fluid stability.

TYPE OF DRILLING FLUID	ρ	ρTOP	ρBOTTOM	SF	EVALUATION
Bentonite Drilling Fluid	1.02	1.025	1.035	0.502	Good Stability
Intelligent Drilling Fluid	1.03	1.01	1.04	0.507	Good Stability

Table 7: Dynamic settlement stability performance evaluation test data.

TYPE OF DRILLING FLUID	P0	τ0	τ30	Δρ
Bentonite Drilling Fluid	1.02	16.863	13.797	0.15
Intelligent Drilling Fluid	1.03	0.511	–0.511	1.72

From Table 6, the average density of intelligent thermosensitive drilling fluid is lower than that of bentonite drilling fluid, which may be due to the large number of thermosensitive molecular long chain on the surface of intelligent thermosensitive bentonite. In addition, the SF value of intelligent temperature-sensitive drilling fluid is slightly lower than that of Bt raw soil drilling fluid, still, the SF values of both are far less than 0.52, so the stability of the two is relatively good [22]. Bentonite particles do not have large settlements, which can meet the stability requirements of drilling fluid.

However, in the conventional case, the measurement of static settlement factor does not discuss the dehydration shrinkage. That, the free liquid at the top of the liquid column is not included in the scope of consideration. Therefore, there is an error in the accuracy of the data of such experiments. At this time, the introduction of dynamic settlement stability evaluation method is further verified [23].

The dynamic settlement test data are shown in Table 7.

According to the relevant data shown in Table 7, the visible Δρ value of intelligent drilling fluid is significantly higher than that of bentonite drilling fluid, indicating that the dynamic settlement of intelligent drilling fluid is higher and the stability is weaker than that of bentonite drilling fluid. It is inferred that the relative quality of intelligent thermosensitive bentonite is higher, increasing by drilling fluid density. At the same time, some hydrophobic groups will be added to on the surface of the modified intelligent thermo-sensitive bentonite, resulting in the decrease of its hydrophilicity, which will increase the dynamic settlement of the intelligent drilling fluid.

4. CONCLUSIONS

In this study, a drilling fluid investigation system was constructed with temperature-sensitive modified bentonite (NIPAM-B). Four properties including rheology, filtration loss reduction, shale wellbore stability, and stability were studied. The results are as follows:

(i) The rheological test of intelligent temperature-sensitive bentonite drilling fluid shows that the intelligent temperature-sensitive bentonite drilling fluid has good viscosity increasing performance. After reaching 60 °C, it can maintain a certain viscosity value and effectively ensure the flow pattern stability of drilling fluid within the range of technical control.

(ii) The filtration loss reduction performance of intelligent temperature-sensitive bentonite drilling fluid system is better than that of bentonite mud system. The filter loss of the former was only 11 mL, the thickness of the filter cake was 0.6 mm, and the filter cake was relatively dense and moderate in thickness, which met the drilling requirements.

(iii) To meet the needs of shale formation drilling and development of shale oil and gas reservoirs, the shale rolling recovery rate of an intelligent temperature-sensitive bentonite drilling fluid system was tested. Finally, it is concluded that the rolling recovery rate of the intelligent thermosensitive bentonite drilling fluid system is 4.92 % higher than that of the bentonite mud system, which is 4.2 times higher than that of the clean water shale.

(iv) In addition, this paper also evaluated the stability of intelligent temperature-sensitive bentonite drilling fluid system. Through the static settlement test and dynamic settlement test of the system, it is concluded that the stability of the intelligent temperature sensitive bentonite drilling fluid system is higher than that of the bentonite drilling fluid system. The reason for this conclusion is the increase of hydrophobic groups on the surface of modified bentonite. But the static settlement factor of the former is much lower than 0.52, which is relatively stable.

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