Petroleum Science 18 (2021) 1698–1708

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

Investigation of regulating rheological properties of water-based drilling fluids by ultrasound

Wei-An Huang [a, d, *], Jing-Wen Wang [a, e], Ming Lei [a], Gong-Rang Li [b], Zhi-Feng Duan [c], Zhi-Jun Li [c], Shi-Fu Yu [c]

[a] School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, 266580, Shandong, China
[b] Sinopec Shengli Petroleum Engineering Co., Ltd. Drilling Technology Research Institute, Dongying, 257017, Shandong, China
[c] Oil and Gas Technology Research Institute of Changqing Oilfield Branch, Xi'an, 710018, Shaanxi, China
[d] Key Laboratory of Unconventional Oil & Gas Development, China University of Petroleum (East China), Qingdao, 266580, Shandong, China
[e] PetroChina Daqing Oilfield Co., Ltd., Research Institute of Oil Production Engineering, Daqing, 163000, Heilongjiang, China

A R T I C L E I N F O

Article history:
Received 4 May 2020
Accepted 26 January 2021
Available online 2 September 2021

Edited by Yan-Hua Sun

Keywords:
Ultrasound
Suspension
Water-based drilling fluid
Rheological property

A B S T R A C T

Regulating rheological properties of water-based drilling fluids has always been a hot topic. This paper proposed a new method for regulating rheological properties of water-based drilling fluids by ultrasonic field. The experimental results showed that the ultrasound increased the viscosity and yield point of bentonite suspension by reducing the particle size of clay, destroying the network structure between clay particles, increasing the mud yield and the cation exchange capacity of bentonite, and promoting the hydration dispersion of bentonite. The change of rheological property showed a memory effect at room temperature and high temperature. Besides, the ultrasonic energy affected the network structure between clays and polymer chains, thus regulating the rheological properties of the bentonite-polymer system. For two types of drilling fluids investigated, the rheology of the poly-sulfonate drilling fluid was regulated by damaging the grid structure between additives and clays by low-power ultrasound and reducing the clay particle size by high-power ultrasound, while the rheology of the deep-water drilling fluid was mainly regulated by disentangling the spatial grid structure between additives. Additionally, ultrasound showed no effect on the lubricity, inhibition and stability of drilling fluids, which proved the feasibility of ultrasound to regulate rheological properties of water-based drilling fluids.

1. Introduction

The increasing demand for oil and gas and the decreasing oil and gas resources in the middle and shallow strata have driven the exploitation of oilfield towards the deep formation and deep-sea field, which puts forward higher requirements for drilling fluids. Oil-based drilling fluid has some advantages in shale stability and temperature resistance, while it is environmentally unfriendly and high-cost (Ning et al., 2010; Zhao et al., 2008). At present, water-based drilling fluid technologies have made breakthrough in the aspects of anti-sloughing performance and high-temperature stability (Zhong et al., 2011, 2012, 2013). However, the regulating method of rheological properties of water-based drilling fluids is still a hot and difficult point worldwide. Presently, the main means of regulating the rheology of water-based drilling fluids, including reducing solids content and adding rheological regulators, have the disadvantages of high cost, inflexible and environmentally hazardous.

In this study, a new method using the ultrasonic field to regulate the rheology of water-based drilling fluids is proposed. Ultrasound is a sound wave with a vibration frequency higher than 20 kHz and a short wavelength, which can generate cavitation, mechanical and thermal effects on the suspension to change the rheology of the suspension (Nguyen et al., 2013; Sainz Herrán et al., 2010). Mechanical effect refers to that ultrasounds force the medium to vibrate intensively and to produce a strong unidirectional force. Cavitation refers to the resonance of the original or new microbubbles as ultrasounds pass through the liquid at a certain

* Corresponding author. School of Petroleum Engineering, China University of Petroleum (East China), Qingdao, 266580, Shandong, China
E-mail addresses: hwanxx@upc.edu.cn, masterhuang1997@163.com (W.-A. Huang).

https://doi.org/10.1016/j.petsci.2021.09.006

frequency (Kirpalani and McQuinn, 2006). Thermal action means that when sound waves pass through the medium, the medium receives certain sound energy and causes local high temperature (Santos-Zea et al., 2019). Ultrasonic dispersion mainly comes from ultrasonic cavitation (Li et al., 2001). Ultrasonic cavitation means that the alternating ultrasonic pressure is greater than the static fluid pressure when there exists strong enough ultrasonic action in a liquid medium. In the negative pressure region of sound pressure, the peak value of the negative pressure can not only counteract the static pressure but also form a local negative pressure zone in the liquid. When the negative pressure is enough to overcome the binding force between the molecules of the liquid, the liquid will be pulled to form a cavity, resulting in cavitation bubbles. When the positive pressure zone of sound pressure arrives, the cavitation bubble produces a closed collapse. Such alternating reciprocating motion forms uniform and effective agitation in the liquid, resulting in the transformation of uniform dispersion of solid particles in the suspension into a continuous phase. The effect of ultrasound on rheological properties of the suspension has been widely applied in the field of food processing. Ultrasound can effectively reduce particle size and decompose some molecules in plants, thus regulating rheological properties of the suspension (Fu et al., 2019; Huang et al., 2018; Laux et al., 2018; Ruiz-Hernando et al., 2010). Ultrasonic cavitation can produce huge energy, affecting the morphology and surface properties of the suspension phase and controlling rheological properties of other suspension systems such as water-based drilling fluid (Dong et al., 1998; Marchessault et al., 1961; Shafiei-Sabet et al., 2012, 2013; Wang et al., 2003).

Recently, a series of studies have been made based on this theory. Yang et al. (2005) treated clay suspension with ultrasound and the particle size became smaller, correspondingly the specific surface area and the desorption rate of hexadecyl trimethyl ammonium bromide increased. Yu et al. (2009) proposed that the ultrasonic oscillation would efficiently reduce sludge particle size without pollution. Manoochehri et al. (2015) prepared submicron vermiculite particles by using a probe supersonic instrument. Kuang et al. (2017) found that ultrasonic dispersion significantly improved the dispersion stability of some substances in water. However, the effect of ultrasound on rheological properties of different systems has not been thoroughly investigated in these studies.

At present, the research and application of ultrasound in the oil field mainly include oil displacement, scale removal, cleaning micro-cracks (Hamida and Babadagli, 2008; Ye et al., 2010). There is no report on the improvement of drilling fluid performance by ultrasound. Therefore, in this study, a new method is proposed to regulate the rheology of water-based drilling fluid by ultrasound. The mechanism of ultrasonic-assisted rheological regulation is investigated. The rheological behavior of water-based drilling fluids treated by ultrasound at different ultrasonic parameters is analyzed. Besides, the influence of ultrasound on other properties including lubricity, inhibition and settling stability of the water-based drilling fluid is studied, and the feasibility of ultrasound regulating the rheology of the water-based drilling fluid is investigated.

2. Materials and methods

2.1. Materials and facilities

Calcium bentonite, sodium bentonite, commonly-used drilling fluid tackifiers including amphoteric polymer (FA367 and 80A51), polyacrylamide potassium salt (KPAM) and xanthan gum (XC) and viscosity reducers involving sulfonated tannins (SMT), zwitterionic viscosity reducer (XY-27) and silicon fluoride viscosity reducer (SF260) were all industrial grade. Methylene blue was purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). The poly-sulfonate drilling fluid contained 4 wt% calcium bentonite-base slurry, 0.2 wt% sodium hydroxide, 0.5 wt% flow regulator, 5 wt% fluid loss additive (SD101), 3 wt% fluid loss additive (SD201), 2 wt% anti-collapse agent, 3 wt% white oil (7#), 0.3 wt% Span80 and barite. The deep-water drilling fluid was composed of 2 wt% calcium bentonite-base slurry, 0.2 wt% sodium hydroxide, 0.35 wt% flow regulator, 1 wt% inhibitor (SDJA), 0.5 wt% polyanionic cellulose filtration reducer (PAC-LV), 5 wt% sulfonated phenolic resin filtration reducer (SMP-3), 1.5 wt% lubricant (LUBE), 4 wt% KCl, 10 wt% NaCl and barite. The density of the poly-sulfonate drilling fluid and the deep-water drilling fluid is 1.5 g/cm^3.

Ultrasound generator (JY-92IIDN ultrasonic cell disruptor, Ningbo Xinzhi Biotechnology Co., Ltd. Shanghai, China) possesses a single processing capacity of 300 mL, an ultrasonic frequency of 20–24 kHz, an ultrasonic power of 0–950 W (watt), and an adjustable temperature range from 25 °C to 90 °C.

2.2. Methods of ultrasonic treatment

During ultrasonic treatment, the suspension was placed in the closed chamber of the ultrasonic cell pulverizer. The tip of the amplitude transformer was submerged in liquid, and then the chamber was closed and a desired ultrasonic power and ultrasonic time were set. After ultrasonic treatment, the cooled suspension was removed and its rheological properties were tested. The working diagram of the ultrasound is shown in Fig. 1.

2.3. Rheological measurement

The commonly used Fann35A six-speed rotary viscometer cannot fully characterize the rheological curve and rheological parameters of suspension due to its limitation of shear rate. In this study, the rheological measurement was performed on a Brookfield rotation viscosimeter DV1 (Brookfield, USA) incorporating rheological theory (Huang et al., 2020). According to American Petroleum Institute (API) guidelines (API RP 13B-1 2019) in drilling engineering, the apparent viscosity of the fluid could be measured directly by the viscometer. The rotational speed of the viscometer

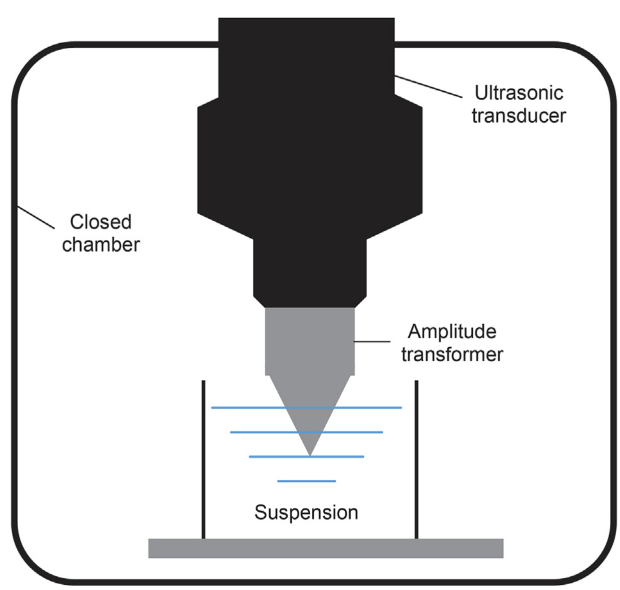

Fig. 1. The working diagram of ultrasonic cell disruptor.

was converted to the value of the shear rate, which is multiplied by the apparent viscosity to obtain the corresponding value of the shear stress. Then, the shear stress-shear rate curve was drawn, and the curve was fitted with the Herba model. According to the Herba rheological equation, the flow index, consistency coefficient and static shear force were obtained. In addition, the points with lower shear rate were eliminated, and the remaining points were fitted with the Bingham model. The fluid plastic viscosity and yield point were obtained according to the Bingham equation.

2.4. Ultrasonic treatment on calcium bentonite suspensions

2.4.1. Investigation of changes in rheological properties

Bentonite is an important part of drilling fluid, and the application of ultrasound has a direct effect on bentonite. In this paper, calcium bentonite was selected to analyze the rule of ultrasound regulating the rheological properties of suspension. The calcium bentonite suspensions of different concentrations 1 wt%, 2 wt%, 3 wt%, 4 wt%, 5 wt%, 6 wt%, 7 wt% and 8 wt% were prepared and placed at room temperature for 24 h, and then the samples were treated by ultrasound at the power of 950 W for 20 min. The rheological parameters including plastic viscosity, apparent viscosity and yield point of suspensions were measured before and after ultrasonic treatment.

The 8 wt% calcium bentonite suspension were prepared and treated by ultrasound at the power of 760 W for 20 min. Then the suspension was divided into 3 parts which were noted as suspension 1, 2, and 3, respectively. The changes of plastic viscosity, apparent viscosity and yield point of 1 over time was evaluated and memorability of effects of ultrasonic treatment was explored. To investigate the influence of ultrasound on the temperature resistance of suspension, suspensions 2 and 3 were aged for 16 h at 70 °C and 120 °C respectively, and the rheological parameters of suspensions 2 and 3 before and after aging were compared.

Ultrasonic power and ultrasonic time are important parameters of ultrasonic. The 4 wt% calcium bentonite suspension was prepared and divided into 10 parts. The plastic viscosity, yield point, fluidity index and consistency coefficient of suspensions under different ultrasonic power (95, 285, 475, 665 and 855 W) and ultrasonic time (5, 10, 15, 20, and 25 min) were explored, respectively, and the rules of ultrasonic regulation of suspension rheological properties were further analyzed.

2.4.2. Evaluation of calcium bentonite properties

The particle size distribution, mud yield and cation exchange capacity of calcium bentonite in suspension were evaluated, and the influence of ultrasound on calcium bentonite was analyzed. The 8 wt% calcium bentonite suspension was prepared and treated by ultrasound at the power of 190, 380, 570, and 760 W for 10, 20, and 30 min, respectively. The particle size distribution and specific surface area of bentonite particles before and after treatment were determined by a Laser Particle Size Analyzer (Bettersizer 2000, Dandong Baxter Instrument Co., Ltd, Liaoning, China).

Mud yield indicates the slurry-making capacity of bentonite, that is the volume of suspension, whose apparent viscosity is 15 mPa•s, prepared by bentonite per unit weight. The less bentonite is needed for the suspension to reach a certain viscosity, the higher the mud yield is, and the stronger the slurry-making capacity is. The calcium bentonite with different mass (70, 80, 90, and 100 g/L) was used to prepare suspensions with different viscosities. The suspensions were treated by ultrasound for 20 min at the power of 760 W, and the apparent viscosities before and after treatment were tested.

The 0.5 wt% calcium bentonite suspension was prepared and treated by ultrasound for 20 min at the power of 190, 380, 570, and 760 W, respectively. The methylene blue capacity of the suspension before and after ultrasonic treatment was determined by methylene blue titration, that is, the total cation capacity of bentonite.

2.5. Ultrasonic treatment on calcium bentonite suspension containing additives

The additives of FA367, 80A51, KPAM, XC, SMT, XY-27, and SF260 were added to the calcium bentonite suspensions (4 wt%) and the plastic viscosity, apparent viscosity, yield point and API filtration of suspensions before and after ultrasonic treatment (760 W, 20 min) were tested. After ultrasonic treatment for 20 min at 760 W, the suspensions were then aged at 120 °C for 16 h and the parameters were measured.

2.6. Ultrasonic treatment on water-based drilling fluids

2.6.1. Rheological property investigation

The conventional poly-sulfonate drilling fluid and deep-water drilling fluid were aged at 77 °C for 16 h. The aged drilling fluids were treated by ultrasound at the ultrasonic power of 95, 285, 475, 665, 855 W, respectively. The rheological properties of drilling fluids before and after ultrasonic treatment were tested to investigate the changes of the rheology of water-based drilling fluids by ultrasound with different ultrasonic power.

In addition, the two aged drilling fluids were treated by ultrasound with the ultrasonic power of 475 W for 5, 10, 15, 20, 25, and 30 min, respectively, to investigate the changes of rheology of water-based drilling fluids caused by ultrasonic time.

2.6.2. Measurements of other properties

The lubricity, inhibition and settling stability of drilling fluids before and after ultrasonic treatment were tested.

(1) Lubricating property

Excellent lubricity of drilling fluids is essential for normal drilling. The hydraulic lubrication coefficient of the aged drilling fluids was measured by an extreme pressure lubrication instrument EP-2A (Qingdao Taifeng Petroleum Instrument Co., Ltd, Shandong, China) before and after ultrasonic treatment with the power of 760 W.

(2) Hydration inhibition property

The aged deep-water drilling fluid and poly-sulfonate drilling fluid were treated by ultrasound with the ultrasonic power of 760 W for 20 min. According to SY/T 5613-2000, sodium bentonite was selected to measure the linear expansivity in the drilling fluids before and after ultrasonic treatment.

(3) Settling stability

The aged drilling fluids were treated by ultrasound for 20 min at the power of 760 W. The drilling fluids before and after ultrasonic treatment were placed in a measuring cylinder for 24 h, respectively. The densities of the top and the bottom liquid column were measured to calculate the static settling factor *f*, as shown in Eq. (2).

$$f = \frac{\rho_b}{\rho_t + \rho_b} \tag{2}$$

where *f* is the static settling factor, ρ_t and ρ_b are the densities of the top and bottom liquid columns, respectively.

Petroleum Science 18 (2021) 1698–1708

3. Results and discussion

3.1. Effect of ultrasound on calcium bentonite suspension

3.1.1. Effect of ultrasound on calcium bentonite suspensions of different concentrations

The effect of ultrasound on rheological properties of the calcium bentonite suspensions of different concentrations is shown in Fig. 2. The apparent viscosity of the suspension increased after sonication. The change of the plastic viscosity of the suspension fluctuated and there was no obvious distinction before and after ultrasonic treatment. When the bentonite concentration was 7 wt%, the apparent viscosity and yield point of the suspension changes significantly. The above phenomena indicated that ultrasound could regulate the rheology of bentonite suspension. If the suspension was treated by ultrasound at appropriate ultrasonic parameters, the rheological parameters of the suspension would change more regularly to meet different requirements. Given the bentonite is the basic material of the water-based drilling fluid, the results provided an experimental basis for regulating rheology of the water-based drilling fluid by ultrasound.

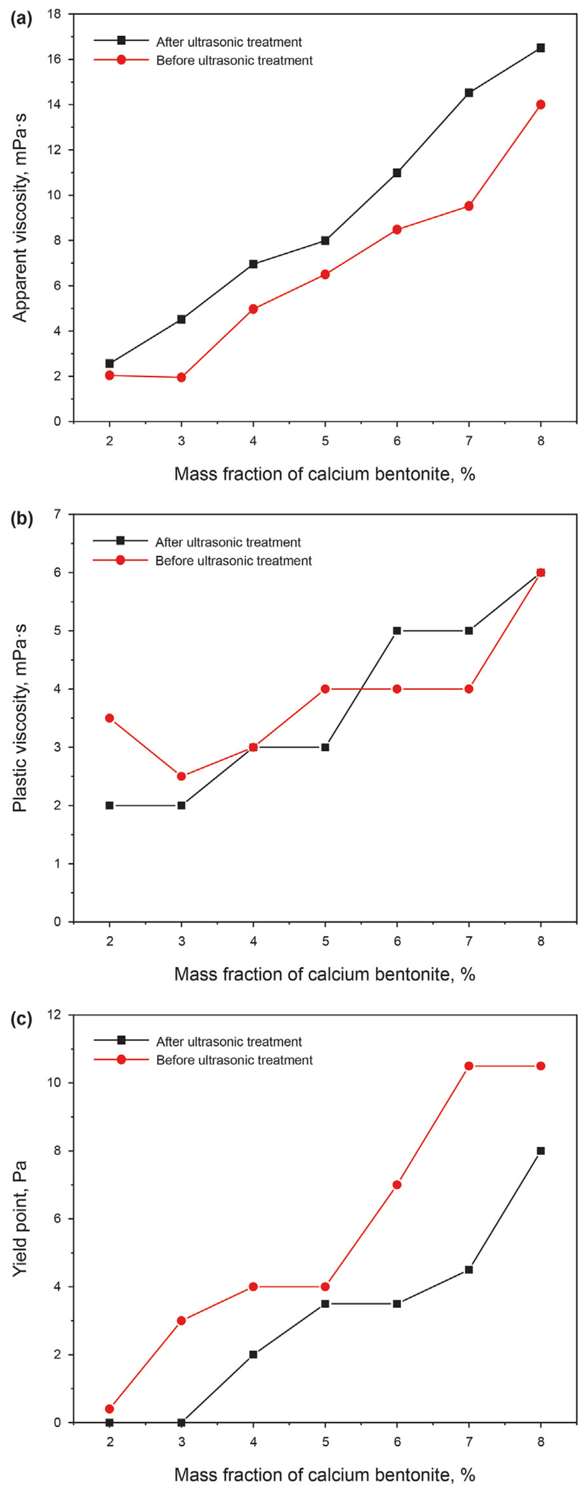

Fig. 2. (**a**) Apparent viscosity, (**b**) plastic viscosity, and (**c**) yield point of bentonite suspensions of different concentrations before and after ultrasonic treatment.

3.1.2. Memory effects of regulating rheology by ultrasound

The changes of rheological properties of the treated suspension over time were evaluated and the results are shown in Fig. 3. The rheological parameters tended to be stable over time, which indicated that the ultrasound changed the properties of the suspension and the change was maintained. The apparent viscosity and the yield point gradually increased after setting for 2 h. Ultrasonic cavitation could produce local high temperature and high pressure, which caused disassembling of clay particles and increased the specific surface area (Liu et al., 2015). The particles were further hydrated and dispersed, and the local high temperature reduced the free water content (Horst et al., 1999; Thompson and Doraiswamy, 1999), which macroscopically increased the viscosity of the suspension. Therefore, the water-based drilling fluid could maintain rheological stability during drilling because of the memory effect.

After ultrasonic treatment, the suspension was aged at 70 °C and 120 °C for 16 h, and its rheological parameters changed slightly, as depicted in Fig. 4. This indicated that ultrasound changed the properties of the suspension, which could be maintained at high temperature. After aging at 120 °C for 16 h, the apparent viscosity and the plastic viscosity of the suspension remained unchanged, and the yield point first increased and then decreased, but the slight change could be ignored. Therefore, the high-temperature aging could retain or even strengthen the regulation of the suspension rheology by ultrasound. This provided a guarantee for the water-based drilling fluid regulated by ultrasound to maintain stable performance in the high-temperature drilling process.

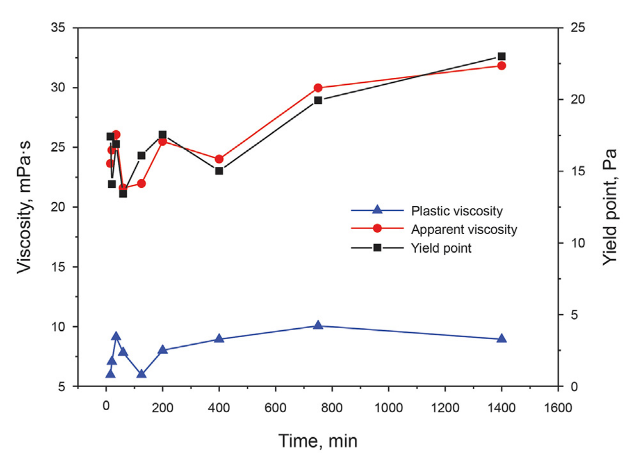

Fig. 3. Changes of rheological parameters of the ultrasound-treated calcium bentonite suspension over time.

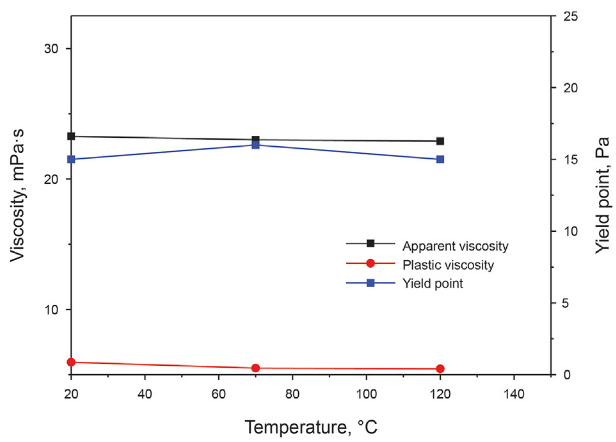

Fig. 4. Changes of rheological parameters of ultrasound-treated calcium bentonite suspension before and after high temperature aging.

3.2. Effect of ultrasonic parameters on rheological properties of calcium bentonite suspension

3.2.1. Ultrasonic power

Fig. 5 shows the changes of the rheological parameters of the calcium bentonite suspension after ultrasonic treatment with different ultrasonic power. The plastic viscosity and yield point increased almost linearly with the increase in ultrasonic power, and there was no rheological mutation. The flow index did not change regularly, while the consistency coefficient decreased greatly after the ultrasonic power exceeded 665 W.

3.2.2. Ultrasound time

The effect of ultrasonic time on rheological properties of suspension is shown in Fig. 6. With the increase in time, the plastic viscosity of the suspension increased rapidly in a short time while changed slowly after 5 min. The yield point gradually increased, and the fluidity index slightly decreased. The consistency coefficient increased rapidly within 10 min, and then changed slowly. All the rheological parameters tended to reach equilibrium after 20 min of sonication, indicating that the rheological parameters of the 100 mL suspension were completely regulated by ultrasound within 20 min.

Therefore, both the ultrasonic power and ultrasonic time changed the rheological parameters of suspension regularly, and the ultrasonic power was the main factor. It is expected that the regular change and controllability of the rheological properties of the suspension can be realized by adjusting the ultrasonic parameters.

3.3. Effect of ultrasound on calcium bentonite in suspension

3.3.1. Particle size distribution

The particle size and specific surface area of the samples before and after ultrasonic treatment are shown in Table 1. D_{50} and the

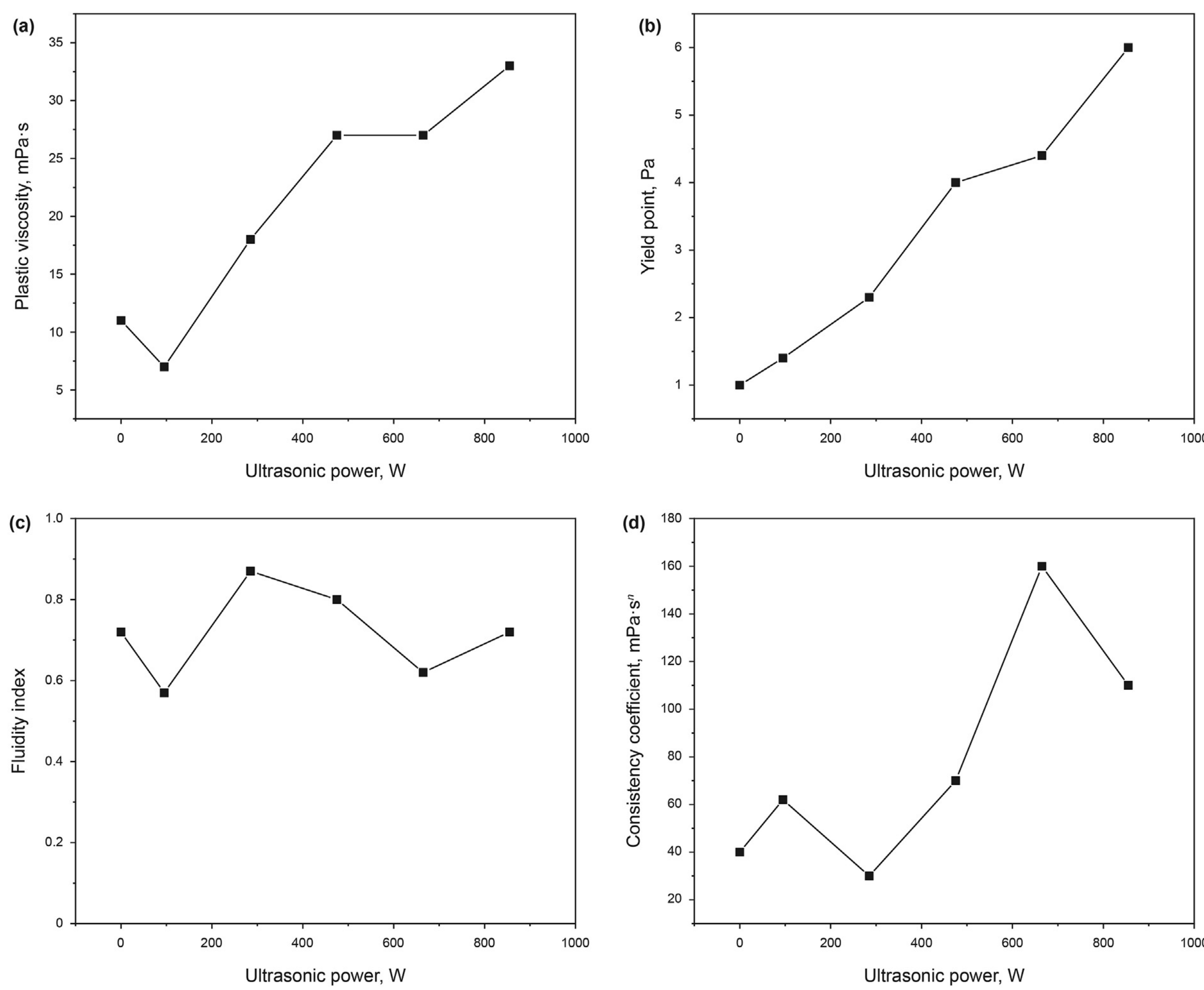

Fig. 5. (**a**) Plastic viscosity, (**b**) yield point, (**c**) flow index, and (**d**) consistency coefficient of the suspension regulated by ultrasound of different power.

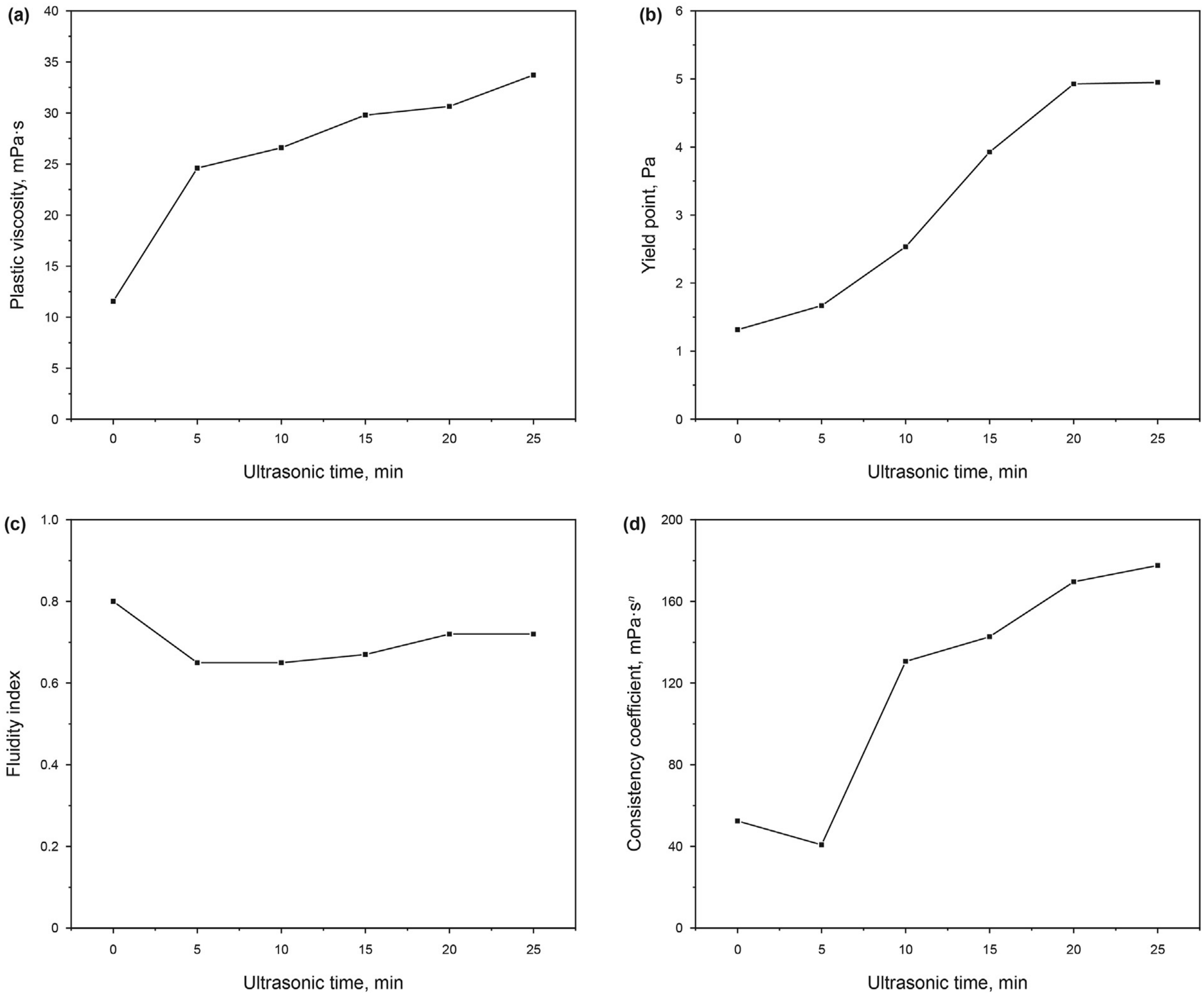

Fig. 6. (**a**) Plastic viscosity, (**b**) yield point, (**c**) fluidity index, and (**d**) consistency coefficient of suspension regulated by ultrasound of different durations.

specific surface area did not change significantly when the ultrasonic power was lower than 570 W, while D_{50} decreased and the specific surface area increased after the power reached 760 W. D_{90} gradually decreased with the increase in ultrasonic power. Due to the ultrasonic cavitation, the cavitation bubble was formed in water. In high-frequency vibration, cavitation bubbles are continuously generated and ruptured, thus releasing energy and further disassembling the bentonite particles (Hwangbo et al., 2013).

Table 1
Effect of ultrasonic treatment on particle size and specific surface area of bentonite.

Treatment conditions	D_{50}, μm	D_{90}, μm	Specific surface area, m^2/g
Unprocessed	5.604	20.50	0.529
190 W/10 min	5.637	23.83	0.565
190 W/20 min	5.570	20.92	0.571
190 W/30 min	5.704	23.06	0.562
380 W/10 min	5.604	23.16	0.579
380 W/20 min	5.316	17.70	0.594
380 W/30 min	5.421	19.65	0.584
570 W/10 min	5.570	18.92	0.571
570 W/20 min	5.617	19.42	0.568
570 W/30 min	5.387	19.76	0.586
760 W/10 min	4.106	18.08	0.732
760 W/20 min	3.482	16.39	0.892
760 W/30 min	3.842	16.67	0.840

Notes: D_{50} is the median particle size; D_{90} is the particle size with cumulative distribution up to 90%.

Therefore, the particle size of the bentonite particles decreased and the specific surface area increased (Chakma and Berruti, 1993; Mohapatra and Kirpalani, 2016; Wang et al., 2004). The reason for the mutation of D_{50} with the increase in ultrasonic power should be that the energy generated by 760 W ultrasound just broke the structure of the bentonite particles. Furthermore, the particle size and specific surface area of bentonite under the same ultrasonic power did not change with time, which indicated that the effect of action time on particle size and specific surface area was not significant. The reason might be that there were so few samples that the clay particles in the suspension were completely treated in a short time (less than 10 min).

3.3.2. Mud yield

Fig. 7 shows the change of apparent viscosity of suspensions before and after ultrasonic treatment. The apparent viscosity of the untreated suspension reached 15 mPa·s when the mass of bentonite in the suspension was 93.5 g/L. After ultrasonic treatment, only 75 g/L of bentonite was needed to make the viscosity of suspension reaching 15 mPa·s, indicating that the suspension after ultrasonic treatment had stronger slurry-making capacity and higher mud yield. Compared with the apparent viscosity curve before treatment, the curve after ultrasonic treatment was more gentle and the increase rate of the apparent viscosity was slow, which indicated that the ultrasound had a great influence on the

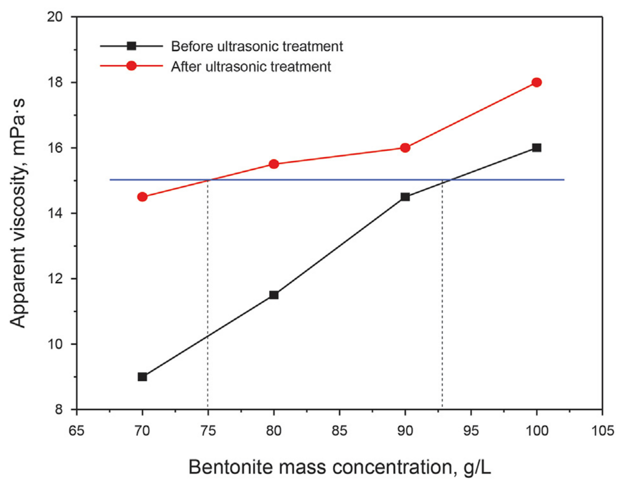

Fig. 7. The apparent viscosity of suspensions with different mass concentrations of calcium bentonite before and after ultrasonic treatment.

apparent viscosity of the calcium bentonite suspension. The improvement of mud yield indicated that ultrasound improved the hydration dispersion of bentonite, thereby increasing the apparent viscosity of the suspension to the required viscosity at a low concentration. Therefore, ultrasound ensured that the low-concentration bentonite suspension possessed excellent rheological performance, which was beneficial to reduce the dosage of solid phase and additive in drilling fluids.

3.3.3. *Cation exchange capacity*

Fig. 8 shows the cation exchange capacity of the suspension treated by ultrasound with different ultrasonic power. The cation exchange capacity increased gradually with the increase in ultrasonic power and tended to be constant after the power was over 600 W. Ultrasound caused the decrease of particle size of bentonite and the increase of specific surface area, which led the bentonite exposed more hydroxide ions and more hydroxide ions dissociated to create an electric charge. Therefore, the cation exchange capacity increased, which is a direct indicator of the enhanced hydration degree of bentonite particles. The exchangeable cations could adsorb the surrounding water molecules and bond to the surface of the clay crystals, resulting in the destruction of the water structure

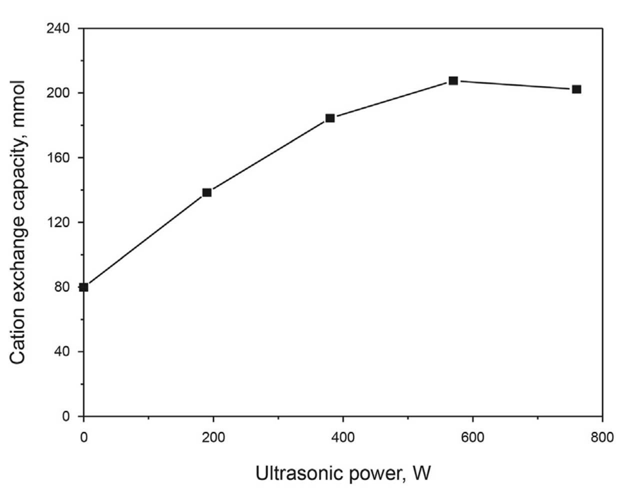

Fig. 8. Cationic exchange capacity of suspension after ultrasonic treatment with different power.

(Kim et al., 2016). The increase in the hydration degree decreased the free water content in the suspension and macroscopically the rheological properties of the suspension changed.

3.4. *Effect of ultrasound on rheological properties of calcium bentonite suspension containing additives*

After ultrasonic treatment, the bentonite-polymer suspension was aged at 120 °C for 16 h, and the rheological changes are shown in Table 2. According to the data in Table 2, the plastic viscosity increased while the yield point decreased largely after ultrasonic treatment. After aging, the apparent viscosity, plastic viscosity and the yield point of all suspensions changed slightly compared with those ultrasound-treated suspensions, which indicated that ultrasound had no influence on the temperature resistance of the suspension containing polymers. This phenomenon came from the adsorption and encapsulation between polymers and bentonite particles, which largely avoided the direct impact of ultrasonic energy on polymer chains. Within the ultrasonic power range studied, the ultrasonic energy was not strong to break the polymer molecular chains. Besides, the decreases in the plastic viscosity and yield point of the suspension indicated that the ultrasonic energy mainly destroyed the network structure formed between bentonite particles and polymer chains, and changed the orientation of the polymers on the bentonite surface.

3.5. *Effect of ultrasound on rheological properties of water-based drilling fluids*

3.5.1. *Effect of ultrasonic power*

The ultrasound with different ultrasonic power had a great influence on the rheology of water-based drilling fluids, as shown in Fig. 9. The plastic viscosity and the flow index of the poly-sulfonate drilling fluid increased gradually when the ultrasonic power was less than 95 W, and the yield point and the consistency coefficient decreased gradually. The bentonite particles did not change significantly when the ultrasonic power was lower than 570 W, so when the ultrasonic power was less than 95 W, the influence of ultrasound on bentonite particles was slight, which mainly affected the adsorption between drilling fluid additives and bentonite. The lower power ultrasound (less than 570 W) destroyed the internal grid structure, resulting in the decrease in yield point. The weakening of the internal interaction force of the drilling fluids also made it closer to the Newtonian fluid, so the flow index increased gradually. Because of the high concentration of bentonite (4.0 wt%) in the poly-sulfonated drilling fluid, the hydration effect of bentonite particles gradually increased with the increase in ultrasonic power and bentonite played a leading role in the rheological change of the drilling fluid. The stronger the ultrasonic power, the stronger the hydration effect of bentonite and the smaller the particle size.

With the increase in ultrasonic power, the plastic viscosity and the yield point of the deep-water drilling fluid decreased steadily, and the fluidity index and the consistency coefficient remained unchanged. According to the formula of the deep-water drilling fluid, the bentonite concentration of the drilling fluid was 2.0 wt%. The viscosity and the yield point of the drilling fluid mainly depended on viscosifiers and filter reducing agents, which belonged to long-chain polymer additives, so the change of interaction between additives and bentonite particles caused by ultrasound play a leading role in regulating the rheological properties of the drilling fluid. With the increase in ultrasonic power, the grid structure between bentonite and polymer chains was destroyed, and the plastic viscosity and yield point of the drilling fluid were reduced.

Table 2
Rheological properties of calcium bentonite suspensions containing additives after ultrasonic treatment and aging.

Additives	Conditions	Apparent viscosity, mPa·s	Plastic viscosity, mPa·s	Yield point, Pa	API filtration, mL
FA367	Before ultrasonic treatment	21.0	11.0	10.0	10.4
	After ultrasonic treatment	19.0	13.0	6.0	11.2
	After aging	14.5	10.0	4.5	9.6
80A51	Before ultrasonic treatment	8.5	5.0	3.5	14.0
	After ultrasonic treatment	8.0	6.0	2.0	14.8
	After aging	7.5	5.0	2.5	12.2
KPAM	Before ultrasonic treatment	14.0	6.0	8.0	13.0
	After ultrasonic treatment	11.0	8.0	6.0	12.0
	After aging	10.0	7.5	2.5	14.4
XC	Before ultrasonic treatment	17.5	11.0	11.0	18.5
	After ultrasonic treatment	14.0	9.0	5.0	17.6
	After aging	12.0	7.0	5.0	15.0
SMT	Before ultrasonic treatment	6.5	5.0	3.0	15.6
	After ultrasonic treatment	7.5	6.0	1.5	18.0
	After aging	7.5	6.0	1.5	11.6
XY-27	Before ultrasonic treatment	5.0	5.0	0	15.2
	After ultrasonic treatment	5.0	4.0	2.0	14.4
	After aging	4.0	2.0	3.5	10.8
SF260	Before ultrasonic treatment	7.5	5.0	5.0	22.0
	After ultrasonic treatment	12.5	10.0	5.0	18.4
	After aging	8.0	5.0	3.5	13.2

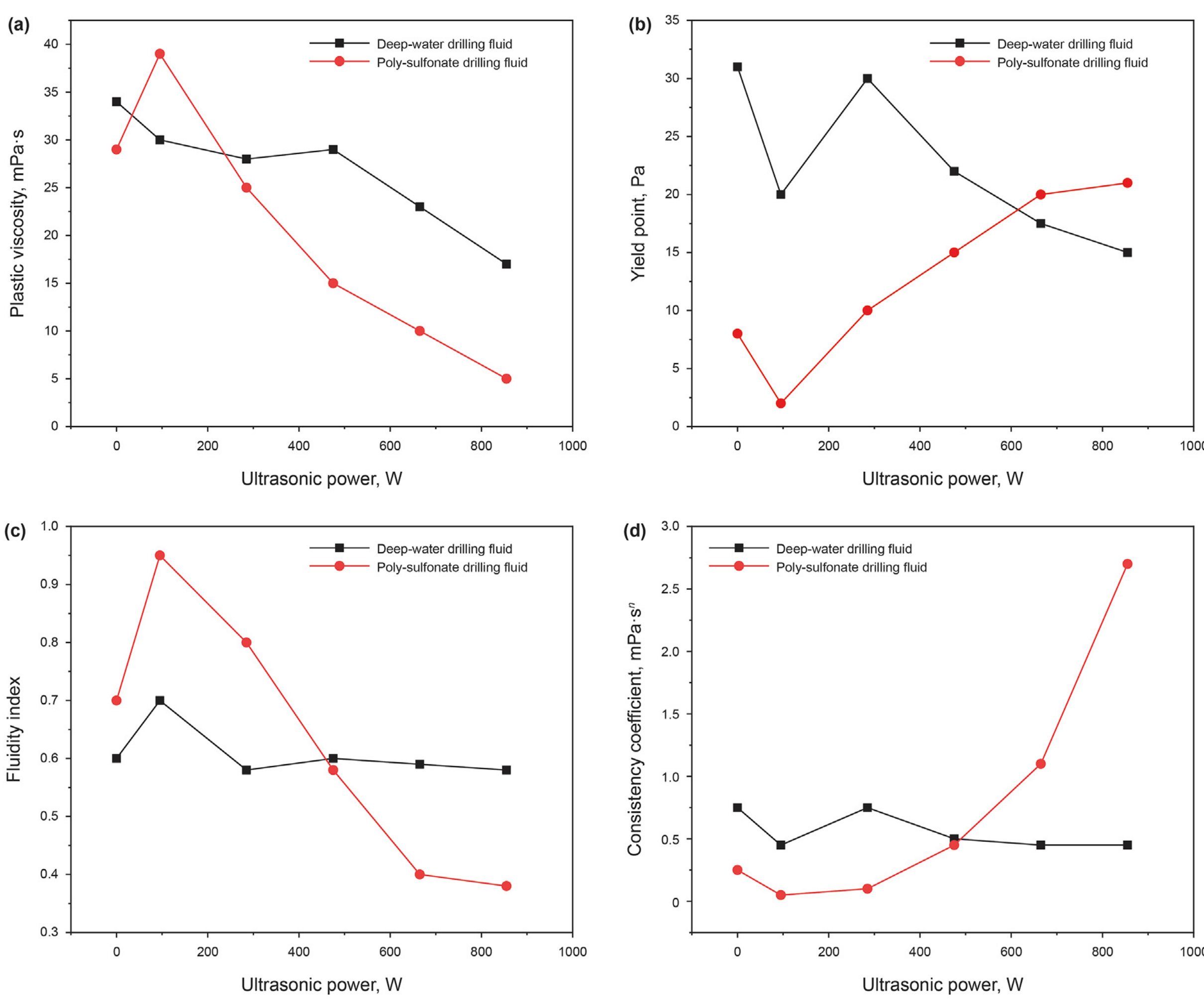

Fig. 9. (**a**) Plastic viscosity, (**b**) yield point, (**c**) fluidity index, and (**d**) consistency coefficient of water-based drilling fluids treated by ultrasound with different power.

3.5.2. Effect of ultrasonic time

Fig. 10 shows that the variation trend of rheological parameters for the deep-water drilling fluid and the poly-sulfonate drilling fluid was similar. With the increase in ultrasonic time, the yield point and the consistency coefficient decreased, while the plastic viscosity and the fluid index changed more smoothly, resulting from the change of bentonite properties caused by ultrasound. It is worth noting that the variation of yield point and consistency coefficient was mainly stable after the first 15 min, which indicated that the influence of ultrasonic treatment on the internal structure of the drilling fluid was tended to reach the balance after 15 min.

3.6. Effect of ultrasound on other properties of water-based drilling fluids

3.6.1. Lubricating property

There was no obvious change in the lubricating performance of the two drilling fluids before and after ultrasonic treatment, as shown in Table 3, which indicated that ultrasonic did not affect the performance of the drilling fluid lubricity.

Table 3
Lubrication coefficient of drilling fluids before and after ultrasonic treatment.

Drilling fluid	Lubrication coefficient	
	Before ultrasonic treatment	After ultrasonic treatment
Deep-water drilling fluid	0.242	0.250
Poly-sulfonate drilling fluid	0.160	0.157

3.6.2. Hydration inhibition property

The linear expansivity of the sodium bentonite were 50.7% in water, 5.77% in the deep-water drilling fluid, and 10.21% in the poly-sulfonate drilling fluid, respectively, as shown in Fig. 11. The results indicated that the two types of drilling fluids had better ability to inhibit clay hydration and swelling. After ultrasonic treatment, the linear expansivity of the sodium bentonite changed to 5.64% in the deep-water drilling fluid and 5.92% in the poly-sulfonate drilling fluid, respectively, indicating that ultrasonic treatment did not change the swelling inhibition performance of drilling fluids significantly. However, the slightly decreased swelling rates after treatment confirm that the ultrasound promoted further hydration and dispersion of bentonite, thus reducing the free water content in the drilling fluid and then improving the inhibition performance.

3.6.3. Settling stability

The settling stability of the drilling fluid is closely related to its rheology. The long-chain polymer additives in drilling fluid can be adsorbed on the surface of bentonite particles and barite to form a spatial grid structure, showing a stabilization effect on the drilling fluids. However, ultrasound affected the structures between bentonite particles or between bentonite particles and polymer additives, which was not conducive to the settling stability of the drilling fluid. As shown in Table 4, the settling stability of the two types of drilling fluids decreased slightly after ultrasonic treatment

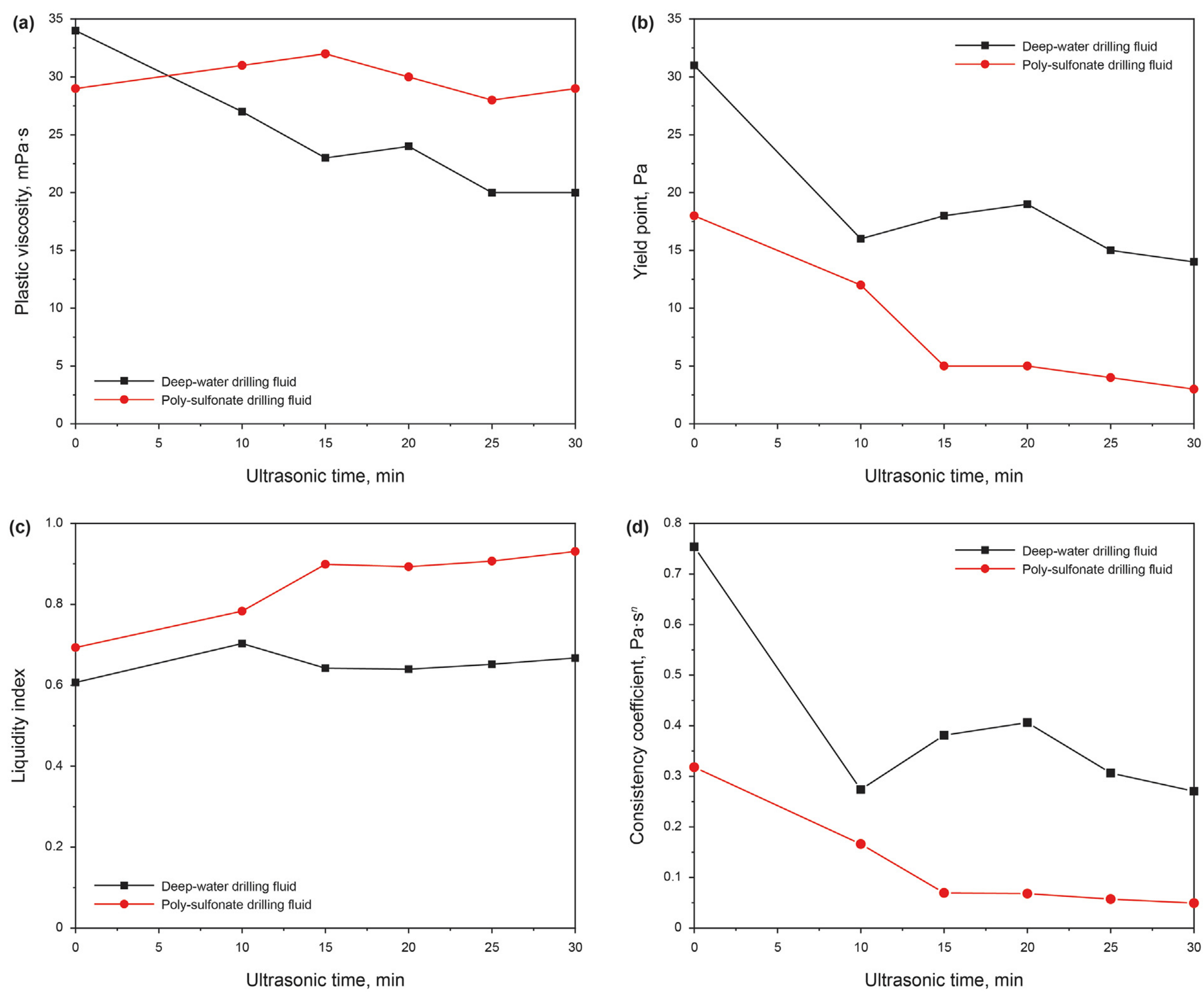

Fig. 10. (**a**) Plastic viscosity, (**b**) yield point, (**c**) fluidity index, and (**d**) consistency coefficient of water-based drilling fluid treated by ultrasound with different ultrasonic time.

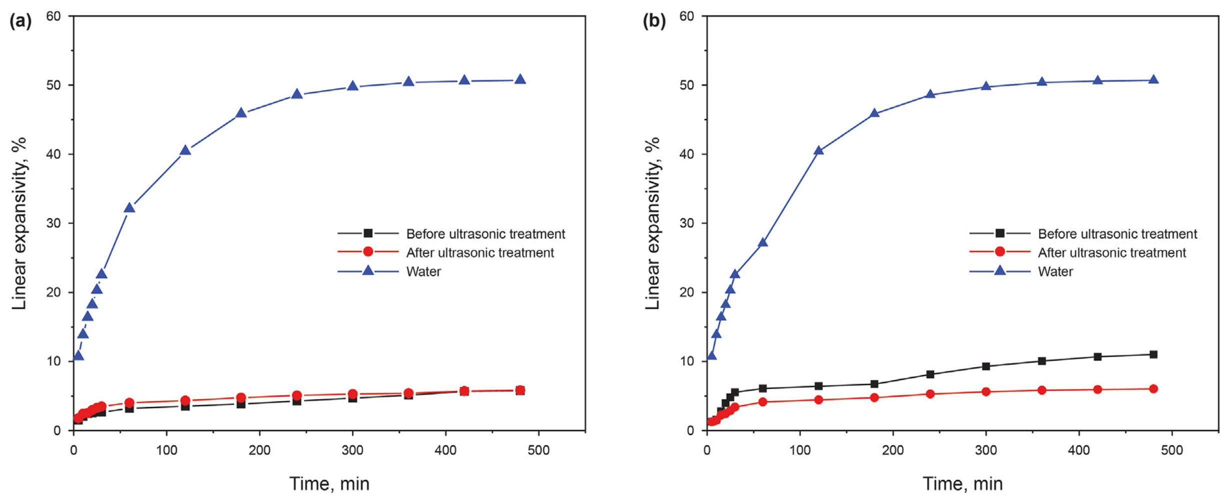

Fig. 11. Linear swelling performance of the deep-water drilling fluid (**a**) and the poly-sulfonate drilling fluid (**b**) before and after ultrasonic treatment.

Table 4
The settling stability of drilling fluids before and after ultrasonic treatment.

Drilling fluid	Settling factor *f*	
	Before ultrasonic treatment	After ultrasonic treatment
Deep-water drilling fluid	0.501	0.503
Poly-sulfonate drilling fluid	0.502	0.505

as expected. The ultrasound destroyed the network structure inside the suspension to a certain extent, thus the newly formed structure was weakened and the plastic viscosity decreased. Notably, the ultrasonic power used in the experiment was not high and the energy was too low to cause a sudden change in drilling fluid density and settling stability. The overall impact of ultrasound on the settling stability was not significant.

To summarize, after ultrasonic treatment, the rheological properties of the water-based drilling fluids changed regularly, while the lubricity, inhibition and settling stability were insensitive to ultrasound. Therefore, the ultrasound could regulate the rheology of the water-based drilling fluid without impacts on the other performance of the drilling fluids. It is promising to apply this physical method of regulating rheology by ultrasound to the drilling process of deep wells and other complex conditions.

4. Conclusions

In this paper, we presented a physical method to regulate rheological properties of water-based drilling fluids by ultrasound and investigated the effects and mechanisms of ultrasound on the calcium bentonite suspension and bentonite-polymer suspension, as well as two types of water-based drilling fluids. Based on the findings presented in this study, our conclusions are as follows:

(1) Ultrasound could regulate the rheological properties of the bentonite suspension and the memory effect of the treated suspension was observed at room temperature and 120 °C, which maintained the rheological stability of water-based drilling fluids during long time drilling. The increase in ultrasonic power and ultrasonic time regularly changed the rheological parameters of the suspension, and ultrasonic power was the main factor. The controllability of the rheological properties of the suspension could be achieved based on the varying regularity with ultrasonic parameters. Ultrasonic cavitation produced local high temperature and high pressure, which decreased the particle size of bentonite and increased the specific surface area, increased the mud yield and reduced the required solids content of drilling fluids, improved the hydration dispersion of bentonite in slurry blending, and brought excellent drilling fluid performance for the low-concentration suspension. Meanwhile, the cation exchange capacity was increased and the free water content was reduced, thus the rheology of the suspension changed.

(2) Ultrasound regularly changed the rheological parameters of the drilling fluid containing a single drilling fluid additive, and the change could be maintained at 120 °C. The ultrasonic energy mainly affected the grid structure formed between bentonite particles or between bentonite particles and polymer additives instead of the polymer additives themselves.

(3) For the poly-sulfonate drilling fluid, ultrasound with ultrasonic power less than 95 W mainly destroyed the grid structure between bentonite particles or between bentonite particles and polymer additives, and weakened the internal interaction force of drilling fluid. The ultrasound at the power of more than 95 W decreased the particle size of bentonite, increased the viscosity of the continuous phase and the internal friction of the dispersed phase, thus causing the rheology change of the drilling fluid. For the deep-water drilling fluid, the rheology of the drilling fluid was regulated by destroyed the grid structure between additives by ultrasound. Ultrasonic time have less effect on the rheology of the water-based drilling fluids. Moreover, the basic properties of water-based drilling fluids including lubricity, hydration inhibition and settling stability were not affected by ultrasound. Therefore, the new method for regulating the rheology by ultrasound showed great potential to be applied for the conventional drilling fluids.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51974351; No. 51704322; Major Program, No. 51991361) and the National Science and Technology Major Project of China (No. 2016ZX05040-005).

References

Chakma, A., Berruti, F., 1993. The effects of ultrasonic treatment on the viscosity of athabasca bitumen and bitumen-solvent mixtures. J. Can. Pet. Technol. 32 (5). https://doi.org/10.2118/93-05-04.

Dong, X., Revol, J.F., Gray, D.G., 1998. Effect of microcrystallite preparation conditions on the formation of colloid crystals of cellulose. Cellulose 5, 19–32. https://doi.org/10.1023/A:1009260511939.

Fu, X., Liu, Q., Tang, C., Luo, J., Wu, X., Lu, L., Cai, Z., 2019. Study on structural, rheological and foaming properties of ovalbumin by ultrasound-assisted glycation with xylose. Ultrason. Sonochem. 58 (May), 104644. https://doi.org/10.1016/j.ultsonch.2019.104644.

Hamida, T., Babadagli, T., 2008. Displacement of oil by different interfacial tension fluids under ultrasonic waves. Colloid. Surface. Physicochem. Eng. Aspect. 316 (1–3), 176–189. https://doi.org/10.1016/j.colsurfa.2007.09.012.

Huang, B., Zhao, K., Zhang, Z., Liu, F., Hu, H., Pan, S., 2018. Changes on the rheological properties of pectin-enriched mango nectar by high intensity ultrasound. LWT - Food Sci. Technol. (Lebensmittel-Wissenschaft -Technol.) 91 (October 2017), 414–422. https://doi.org/10.1016/j.lwt.2018.01.062.

Huang, W., Lei, M., Wang, J., Kaihe, L., Jiang, L., Zhao, H., Chen, W., 2020. Method and mechanism of regulating rheological properties of water-based drilling fluid by high-frequency and high-voltage alternating current electric field. SPE J. 25 (5), 2220–2233. https://doi.org/10.2118/201192-PA.

Hwangbo, S., Chu, M., Kim, J., Kim, M., 2013. Nanoparticle dispersion by focused ultrasound from cylindrical transducer. IEEE Int. Ultrasonics Sympos. IUS 2126–2129. https://doi.org/10.1109/ULTSYM.2013.0543.

Horst, C., Kunz, U., Rosenplänter, A., et al., 1999. Activated solid–fluid reactions in ultrasound reactors. Chem. Eng. Sci. 54 (54), 2849–2858. https://doi.org/10.1016/S0009-2509(98)00316-9.

Kim, J., Yeom, J., Ha, K., Kim, J., Kim, M., 2016. Ultrasonic streaming and cavitation for nano particle dispersion. IEEE Int. Ultrasonics Sympos. IUS 16–19. https://doi.org/10.1109/ULTSYM.2016.7728527. 2016-November.

Kirpalani, D.M., McQuinn, K.J., 2006. Experimental quantification of cavitation yield revisited: focus on high frequency ultrasound reactors. Ultrason. Sonochem. 13 (1), 1–5. https://doi.org/10.1016/j.ultsonch.2005.01.001.

Kuang, Y., Zhang, Z., Ji, X., Zhang, X., 2017. Study on dispersion technology and technology of anatase nano-sized TiO_2 material. J. Hefei Univ. Technol. (Nat. Sci.) 40 (11), 1478–1482 (in Chinese).

Laux, D., Gibert, O., Ferrandis, J.Y., Rosenkrantz, E., Mograne, M.A., Prades, A., 2018. In-pipe coconut water rheological characterization with ultrasonic waves. J. Food Eng. 235, 59–63. https://doi.org/10.1016/j.jfoodeng.2018.04.030.

Li, C., Song, H., Prince, H., 2001. Application and research progress of ultrasound in chemical industry. Acta Pet. Sin. 17 (3), 86–94. https://doi.org/10.3321/j.issn:0253-2697.2001.03.315 (in Chinese).

Liu, C., Yan, F., Zhao, C., 2015. Effects of ultrasonic pretreatment on dispersion stability of nanometer SiO_2. Electroplating and Finish. 37 (8), 32–34 (in Chinese).

Manoochehri, M., Asgharinezhad, A.A., Safaei, M., 2015. Determination of aflatoxins in rice samples by ultrasound-assisted matrix solid-phase dispersion. J. Chromatogr. Sci. 53 (1), 189–195. https://doi.org/10.1093/chromsci/bmu018.

Marchessault, R.H., Morehead, F.F., Koch, M.J., 1961. Some hydrodynamic properties of neutral suspensions of cellulose crystallites as related to size and shape. J. Colloid Sci. 16 (4), 327–344. https://doi.org/10.1016/0095-8522(61)90033-2.

Mohapatra, D.P., Kirpalani, D.M., 2016. Bitumen heavy oil upgrading by cavitation processing: effect on asphaltene separation, rheology, and metal content. Appl. Petrochem. Res. 6 (2), 107–115. https://doi.org/10.1007/s13203-016-0146-1.

Nguyen, A.N., Reinert, L., Lévêque, J.M., Beziat, A., Dehaudt, P., Juliaa, J.F., Duclaux, L., 2013. Preparation and characterization of micron and submicron-sized vermiculite powders by ultrasonic irradiation. Appl. Clay Sci. 72, 9–17. https://doi.org/10.1016/j.clay.2012.12.007.

Ning, F., Zhang, L., Tu, Y., Jiang, G., Shi, M., 2010. Gas-hydrate formation, agglomeration and inhibition in oil-based drilling fluids for deep-water drilling. J. Nat. Gas Chem. 19 (3), 234–240. https://doi.org/10.1016/S1003-9953(09)60077-3.

Ruiz-Hernando, M., Labanda, J., Llorens, J., 2010. Effect of ultrasonic waves on the rheological features of secondary sludge. Biochem. Eng. J. 52 (2–3), 131–136. https://doi.org/10.1016/j.bej.2010.07.012.

Sainz Herrán, N., Casas López, J.L., Sánchez Pérez, J.A., Chisti, Y., 2010. Influence of ultrasound amplitude and duty cycle on fungal morphology and broth rheology of Aspergillus terreus. World J. Microbiol. Biotechnol. 26 (8), 1409–1418. https://doi.org/10.1007/s11274-010-0315-9.

Santos-Zea, L., Gutiérrez-Uribe, J.A., Benedito, J., 2019. Effect of ultrasound intensification on the supercritical fluid extraction of phytochemicals from Agave salmiana bagasse. J. Supercrit. Fluids 144 (October 2018), 98–107. https://doi.org/10.1016/j.supflu.2018.10.013.

Shafeiei-Sabet, S., Hamad, W.Y., Hatzikiriakos, S.G., 2013. Influence of degree of sulfation on the rheology of cellulose nanocrystal suspensions. Rheol. Acta 52 (8–9), 741–751. https://doi.org/10.1007/s00397-013-0722-6.

Shafiei-Sabet, S., Hamad, W.Y., Hatzikiriakos, S.G., 2012. Rheology of nanocrystalline cellulose aqueous suspensions. Langmuir 28 (49), 17124–17133. https://doi.org/10.1021/la303380v.

Thompson, L.H., Doraiswamy, L.K., 1999. Sonochemistry: science and engineering. Ind. Eng. Chem. Res. 38 (4), 1215–1249. https://doi.org/10.1021/ie9804172.

Wang, C., Wei, S., Liu, Y., Jia, H., 2003. Changes of rheological properties of polymer solution by ultrasonic. J. Northeast Petrol. Univ. 27 (4), 18–20 (in Chinese).

Wang, C., Wei, S., Jia, H., 2004. Effect of ultrasonic frequency on rheology of polymer solution. Petrol. Drill. Prod. Process 26 (1), 72–74. https://doi.org/10.3969/j.issn.1001-3849.2015.08.009 (in Chinese).

Yang, Z., Qu, C., Zhang, N., Wang, X., 2005. Effect of ultrasound on surface properties of solid particles. J. Xi'an Univ. Petrol. (Natl. Sci. Ed.) 20 (6), 53–55. https://doi.org/10.3969/j.issn.1673-064X.2005.06.014 (in Chinese).

Ye, G., Lu, X., Han, P., Shen, X., 2010. Desalting and dewatering of crude oil in ultrasonic standing wave field. J. Petrol. Sci. Eng. 70 (1–2), 140–144. https://doi.org/10.1016/j.petrol.2009.11.005.

Yu, Y., Ding, I., Qiu, H., Wang, Y., Jiao, Z., 2009. Effects of ultrasonic treatment on particle size and dissolution of excess sludge. JES (J. Environ. Sci.) 29 (4), 703–708. https://doi.org/10.3321/j.issn:0253-2468.2001.06.009 (in Chinese).

Zhao, S., Yan, J., Shu, Y., Zhang, H., 2008. Rheological properties of oil-based drilling fluids at high temperature and high pressure. J. Cent. South Univ. Technol. 15 (1), 457–461. https://doi.org/10.1007/s11771-008-0399-7.

Zhong, H., Qiu, Z., Huang, W., Cao, J., 2011. Shale inhibitive properties of polyether diamine in water-based drilling fluid. J. Petrol. Sci. Eng. 78 (2), 510–515. https://doi.org/10.1016/j.petrol.2011.06.003.

Zhong, H., Qiu, Z., Huang, W., Cao, J., 2012. Poly (oxypropylene)-amidoamine modified bentonite as potential shale inhibitor in water-based drilling fluids. Appl. Clay Sci. 67–68, 36–43. https://doi.org/10.1016/j.clay.2012.06.002.

Zhong, H.Y., Qiu, Z.S., Huang, W.A., Cao, J., Wang, F.W., Xie, B.Q., 2013. Inhibition comparison between polyether diamine and quaternary ammonium salt as shale inhibitor in water-based drilling fluid. Energy Sources, Part A Recovery, Util. Environ. Eff. 35 (3), 218–225. https://doi.org/10.1080/15567036.2011.606871.