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Synthesis and properties of high temperature rheology modifier for high density synthetic-based drilling fluids

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A low-molecular-weight fatty acid amide-based rheology modifier, HRM, suitable for use at high temperatures was synthesized by reacting a dimeric fatty acid with 2-amino-1,3-propanediol in a 1:1.5 molar ratio. It was designed to address the insufficient sag resistance of high-density synthetic drilling fluids at high temperatures. Structural characterization, mechanism analysis, and performance evaluation were also conducted. The results of thermogravimetric analysis and emulsion stability showed that HRM has excellent thermal stability below its decomposition threshold of 307 °C, and it can adsorb at the oil-water interface, effectively reducing interfacial tension and enhancing the demulsification voltage and the emulsification rate. HRM effectively improved the structural strength of the synthetic-based drilling fluid system by bridging the emulsion droplets to form a gel-like network structure, thereby effectively improving solid-phase suspension ability and settlement stability.
Keywords: Synthetic-based drilling fluid; Rheology modifier; Organic clay, High-temperature, Suspension capability

Синтез та властивості високотемпературного реологічного модифікатора для бурових розчинів на синтетичній основі високої щільності. *Qiang Sun, Zheng-song Qiu, Tie Geng, Han-yi Zhong, Wei-li Liu, Yu-lin Tang, Jin-cheng Dong*

Модифікатор реології типу аміду жирної кислоти HRM, який може використовуватися в умовах високих температур, був синтезований шляхом реакції димерної жирної кислоти і 2-аміно-1,3-пропандіолу. Проведена структурна характеристика, аналіз механізму та оцінка продуктивності. Результати термогравіметричного аналізу та стабільності емульсії показали, що HRM має чудову термічну стабільність нижче за поріг розкладання 307 °C і може адсорбуватися на межі розділу нафта-вода, ефективно знижуючи міжфазний натяг і підвищуючи напругу деемульгування та швидкість емульгування. HRM ефективно поліпшив структурну міцність системи синтетичного бурового розчину, пов'язуючи краплі емульсії з утворенням сітчастої гелеподібної структури, тим самим ефективно покращуючи здатність до суспензії твердої фази і стійкість до осаду.

1. Introduction

In recent years, China's growing energy demand has driven oil exploration and development into deeper and more geologically complex formations [1-3]. The growing number of complex wells, including deep, ultra-deep, and extended-reach horizontal wells, has placed increasingly stringent demands on drilling fluid performance [4-6]. Compared to water-based drilling fluids, oil-based systems demonstrate superior high-temperature stability, shale inhibition, and lubricity. These advantages significantly reduce drilling complications, making oil-based fluids the preferred choice for high-temperature deep wells [7-9]. Diesel oil, commonly used as the base fluid in oil-based drilling fluids, has a high aromatic hydrocarbon content that promotes a strong colloidal interaction with organic clay, significantly enhancing viscosity and improving shearing strength [10]. As a result, the fluid exhibits excellent rheological properties, which can withstand the transportation of slurry under high temperature and high pressure and effectively prevent the easy settling of barite [11-12]. However, diesel oil contains environmentally hazardous components, including aromatic hydrocarbons and sulfur compounds, which may pose significant toxicity risks and cause environmental pollution problems [13].

With growing environmental awareness, synthetic-based drilling fluids have gained increasing demand. Unlike diesel oil, synthetic oil does not contain harmful aromatic hydrocarbons or sulfur; it can provide excellent biodegradability and is a more environmentally friendly alternative [14-15]. However, synthetic oil exhibits lower kinematic viscosity than diesel oil, which substantially reduces the colloidal efficiency of organic clay. This leads to operational challenges such as worsened electrical stability, increased fluid loss, and settling of solid phases (barite). These issues can subsequently cause well control incidents, increased risk of differential sticking, and reduced wellbore cleaning efficiency, which ultimately compromises drilling safety and operational continuity [16-17]. Consequently, developing high-performance, environmentally friendly synthetic-based drilling fluids demands more advanced additives to overcome these technical challenges.

Current rheology modifiers for drilling fluids, including organic clays, fatty acid amides, and oil-soluble polymers, are employed to improve suspension capacity and prevent the settling of weighting materials [18-20]. Organic clays were prepared through ion exchange reactions, whereby cationic surfactants were intercalated into the interlayer spaces of the clay structure. The short alkyl chains exhibit limited lipophilicity, leading to poor oil compatibility. Consequently, the modified organoclay demonstrates inadequate swelling performance or even structural contraction, failing to achieve the desired viscosity enhancement effect. In contrast, organic clays modified with double long-chain alkyl surfactants demonstrate superior rheological performance in drilling fluids. This enhancement arises from two key factors: (1) the exceptional lipophilicity of surfactants improves oil compatibility and (2) their molecular structure effectively expands the interlayer distance of montmorillonite [21]. However, most organic clays face dual limitations: they lose viscosity-enhancing capacity at 200 °C due to modifier decomposition, while excessive concentrations cause over-thickening that reduces drilling efficiency [22]. As rheology modifiers, oil-soluble polymers were mainly formed by the polymerization of oil-soluble monomers such as styrene, styrene derivatives, acrylate and its derivatives, or the reaction of metal crosslinking agents with polymers containing phosphate ester structures [20, 23]. Many scholars have conducted extensive research on rheology modifiers promoting the development of drilling fluid. Unfortunately, polymer-based rheology modifiers face inherent thermal stability limitations, and their macromolecular structures undergo chain scission and degradation at elevated temperatures, ultimately leading to performance failure due to insufficient thermal resistance [24]. Fatty acid amide rheology modifiers primarily enhance the dynamic shearing strength of drilling fluids by forming hydrogen bonds with other functional groups via the amide groups within the molecule, thereby creating a network structure. Additionally, the interactions between hydroxyl and carbonyl groups in the molecule and other groups further reinforce this network structure, enabling the drilling fluid system to exhibit enhanced dynamic shearing strength and suspension capabilities [25]. This rheology modifier significantly enhances shearing strength performance, while the amide groups in its molecular structure ensure outstanding high-temperature stability in drilling fluids. In summary, fatty acid amides represent an important direction for the development of drilling fluid rheology modifiers and offer great potential for future applications. Therefore, developing high-performance rheology modifiers to improve barite suspension in high-density synthetic-based drilling fluids, particularly under elevated temperatures, remains a critical technological challenge for the drilling industry. Through rational molecular structure design, a high-temperature rheology modifier (HRM) was synthesized by reacting dimer fatty acid with 2-amino-1,3-propanediol at a molar ratio of 1:1.5. The resulting compound significantly enhanced the structural strength experimental workflow designed to accomplish the research objectives.

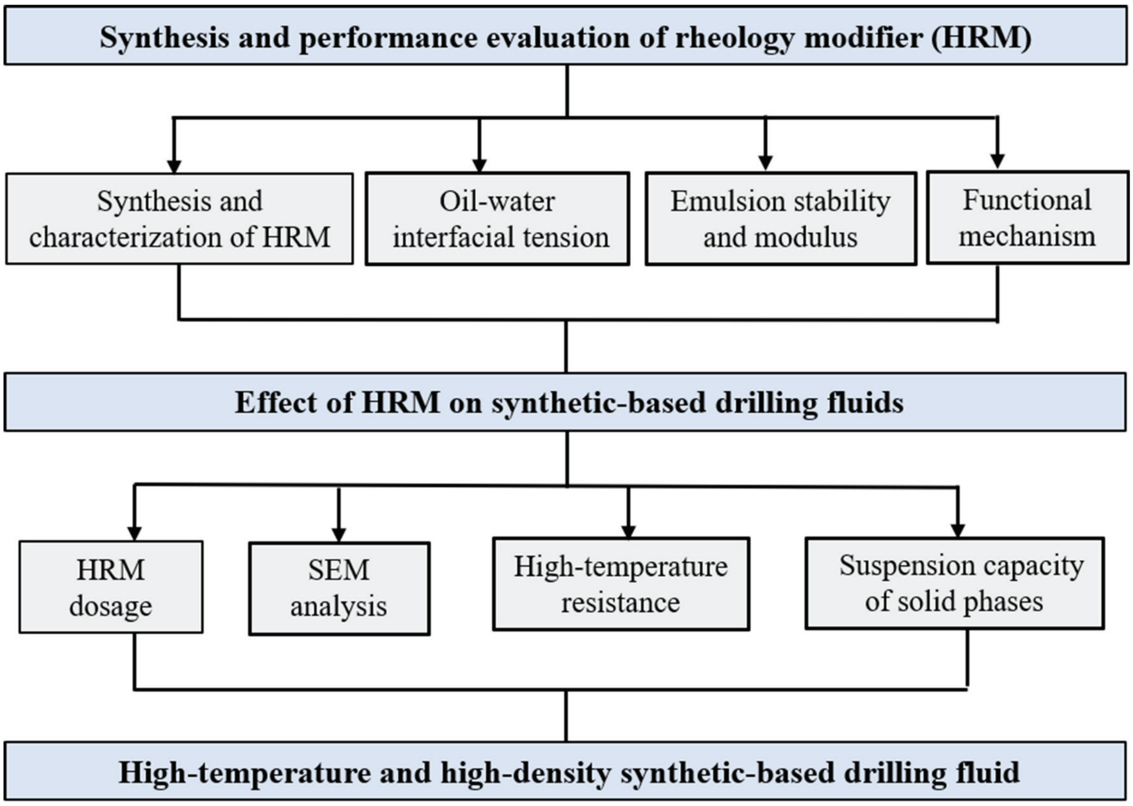

Fig. 1. Experimental flow chart

of synthetic-based drilling fluid systems and improved the suspension capacity of barite. HRM demonstrated exceptional thermal stability, maintaining performance at temperatures up to 200 °C, thereby meeting the stringent requirements for deep well drilling applications.

2. Experimental

2.1. Materials

Analytical-grade dimer fatty acid, potassium hydroxide (KOH), 2-amino-1,3-propanediol, calcium oxide (CaO), and calcium chloride ($CaCl_2$) were supplied by Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). Gas-made oil, used as the base oil for synthetic-based drilling fluid, was provided by China Oilfield Services Co., Ltd. (Zhanjiang, China). The primary emulsifier (HIEMUL), auxiliary emulsifier (HICOAT), wetting agent (HIWET), organic clay (HIGEL), filtrate reducer (HIFLO), and barite (density: 4.2 g/cm^3, as weighting agent) were obtained from Jingzhou Jiahua Tech. Co., Ltd. (Jingzhou, China).

2.2. Methods

In this study, a high-temperature rheology modifier (HRM) was synthesized and applied in high-density synthetic-based drilling fluids. Fig. 1 illustrates the experimental workflow designed to accomplish the research objectives.

2.2.1. Synthesis and structural characterization of HRM

Dimer fatty acids exhibit high viscosity due to hydrogen bonding, making them effective rheology modifiers for synthetic-based drilling fluids. However, their low hydrophilicity limits their performance. To address this, dimer fatty acids were chemically modified with 2-amino-1,3-propanediol to enhance hydrophilicity. The synthesis route is illustrated in Fig. 2. The high-temperature rheology modifier (HRM) was synthesized as follows: A mixture of 0.1 mol dimer fatty acid, 0.15 mol 2-amino-1,3-propanediol, and 0.1 g KOH was added to a three-neck flask and stirred at 250 rpm. The mixture was heated to 100 °C for 30 min under continuous stirring, followed by N_2 purging for 30 min. Subsequently, the temperature was raised to

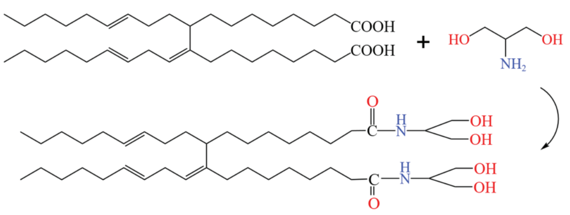

Fig. 2. Synthesis route of HR

175 °C, and the reaction proceeded for 4 h. The water produced by the reaction was removed via vacuum distillation, and the final product was obtained and named the high-temperature rheology modifier (HRM).

The molecular structure of HRM was characterized by Fourier Transform Infrared (FT-IR) spectroscopy using a WQF-520 spectrometer (Beijing Jingke Ruida Technology Co., Ltd., China). The spectrum was acquired in transmission mode with 32 scans at a resolution of 4 cm^{-1}, covering the wavenumber range of 4000-500 cm^{-1}. In addition, the thermal stability of HRM was evaluated using a Q500 series Thermogravimetric Analyzer (Shanghai Lerui Scientific Instrument Co., Ltd., China). Approximately 5 mg of HRM sample was heated from 50 to 500 °C under a nitrogen atmosphere at a constant heating rate of 10 °C/min, and the resulting thermogravimetric (TGA) curve was recorded.

2.2.2. Effect of HRM on oil-water interfacial tension

In synthetic-based drilling fluids, emulsion stability is critical for optimal performance. To evaluate the effect of HRM on water-in-oil emulsion stability, the oil-water interfacial tension was measured at varying HRM dosages using a Teclis Tracker tensiometer (Teclis Instruments, Azergues, France) at 25 °C.

2.2.3. Effect of HRM on emulsion stability

The effect of HRM dosage on water-in-oil emulsion stability was further investigated through demulsification voltage measurements and emulsification rate testing. The emulsion formula is: base fluid (the volume ratio of gas-made oil to 26 wt% $CaCl_2$ aqueous solution is 80:20) +4.0 wt% HIEMUL +1.0 wt% HICOAT + 3.0 wt% CaO + HRM. The emulsions containing varying HRM concentrations were thermally aged at 200 °C for 16 h. Subsequently, the demulsification voltage of the emulsions was measured using a Fann 21,200 electrical stability tester (Fann Instrument Company, Houston, USA) at room temperature. To determine the emulsification rate, the prepared emulsions were transferred to graduated cylinders and statically maintained at room temperature for 24 h. The volume of separated oil phase was quantified to determine the emulsification rate.

2.2.4. Effect of HRM on emulsion modulus

The storage modulus (G') and loss modulus (G") of the emulsions containing varying HRM concentrations were measured using a Haake MARS III rheometer (Thermo Fisher Scientific, USA). The dynamic frequency of the emulsions was scanned in cone-plate mode. The scanning frequency ranged from 0.1 to 10 s^{-1} at a constant temperature of 25 °C.

2.2.5. Effect of HRM on synthetic-based drilling fluids

The basic formula of the synthetic-based drilling fluid was: base fluid (the volume ratio of gas-made oil to 26 wt% $CaCl_2$ aqueous solution is 80:20) +4.0 wt% HIEMUL +1.0 wt% HICOAT + 3.0 wt% CaO + 1.5 wt% HIGEL + 5.0 wt% HIFLO + 1.5 wt% HIWET + barite (ρ = 2.0 g/cm^3). The synthetic-based drilling fluids containing varying concentrations of HRM were thermally aged at 200 °C for 16 h. Following aging, the demulsification voltage was determined, and rheological properties were evaluated at six shear rates (600, 300, 200, 100, 6, and 3 rev/min). These measurements were used to calculate key rheological parameters: apparent viscosity (*AV*), plastic viscosity (*PV*), and yield point (*YP*). The properties were measured at 50 °C in compliance with GB/T 16783.1-2006 (2014), with the calculation formulas provided in Equations 1 to 3. The filtrate loss (*FL*) was measured with a Fann HT4700 high-temperature and high-pressure fluid loss meter (Fann Instrument Company, Houston, USA), and the test temperature was 180 °C. After filtration, the filter cake was air-dried and analyzed using a field-emission scanning electron microscope (Model MIRA-LMS, Tescan Company, Brno, Czech Republic) at an acceleration voltage of 15 keV to evaluate the influence of HRM on its properties.

$$AV = \theta_{600}/2 \tag{1}$$

$$PV = \theta_{600} - \theta_{300} \tag{2}$$

$$YP = 0.511(\theta_{300} - PV) \tag{3}$$

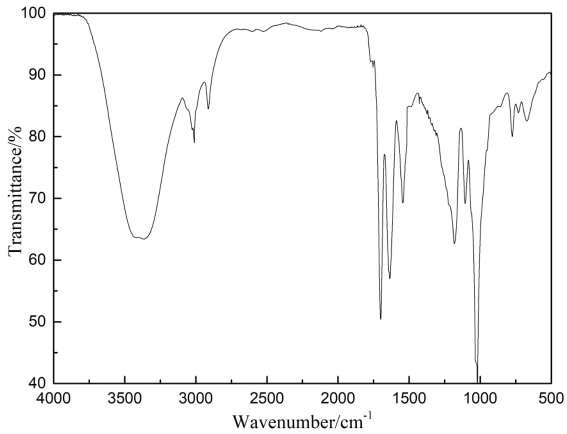

Fig. 3. The FT-IR spectrum of HRM

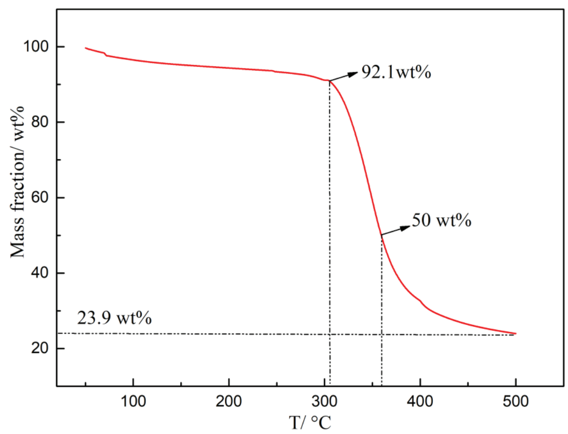

Fig. 4. Thermal stability of HRM

Where:

AV is the apparent viscosity (mPa·s)

PV is the plastic viscosity (mPa·s)

YP is the yield point (Pa)

θ_{600} is the dial reading at 600 rev/min (dimensionless)

θ_{300} is the dial reading at 300 rev/min (dimensionless)

2.2.6. The stability evaluation of synthetic-based drilling fluids

The high-temperature stability of synthetic-based drilling fluids was assessed using samples prepared according to the base formulation and subjected to thermal aging at 180 °C, 200 °C, and 220 °C for 16 h. After aging, the filtrate loss, demulsification voltage, and rheological properties were measured.

The suspension capacity of solid phases in synthetic-based drilling fluids was assessed by pre-aging the fluid at 200 °C for 16 hours. The aged samples were then subjected to static sag testing at 200 °C in an ML-30B precision constant-temperature oven (Suzhou Sutai Electric Heating Equipment Co., Ltd., China) for different periods of time (1, 3, and 5 days) to assess the sedimentation behavior of particles. To quantify the suspension capacity, the density differential (Δρ) between upper and lower fluid layers was measured after static aging. This density variation served as a key parameter to evaluate the effectiveness of HRM in maintaining solid-phase homogeneity in synthetic-based drilling fluids under high-temperature conditions.

3. Results and discussion

3.1. Analysis of Infrared Spectrum

Fig. 3 presents the FT-IR spectrum of HRM with characteristic vibrations of functional groups, confirming its successful synthesis. The broad characteristic peak at 3380 cm^{-1} corresponds to the absorption of the -OH stretching vibrations. The peaks at 2930 and 2850 cm^{-1} belonged to the stretching vibrations of -CH_2-. The characteristic peaks of amide group appeared in the range of 1650 - 1690 cm^{-1}. At 1600 cm^{-1}, the stretching vibration of the carbon-carbon double bond (C=C) was observed. The peak at 720 cm^{-1} is the characteristic peak of -$(CH_2)_n$-. These vibrational signatures collectively verify the expected molecular structure of the high-temperature rheology modifier.

3.2. Thermogravimetric Analysis of HRM

Fig. 4 presents the thermogravimetric analysis (TGA) profile of HRM, demonstrating its thermal decomposition behavior. The material exhibited progressive mass loss with increasing temperature, with three stages of degradation being identified. An initial 2.1% mass loss in the temperature range from 50°C to 100 °C corresponded to the evaporation of free interstitial water molecules within the sample matrix. This low-temperature mass loss represented physically adsorbed moisture that was readily released below the boiling point of water, consistent with the hygroscopicity of the material observed during storage. In the temperature range from 100°C to 307 °C, the sample exhibited a gradual decrease in mass by 7.9%, which corresponded to the release of both adsorbed water (hydrogen-bound to surface sites) and low-molecular volatile components [26, 27]. It is important to note that this step did not have a negative impact on the effectiveness of the rheology modifier. In the temperature range from 307°C to 500 °C, the sample underwent rapid thermal decomposition exhibiting a sharp mass

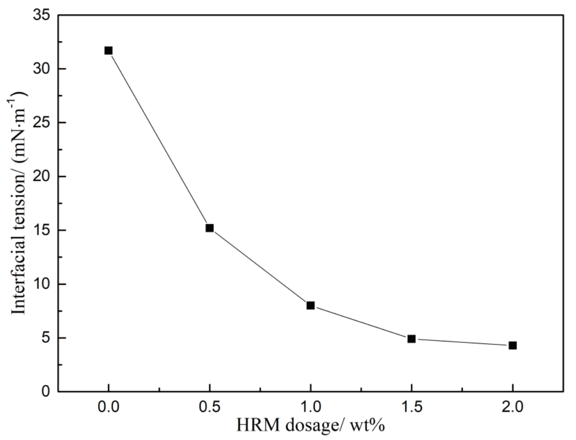

Fig. 5. Effect of HRM on oil-water interfacial tension

loss of 68.2%. This transition corresponded to the splitting of functional groups (amide group, carboxyl group) and the rupture of aliphatic main chains (C-C bond dissociation) [28]. The sample demonstrated excellent thermal stability below its decomposition threshold of 307 °C, maintaining structural integrity under high-temperature drilling conditions.

3.3. Analysis of oil-water interfacial tension

Fig. 5 demonstrates the dose-dependent interfacial activity of HRM. As indicated, the oil-water interfacial tension decreased significantly with increasing HRM concentration, reaching a critical micelle concentration (CMC) at 1.5 wt%, beyond which no significant further reduction occurred. In principle, the lower the oil-water interfacial tension, the more stable the water-in-oil drilling fluid becomes. This was due to the presence of multiple hydrophilic groups in HRM molecules, derived from 2-amino-1,3-propanediol, which exhibited characteristics similar to those of Gemini surfactants [29, 30]. These HRM molecules can adsorb at the oil-water interface, effectively reducing interfacial tension and enhancing the emulsion stability of the water-in-oil drilling fluid system.

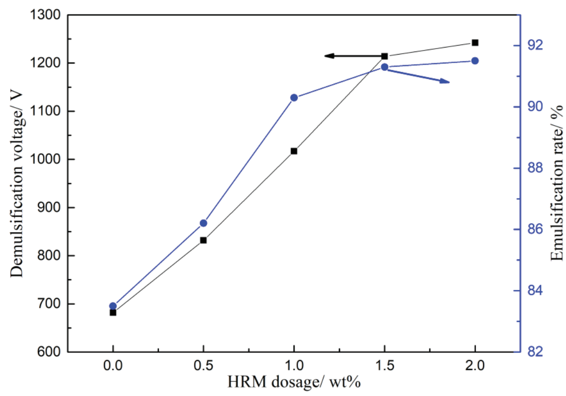

Fig. 6. Effect of HRM on emulsion stability

3.4. Analysis of emulsion stability

The effect of HRM dosage on the stability of water-in-oil emulsion is shown in Fig. 6. In water-in-oil emulsions, both the demulsification voltage (increasing from 678 to 1235 V) and the emulsification rate (rising from 83.3% to 91.4%) systematically increased with HRM concentration (0-2.0 wt%), indicating that HRM can effectively stabilize the emulsion. HRM molecules spontaneously adsorb at the oil-water interface, self-assembling into elastic-dominant interfacial films that provided a mechanical barrier against droplet coalescence [25]. Consequently, the stability of the water-in-oil drilling fluid system can be enhanced by the addition of HRM.

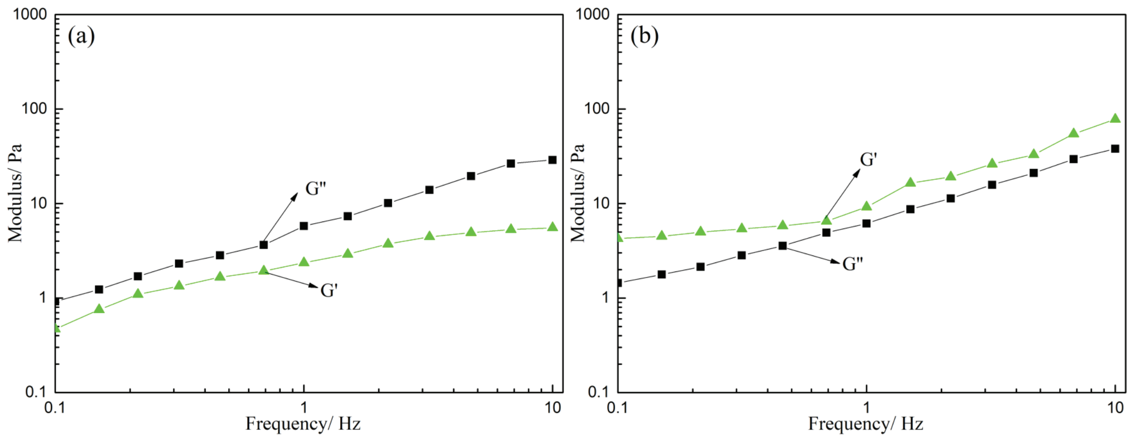

Fig. 7. Effect of HRM on emulsion stability. (a) the emulsion without HRM; (b) the emulsion with 1.5 wt% HRM.

Table 1 Performance of drilling fluids with varying HRM concentrations

HRM dosage/ wt%	Condition	*AV*/ mPa·s	*PV*/ mPa·s	*YP*/ Pa	φ6 /φ3	Demulsification voltage/ V	*FL*/ mL
0	Before aging	44	39	5	5/3	573	
	After aging	33.5	31	2.5	2/1	424	10.8
0.5	Before aging	46	40	6	6/5	738	
	After aging	43	38	5	5/4	689	6.4
1.0	Before aging	52	44	8	9/8	832	
	After aging	49	42	7	10/8	910	4.2
1.5	Before aging	56	46	10	12/11	921	
	After aging	54	43	11	12/10	1029	3.6

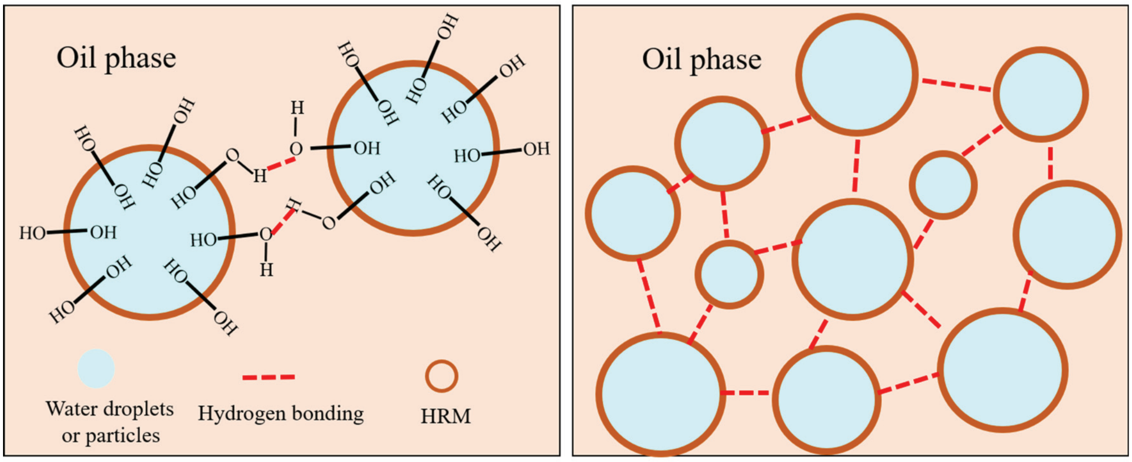

Fig. 8. Functional mechanism of HRM

3.5. Analysis of emulsion modulus

The effect of HRM on the storage modulus (*G*') and loss modulus (*G*") of the emulsions is shown in Fig. 7. As the oscillation frequency increased, both the storage modulus (*G*') and loss modulus (*G*") of the emulsions showed an upward trend, indicating that the increased frequency enhanced the interactions between emulsion droplets. For the emulsion without HRM, *G*" was higher than *G*', showing that the viscous transition occurred and the emulsion was in liquid state. For the emulsion with 1.5 wt% HRM, *G*' was greater than *G*", indicating a transition from a liquid state to a "gel state". This change was attributed to HRM adsorption at the oil-water interface, which enhanced the elasticity of the emulsion film and improved the emulsion's stability [31, 32].

Functional mechanism of HRM: As shown in Fig. 8, in the emulsions, the synergistic action of the primary and auxiliary emulsifiers led to the formation of a relatively stable system. The high-temperature rheology modifier (HRM) with amphiphilic molecular structure can tend to adsorb at the oil-water interface. Additionally, due to the solubilization of the emulsifiers at the oil-water interface, the concentration of HRM at the oil-water interface was further enhanced. The HRM molecules can form a "film" on the oil-water interface due to hydrogen bonding. On one hand, the accumulation of HRM at the interface strengthened the interfacial film, contributing to the stability of the emulsion. On the other hand, the hydrogen bonding between HRM adsorbed on the surfaces of different droplets enhanced the interaction forces between droplets within the emulsions.

3.6. Performance of drilling fluids with varying HRM concentrations

Table 1 shows the effect of HRM dosage on drilling fluid performance. The drilling fluid without HRM displayed a low demulsification voltage, and after thermal aging, its viscosity and shearing strength dropped significantly, leading to increased filtration loss. As the HRM concentration increased, the demulsification stress of the drilling fluid gradually increased and the filtration losses decreased accordingly. It is important to note that the viscosity and shearing strength of the drilling fluid contain-

Table 2 High-temperature characteristics of drilling fluids

Aging Condition	HRM dosage/ wt%	*AV*/ mPa·s	*PV*/ mPa·s	*YP*/ Pa	φ6 /φ3	Demulsification voltage/ V	*FL*/ mL
180 °C × 16 h		40	34	6	4/3	583	6.6
200 °C × 16 h	0	33.5	31	2.5	2/1	424	10.8
220 °C × 16 h		30	29	1	2/0	367	28.3
180 °C × 16 h		58	45	13	12/10	1130	3.4
200 °C × 16 h	1.5	54	43	11	12/10	1029	3.6
220 °C × 16 h		48	40	8	10/9	865	5.6

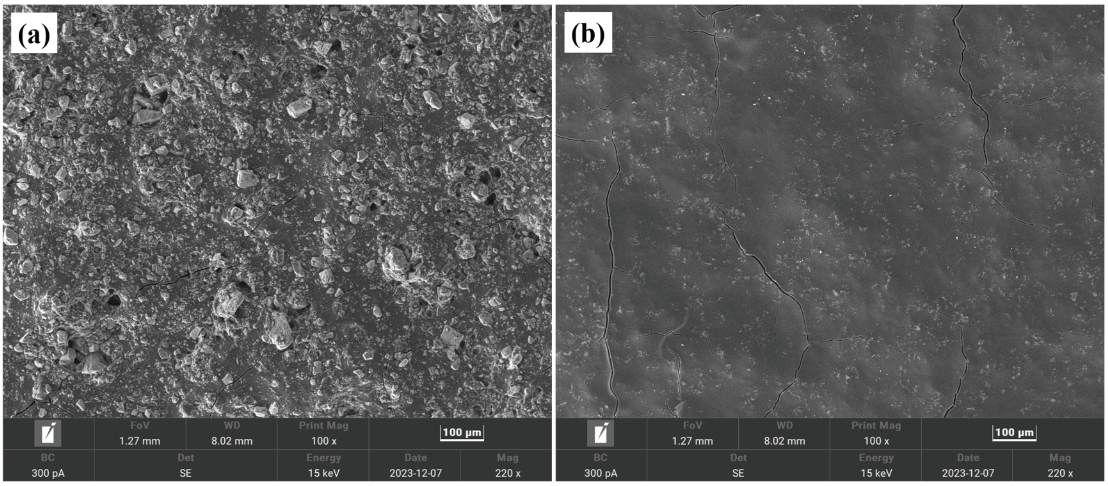

Fig. 9. SEM images of filter cakes. (a) the fluid without HRM; (b) the fluid with 1.5 wt% HRM.

ing HRM remained relatively stable even after high-temperature hot rolling, indicating that HRM enhanced the thermal stability of drilling fluids. An explanation for this phenomenon was as follows: the surfaces of the filtrate reducer and barite materials contain hydroxyl groups, and in the drilling fluid, the HRM was not only adsorbed at the oil-water interface but also interacted with the surfaces of particles and droplets through hydrogen bonding. This can strengthen droplet-droplet, droplet-particle and particle-particle interactions, leading to the formation of 3D network structures that can enhance viscosity and improve shearing strength [33, 34], thereby increasing the thermal stability of the drilling fluids, as illustrated in Fig. 8.

Fig. 9 presents comparative SEM images of the filter cakes, clearly demonstrating significant microstructural refinement through incorporation of the rheology modifier. The filter cake without HRM (Fig. 9a) exhibited a loose, porous microstructure which resulted in poor sealing and increased filtration losses. The filter cake with 1.5 wt% HRM (Fig. 9b) showed a dense and uniform layered structure. HRM facilitated the formation of a continuous solid-phase network via bridging effects, thereby enhancing the structural integrity and reducing the permeability of the filter cake.

3.7. High-temperature stability of drilling fluids

Table 2 shows high-temperature stability of drilling fluids. As aging temperature increased, the drilling fluids without HRM showed progressive deterioration in rheological properties (viscosity and shearing strength) and emulsion stability (demulsification voltage), leading to significantly elevated filtration loss. The addition of 1.5 wt% HRM to the drilling fluids significantly enhanced both the shearing strength and demulsification voltage. The optimized fluids exhibited outstanding high-temperature performance, stable rheological properties, excellent emulsion stability and low filtration loss, indicating that HRM improved the high-temperature resistance of the drilling fluid, enabling the drilling fluid to withstand temperatures up to 220 °C.

3.8. Sedimentation of drilling fluid particles

Table 3 presents effect of HRM on the sedimentation properties of drilling fluid particles.

Table 3. Effect of HRM on particle sedimentation behavior of drilling fluids

HRM dosage/ wt%	Standing times/ d	ρ_{upper} / g·cm^{-3}	ρ_{lower} / g·cm^{-3}
0	0	2.0	2.0
	1	1.96	2.08
	3	1.71	2.24
	5	1.56	2.31
1.5	0	2.0	2.0
	1	2.0	2.0
	3	1.99	2.07
	5	1.94	2.10

Prior to static aging, the drilling fluid exhibited homogeneous density distribution. As static aging progressed, the density difference (Δρ) between the upper and lower layers of the liquid gradually increased. The incorporation of 1.5 wt% HRM significantly enhanced the suspension ability of the drilling fluid for the solid phase, and no obvious sedimentation phenomenon occurred at the bottom of the drilling fluid, indicating that HRM improved the high-temperature static stability performance.

4. Conclusions

(1) A high-temperature rheology modifier (HRM) was synthesized by reacting dimer fatty acid with 2-amino-1,3-propanediol at a molar ratio of 1:1.5; it exhibited characteristics similar to those of Gemini surfactants. HRM molecules can be adsorbed at the oil-water interface, effectively reducing interfacial tension and enhancing the emulsion stability of the water-in-oil drilling fluid system.

(2) HRM molecules form an interfacial film via hydrogen bonding. The hydrogen bonding between HRM adsorbed on the surfaces of different droplets enhance the interaction forces between droplets within the emulsions, which can increase the viscosity and improve the shear strength, thereby improving the suspending ability and preventing the sedimentation of weighting agents.

(3) HRM increased the thermal stability and structural integrity of the drilling fluids and reduced the permeability of the filter cake. The incorporation of HRM significantly enhanced the suspension ability of the drilling fluid for the solid phase, indicating that HRM improved the high-temperature static stability performance.

CRediT authorship contribution statement: Qiang Sun: Conceptualization, Methodology, Investigation, Writing - original draft. Zheng-song Qiu: Data curation, Investigation. Tie Geng: Formal analysis, Investigation. Han-yi Zhong: Funding acquisition. Weili Liu: Project administration. Yu-lin Tang: Data curation. Jin-cheng Dong: Investigation.

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