



Effects of carbon ash on rheological properties of water-based drilling fluids

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ABSTRACT

The rheological properties of drilling fluid play a fundamental role in drilling operations, and the water-based drilling fluid is based on bentonite dispersion. According to Bingham-plastic model, the influences of carbon ash and commercial rheological modifier (RM) on rheological properties of bentonite dispersion are investigated systematically from apparent viscosity (AV), plastic viscosity (PV), yield point (YP) as well as the ratio of yield point and plastic viscosity (RYP). The results indicate that the rheological properties of bentonite dispersion with carbon ash are improved markedly in YP, and especially for the low solid content of bentonite dispersion. The filtration and density test are also carried out using an API Filter Press and mud balancer respectively. From the results, it could be observed that the filtrate loss and filter cake thickness increase dramatically whereas the density of bentonite dispersion decreases slightly as the addition of carbon ash increases. Furthermore, the stability of bentonite dispersion incorporated with carbon ash is evaluated. The experimental results indicate that carbon ash is better than RM in stability. Through this study, carbon ash is an excellent potential additive for improving the rheological properties of water-based drilling fluids.

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1. Introduction

Drilling fluids, which could be called as the “blood” in drilling industry, play a major role in drilling operations. With the rapid development in drilling industry, it is necessary to improve the properties of drilling fluids in order to satisfy the increasing demands. Drilling fluids are often described as thixotropic shear-thinning fluids with a yield stress (Coussot et al., 2004). Their functions include suspending and carrying drilling cuttings, cooling and cleaning drilling tools as well as maintaining the stability of wellbores, and so on (Caenn and Chillingar, 1996; Darley and Gray, 1988; Luckham and Rossi, 1999; Menezes et al., 2010). There are two primary types of drilling fluids, oil-based and water-based. Generally speaking, oil-based drilling fluids have excellent properties such as stability, lubricity, and temperature stability (Mohamed et al., 2010). However, excessive use of oil-based drilling fluids may harm the environment and it is important to develop more environmentally-friendly drilling fluids. In this respect, water-based drilling fluids are more acceptable. As well known, bentonite is widely applied in the water-based drilling fluids, which could enhance the clean properties and form a thin filter with low permeability. The functions of bentonite are to make the fluids more viscous and reduce the loss of fluids (Kanchan et al., 2011). Furthermore, in order to obtain better

comprehensive properties, others additives such as rheological modifiers and shale inhibitor (Qu et al., 2009) are frequently added into water-based drilling fluids. The rheological properties are important to drilling fluids as they are essential for transporting the drilling cuttings, improving the penetration rate, and ensuring downhole safety. According to the literatures, the common rheological modifiers for improving the rheological properties of drilling fluids are polymers, such as xanthan gum (Benchabane and Bekkour, 2006; Benyounes et al., 2010; Hamed and Belhadri, 2009; Hamida et al., 2009), scleroglucan (Hamed and Belhadri, 2009), sodium carboxymethylcellulose (Benchabane and Bekkour, 2006; Benyounes et al., 2010; Iscan and Kok, 2007; Menezes et al., 2010), polyoxyalkyleneamine (Qu et al., 2009), polyethyleneimine (Alemdar et al., 2005), polyvinyl alcohol (Isci et al., 2004) and carbopol 980 (Kelessidis et al., 2011). However, the viscosity of drilling fluids increased dramatically with the addition of polymers, which indicates the liquidity of drilling fluids becomes poor. Hence, it is necessary to develop the excellent rheological modifiers with low tackify performance. Carbon ash is a type of industrial dust originating from carbonization of polymers at high temperature. During steel recovery, the polymers outside the steel are carbonized into amorphous carbon. In addition, metallic oxides such as zinc oxide and iron oxide offer protection and although the use of carbon ash in drilling fluids has commercial potential, it has seldom been studied.

The aim of this paper is to study the influence of carbon ash on rheological properties of bentonite dispersion. According to

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Nomenclature

τ	shear stress
γ	shear rate
AV	apparent viscosity
PV	plastic viscosity

YP	yield point
RYP	ratio of yield and plastic viscosity
RM	rheological modifiers
NaCl	sodium chloride
CTAB	hexadecyl trimethyl ammonium bromide
°C	unit of Celsius degree

Bingham-plastic model, the rheological properties are described from the apparent viscosity (AV), plastic viscosity (PV), yield point (YP) as well as the ratio of yield point and plastic viscosity (RYP). In this work, the influence of carbon ash on the rheological properties of bentonite dispersion is evaluated systematically. The stability of carbon ash in improving the rheological properties of bentonite dispersion is also discussed from the resistance to salt and temperature. The commercial rheological modifier (RM) is used for comparison. Furthermore, the filtration and density of bentonite dispersion with carbon ash are also investigated.

2. Materials and experimental methods

2.1. Materials

The bentonite was obtained from Tianyu bentonite factory (Henan, China) and carbon ash was provided by Kaitai Company (Shandong, China). RM was obtained from the Yangshi Co. (Shanghai, China). Sodium chloride (NaCl) and hexadecyl trimethyl ammonium bromide (CTAB) were purchased from Beijing Reagent Co. (Beijing, China).

2.2. Experimental methods

2.2.1. Preparation of bentonite dispersion

High-quality bentonite was used to produce the bentonite dispersion. The bentonite dispersion was prepared by adding different amounts of bentonite (3 g, 4 g and 5 g) to distilled water (100 mL) and stirred at about 10,000 rpm for 20 min. The bentonite dispersion was aged for 24 h at room temperature in order to pre-hydrate the bentonite dispersion fully.

2.2.2. Modification of carbon ash

Carbon ash being an inorganic dust was difficult to disperse in water and so CTAB was used to modify the surface of carbon ash. 0.05 g of CTAB was added to 100 mL of water, and then carbon ash (5 g) was added to the CTAB solution with stirring for 30 min. Then filtrated and dried at 80 °C for 2 h in order to remove the moisture.

2.2.3. Rheological characterization

The experiment of rheological properties was carried out by a ZNN-D6S type rotating viscometer. The bentonite dispersion was stirred at 10,000 rpm for 5 min, and then the addition was added under stirring for 5 min. In order to evaluate the resistance to temperature, the bentonite dispersion incorporation additives was rolled for 16 h using a hot rolling furnace, and then the rheological properties are also determined by a rotating viscometer.

Filtration loss of bentonite dispersion was measured by using an API filter press under a pressure of 689.5 kPa (100 psi) for 30 min, and the filter cake thickness was measured. The density of bentonite dispersion was determined by mud balancer at the room temperature.

2.2.4. Rheological theory

It is generally accepted that drilling fluid can be typified by the Bingham-plastic model (Lauzon and Reid, 1979). The Bingham-plastic model of flow differs most notably from a Newtonian fluid by the presence of a yield stress. A Bingham-plastic fluid will not flow until the applied shear exceeds a minimum value that is known as the yield stress. The Bingham-plastic model relates shear stress and shear rate by the equation (Darley and Gray, 1988; Falode et al., 2008)

$$\tau = \tau_0 + \mu_0 \gamma, \quad (1)$$

where τ is the shear stress, τ_0 the yield point, μ_0 plastic viscosity, and γ the shear rate.

According to Bingham-plastic model, the rheological parameters, including AV, PV, YP, and RYP were calculated from 300 and 600 rpm readings using the following formulas according to the American Petroleum Institute (API) recommended practice of standard procedures (Recommended Practice, 1988).

$$\begin{aligned} AV &= 0.5\theta_{600} \quad (\text{mPa s}) \\ PV &= \theta_{600} - \theta_{300} \quad (\text{mPa s}) \\ YP &= 0.511(\theta_{300} - PV) \quad (\text{Pa}) \\ RYP &= YP/PV \quad (\text{Pa/mPa s}) \\ \Delta RYP &= (RYP_1 - RYP_0)/RYP_0 \quad (\%) \end{aligned} \quad (2)$$

where θ_{600} is 600 rpm dial reading, θ_{300} is 300 rpm dial reading, RYP_0 and RYP_1 are the RYP of drilling fluids before and after adding the additives, respectively.

3. Results and discussion

3.1. Characterization of carbon ash

The composition of carbon ash is determined by WD-XRF on the Thermo Electron Corporation ARL ADVANT XP⁺ at room temperature and the result is shown in Table 1. The main elements include C, O, Zn, and Fe. X-ray diffraction (XRD) is used to study the structure of carbon ash and the result is shown in Fig. 1. Table 1 and Fig. 1 show that carbon exists mainly in the form of amorphous carbon. Besides amorphous carbon, carbon ash contains Zn and Fe probably in as oxides as indicated by XRD. Zinc oxide belongs to the hexagonal system and the characteristic peaks of zinc oxide can be observed from Fig. 1. There are seven characteristic peaks at 31.7°, 34.4°, 36.2°, 56.6°, 62.9°, 67.9°, and 69.0° corresponding to orientations of (100), (002), (101), (110), (103), (112), and (201) respectively. The peak of ferric oxide can be inferred from the peak at 33.5°. Hence, it could be stated that carbon ash is composed of mainly amorphous carbon, zinc oxide, and ferric oxide.

Table 1
Composition of carbon ash.

Component	C	O	Si	S	Cl	Ca	Fe	Zn	Br	Others
(%)	53.6	9.73	0.304	1.18	1.51	0.224	1.96	30.2	0.402	0.89

Carbon ash is an inorganic dust with strong hydrophobic property and difficult to disperse in water uniformly. In order to improve the dispersion efficacy, CTAB is used to modify carbon ash and the results of FTIR are shown in Fig. 2, including the comparison between carbon ash before and after modification in water. It could be clearly seen that there are two new characteristic absorption peaks at 2852 cm^{-1} and 2923 cm^{-1} after the modification in Fig. 2. The new characteristic absorption peaks

demonstrate the existence of symmetric and asymmetric vibration of C–H stretch ($-\text{CH}_2$) which could form micelles in water and facilitate dispersion of carbon ash in water. The dispersions of carbon ash before and after modification in water are also shown in Fig. 2, and it could be clearly seen that the modified carbon ash could be suspended in water homogeneously, which is due to the formation of micelles.

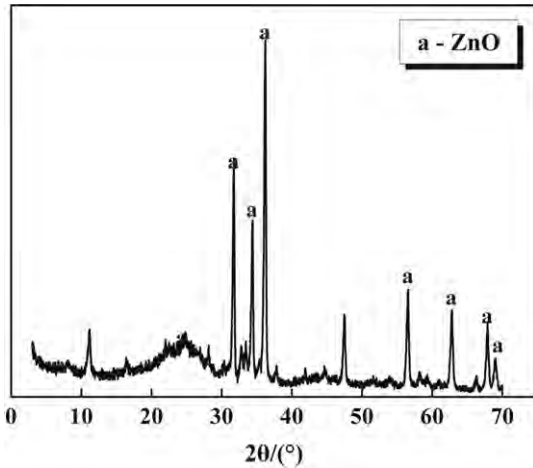


Fig. 1. X-ray diffraction patterns of carbon ash.

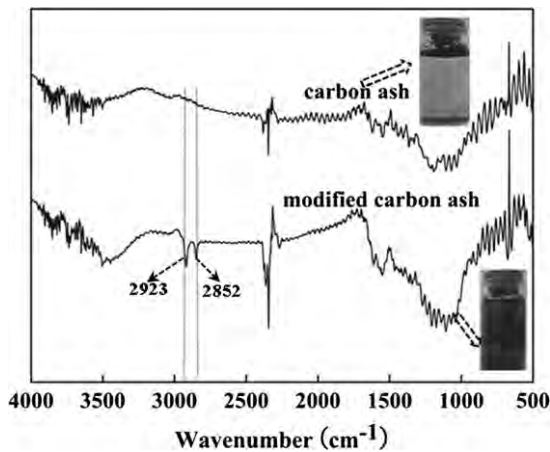


Fig. 2. FTIR spectra of carbon ash and modified carbon, including the comparison between carbon ash before and after modification in water.

3.2. Influence of carbon ash on rheological properties of water drilling fluids

In order to investigate the effects of carbon ash on rheological properties of water-based drilling fluids, carbon ash is added into bentonite dispersion at different concentrations (0.2, 0.4, 0.6, 0.8 and 1.0 wt%, respectively, i.e. 0.2 wt% means 0.2 g of carbon ash is introduced into 100 g of bentonite dispersion at 0.2 g/100 g), and the experimental results were shown in Figs. 3–5. The variations in the viscosity are illustrated in Fig. 3, including AV and PV, which could reflect the flowability of drilling fluids. According to the previous literatures, AV reflects the flowability of drilling fluids and is related to the rate of penetration, and PV is caused by the friction between the suspended particles and influenced by the viscosity of the base liquid (Falode et al., 2008). As observed in Fig. 3(a), AV of bentonite dispersion incorporate carbon ash increases gradually as the addition of carbon ash increases, which indicates that the bentonite dispersion has the better flowability. Compared to the 3% and 5% bentonite dispersion, it can be found that when the solid content in the drilling fluids is small, AV increases steadily enabling good control of the drilling fluids flow. As shown in Fig. 3(b), PV of bentonite dispersion incorporate carbon

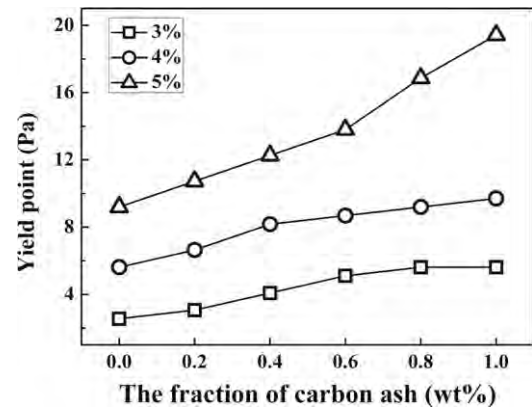


Fig. 4. YP of bentonite dispersion with different concentrations of carbon ash.

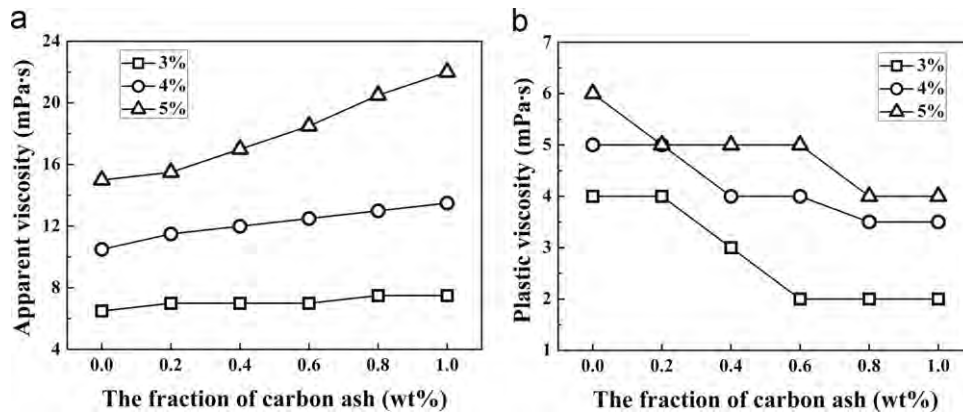


Fig. 3. Viscosity of bentonite dispersion with different concentrations of carbon ash: (a) AV; (b) PV.

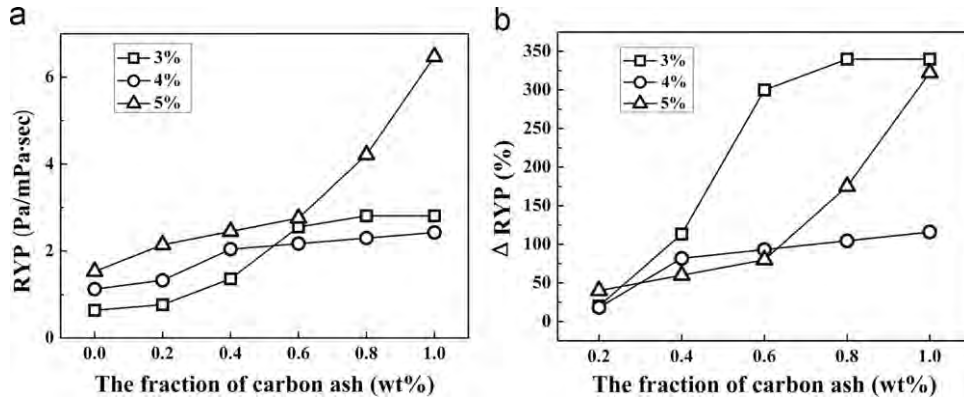


Fig. 5. RYP of bentonite dispersion with different concentrations of carbon ash: (a) RYP; (b) percentage change.

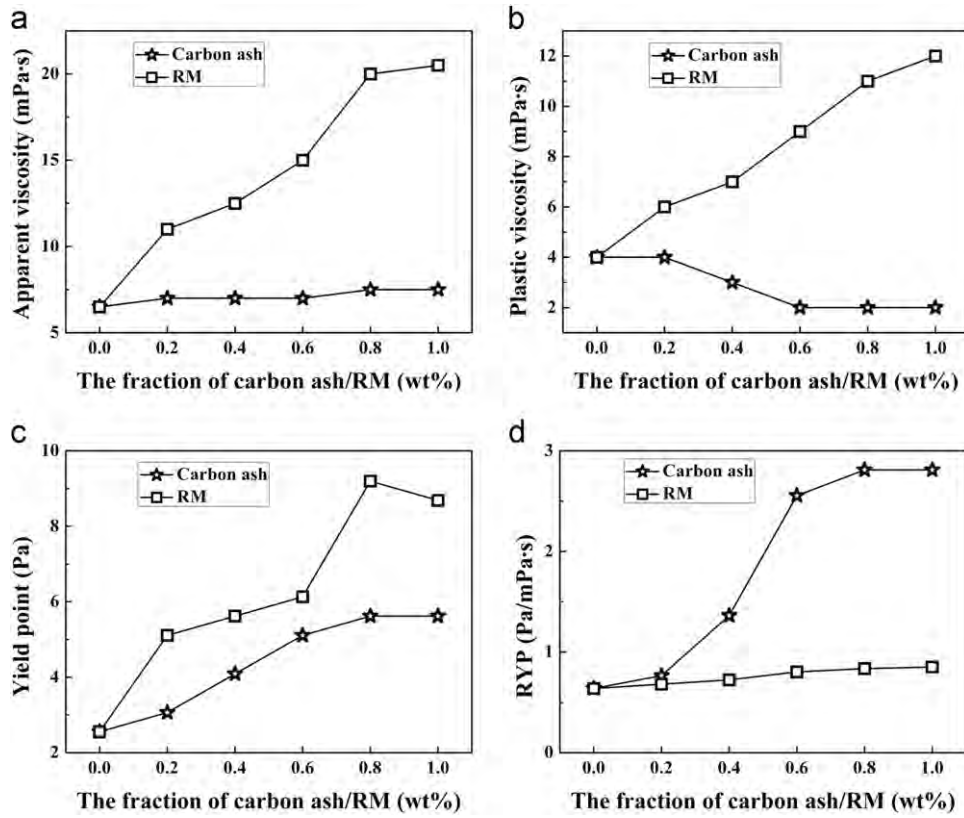


Fig. 6. Influence of bentonite dispersion with different concentrations of carbon ash/RM: (a) AV; (b) PV; (c) YP; (d) RYP.

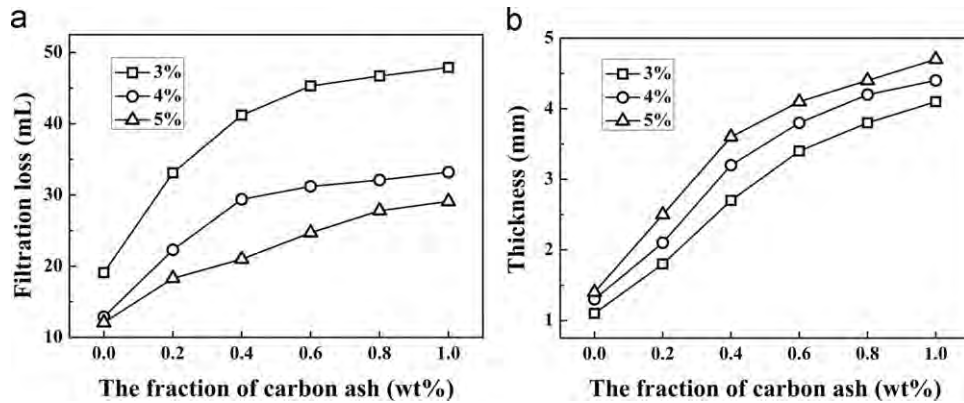


Fig. 7. (a) Filtration loss and (b) mud thickness of bentonite dispersion with different concentrations of carbon ash.

ash displays a decreasing trend with the increasing concentration of carbon ash, which indicates that the internal friction of bentonite dispersion increases gradually. The decrement of PV reduces as the solid content of bentonite dispersion increases. The change in viscosity shown in Fig. 3 is due to the electrostatic interactions between bentonite particles and carbon ash. As carbon ash is adsorbed onto bentonite particle, the gel structure of bentonite dispersion is destroyed, which results in the viscosity affected availably.

YP is an important rheological parameter for drilling fluids and reflects the resistance to initial flow or the stress required to initiate fluid movement. Fig. 4 depicts the YP of bentonite dispersion with different carbon ash concentrations. YP of bentonite dispersion goes up as the carbon ash concentration increases. It could be explained that carbon ash is absorbed on the surface of bentonite particles and the agglomeration among bentonite particles declines. From Fig. 4, it also be seen that YP increases slightly when the solid content of bentonite dispersion is low, and the results indicates that the rheological properties of drilling fluids could be controlled by adding carbon ash, especially for the low solid content of bentonite dispersion.

RYP is another important rheological parameter reflecting the capability of carrying drillings. According to Fig. 5, the variation in RYP is similar to that of YP shown in Fig. 4, and RYP increases with the increasing concentration of carbon ash. From Fig. 5(a), RYP of bentonite dispersion incorporation carbon ash shows the abrupt rise at 0.4 wt% and 0.8 wt% when the solid content of bentonite dispersion is 3 wt% and 5 wt% respectively. In order to describe the variation visually, Δ RAY is illustrated and shown in Fig. 5(b). It could be seen clearly that Δ RAY of bentonite dispersion with carbon ash increases dramatically with the

increasing concentration of carbon ash, which indicates the capability of carrying drilling cuttings of bentonite dispersion is improved availably. Among the different solid contents of bentonite dispersion, the increment of Δ RAY reaches the maximum when the solid content is low (3%) and it illustrates the capability of carrying drilling cuttings is the strongest. Take the viscosity, YP and RYP into consideration, carbon ash is more suited for the low solid content of bentonite dispersion, and the solid content of bentonite dispersion was determined at 3% in the further study.

In order to evaluate the effects of carbon ash on rheological properties of drilling fluids, the commercially available rheological modifier (RM) is used for comparison and the comparative results including AV, PV, YP and RYP are displayed in Fig. 6. As observed in Fig. 6(a), AV of bentonite dispersion with RM goes up remarkably with the increasing concentrations of RM, whereas that of carbon ash exhibits a gentler trend, which indicates the bentonite dispersion incorporation carbon ash has the better flowability than RM. As the AV of drilling fluids reflects the mobility of drilling fluids, if it is too high, inefficient drilling is easy to result (Yan, 2003). The variations in PV are illustrated in Fig. 6(b). The PV of bentonite dispersion with RM also shows a sharp increase from 4.0 mPa s to 12.0 mPa s. However, the addition of carbon ash leads to a slight decrease in PV from 4.0 mPa s to 2.0 mPa s. The experimental results illustrates that carbon ash could weaken the internal friction of bentonite dispersion. In Fig. 6(c), YP of bentonite dispersion with carbon ash and RM show the increasing trend. The increase resulted from the addition of carbon ash is more slight than that of RM, which indicates YP of bentonite dispersion is easier to control with the addition of carbon ash. According to the literature, YP of drilling fluids should be controlled to within a proper range, but a sharp

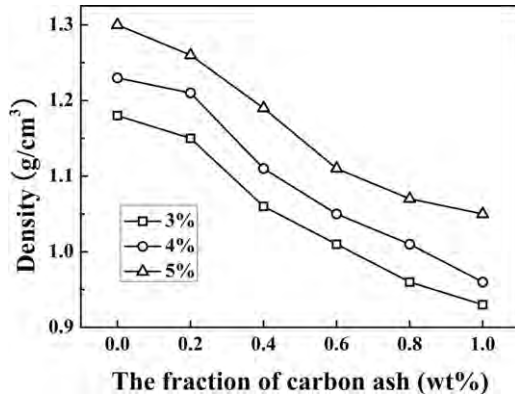


Fig. 8. Density of bentonite dispersion with different concentrations of carbon ash.

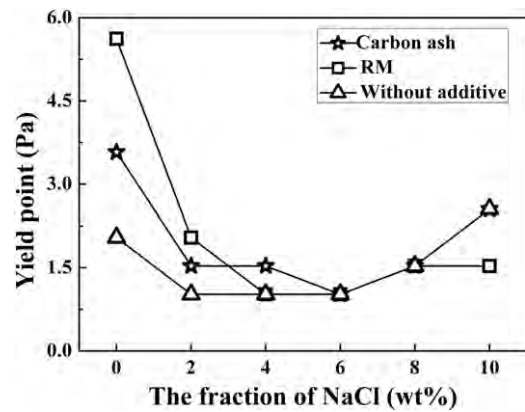


Fig. 10. Influence of NaCl on YP of bentonite dispersion containing carbon ash/RM.

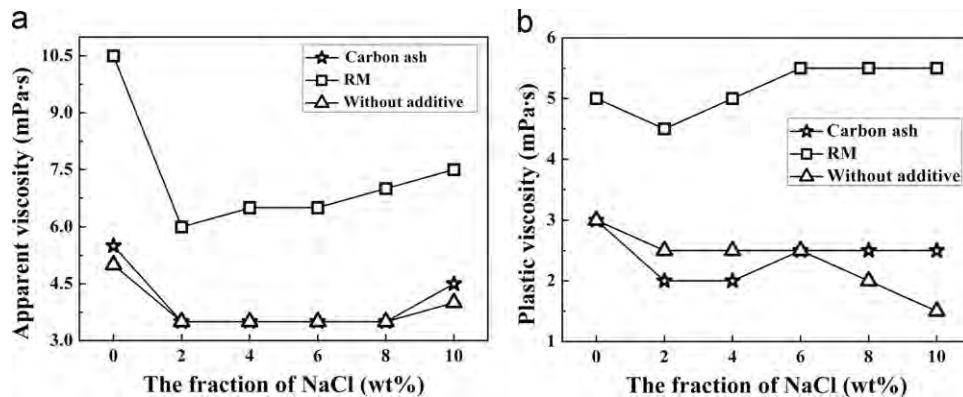


Fig. 9. Influence of NaCl on viscosity of bentonite dispersion containing carbon ash/RM: (a) AV; (b) PV.

increase renders control of YP difficult (Yan, 2003). RYP of bentonite dispersion with carbon ash and RM are shown in Fig. 6(d), and it could be clearly seen that the addition of carbon ash leads to the more dramatic increase than RM in RYP, which indicates bentonite dispersion incorporation carbon ash has the stronger capacity of carrying drilling cuttings. Take AV, PV, YP and RAY into consideration, carbon ash could improve the rheological properties of bentonite dispersion more available. It could be explained that carbon ash is absorbed onto the surface of bentonite particles by electrostatic interaction, and reduce the agglomeration among bentonite particles, which leads to the better rheological properties. Furthermore, according to Fig. 6, the addition concentration of carbon ash is determined at 0.4 wt% in the further experiments.

3.3. Influence of carbon ash on filtration loss and density of water drilling fluids

The filtration loss of bentonite dispersion incorporation carbon ash and the filter cake thickness after filtration are shown in Fig. 7. As observed in Fig. 7, the filtration loss and filter cake thickness increase with the increasing concentration of carbon ash. This is due to the electrostatic adsorption of bentonite particles, which reduces the capacity of holding water and agglomeration among bentonite particles. It could be also seen that the filtration loss declines and filter cake thickness increases as the solid contents of bentonite dispersion increases. According to the literature, the increasing solid contents could form the pyknotic film and reduce the filtration loss (Falode et al., 2008). The increasing thickness of filter cake is due to the reduction of agglomeration among bentonite particles adsorbed carbon ash.

The influence of carbon ash on the density of bentonite dispersion is shown in Fig. 8, and the results depicts that the density decreases gradually as addition of carbon ash increases. This is also due to the reduction of agglomeration among bentonite particles.

3.4. Stability of carbon ash in modifying the rheological properties of water drilling fluids

During drilling, drilling fluids are often affected by many specific factors, such as the invasion of inorganic salt and high temperature. Hence, the stability of carbon ash in modifying the rheological properties of water drilling fluids are evaluated from the resistance to salt and temperature systematically, and RM is also used for comparison. According to the previous study, the

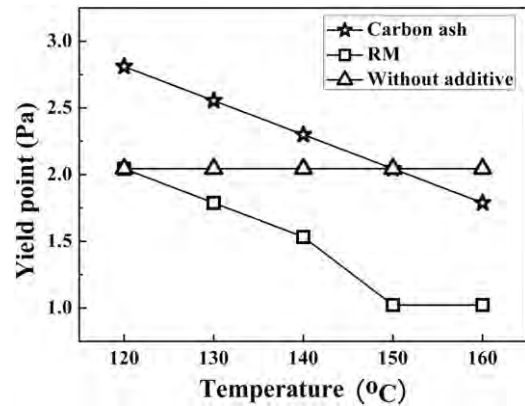


Fig. 13. Effects of temperature on YP of bentonite dispersion with carbon ash/RM.

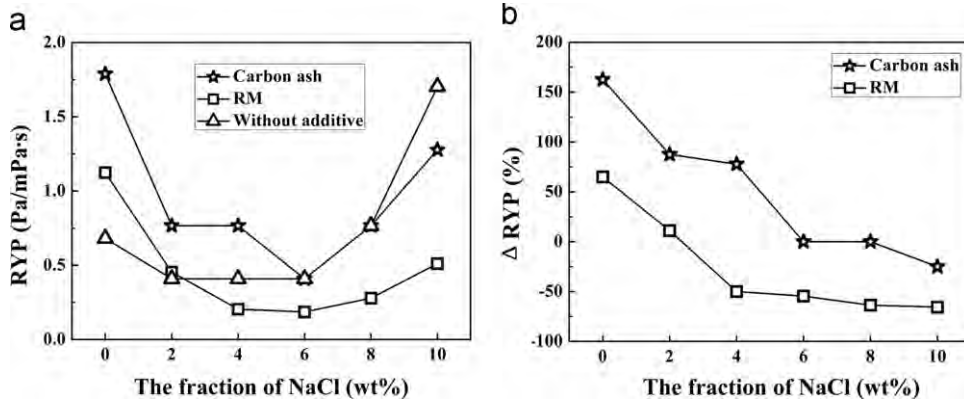


Fig. 11. Influence of NaCl on RYP of bentonite dispersion with carbon ash/RM: (a) RYP; (b) percentage change.

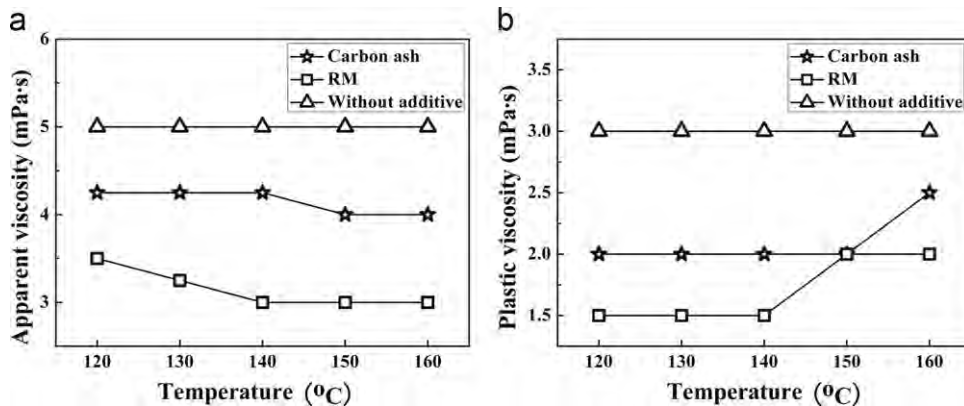


Fig. 12. Effects of temperature on viscosity of bentonite dispersion with carbon ash/RM: (a) AV; (b) PV.

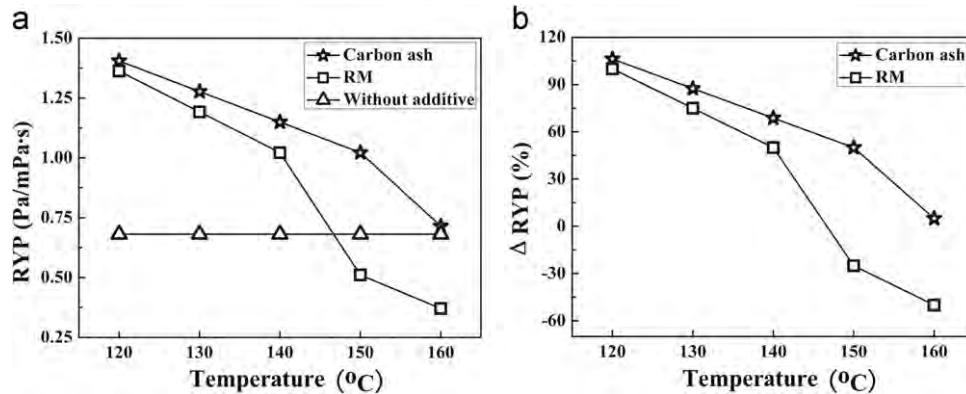


Fig. 14. Effects of temperature on RYP of bentonite dispersion with carbon ash/RM: (a) RYP (b) percentage change.

solid content of bentonite dispersion and concentration of additives including carbon ash and RM are determined at 3 wt% and 0.4 wt% respectively.

The network structure of drilling fluids is destroyed by the inorganic salt from stratum, which renders the additives useless. On the other hand, according to the literature, the inorganic salt is often used as the antifreeze agent (Hao, 2011) and inhibitors (Mohamed et al., 2010) of drilling fluids. Sodium chloride (NaCl) is used to evaluate the resistance to salt, and the different amounts of NaCl (2 g, 4 g, 6 g, 8 g and 10 g) are added into bentonite dispersion (100 g). The experimental results are shown in Figs. 9–11, and the viscosity is depicted in Fig. 9. As observed, the viscosity of bentonite dispersion exhibits a sharp fall due to the effect of NaCl, including AV and PV. When the concentration of NaCl is 2 wt%, AV of bentonite dispersion with RM and carbon ash decreases from 10.5 mPa s to 6.0 mPa s and 5.5 mPa s to 3.5 mPa s in Fig. 9(a), respectively. It could be explained that the surface charge of bentonite particles is affected by Na^+ and the adsorption of bentonite particles becomes poor, which results in the additives useless. As the concentration of NaCl continues increasing, AV of bentonite dispersion with RM increases gradually, whereas that of bentonite dispersion with carbon ash keeps steady until the concentration of NaCl reaches 10 wt%. The slight increase is due to the formation of flocculent structure. The similar phenomenon could be seen in Fig. 9(b), which illustrates PV of bentonite dispersion with additives as a function of NaCl. PV decreases firstly and then increase gradually with the increasing concentration of NaCl. The decrease is resulted from poor agglomeration whereas the subsequent increase is resulted from the formation of flocculent structure. YP of bentonite dispersion incorporation additives is shown in Fig. 10. When NaCl is added, YP goes down remarkably, including carbon ash and RM. When the NaCl concentration is 4 wt%, YP of bentonite dispersion with RM returns to that without additives. However, it occurs at 6 wt% when carbon ash is added. The influence of NaCl on RYP of bentonite dispersion with different additives is also investigated and the results are shown in Fig. 11, and it shows a remarkable downward trend with increasing NaCl concentration. However, as the concentration of NaCl is enough high, YP of bentonite dispersion increase again. This is due to the formation of flocculent structure in bentonite dispersion. As observed in Fig. 11(a), the decrease of bentonite dispersion with carbon ash is less than that of RM, and it indicates carbon ash has the better resistance to salt than RM in adjusting YP. The comparison results could be seen more directly in Fig. 11(b). Through the section of study, it could be stated that carbon ash has the better resistance to salt in improving the rheological properties.

In the drilling process, because of the geothermal gradient and formation pressure gradient, the deeper the bore hole, the higher are the temperature and pressure in the well bore. The high

temperature and pressure often lead to adverse effects, such as the increase of density and viscosity, the degradation of additives, which degrades the properties of drilling fluids. The resistance to temperature of carbon ash in adjusting the rheological properties is evaluated as a function of temperature, and the temperature is determined at 120, 130, 140, 150 and 160 °C respectively. The experimental results are shown in Figs. 12–14. Compared to Fig. 6(a) and (b), the influences of temperature on the viscosity of bentonite dispersion with carbon ash and RM are remarkable shown in Fig. 12. After the high temperature hot rolling, the viscosity including AV and PV are both less than that at room temperature. This may be due to the influence of temperature on the surface charge and adsorption of bentonite particles. The other reason is possible that the additives are rendered useless after high-temperature rolling. As the temperature increases, the slight decrease in AV may be due to the high-temperature dispersion, whereas the increase in PV indicates the increase of internal friction resulted from the incompletely absorbed additives. However, it could be seen clearly that carbon ash provides the less variation in viscosity than RM, which proves that carbon ash has the better resistance to temperature. The variation in YP is displayed in Fig. 13, and it could be seen that the YP of bentonite dispersion with carbon ash and RM fall gradually with increasing temperature. The YP of bentonite dispersion with RM returns to that of without additives when the temperature reaches 120 °C, whereas the YP of bentonite dispersion with carbon ash shows no increase at 150 °C. Thus, it can be inferred that carbon ash is better than RM from the standpoint of stability under high-temperature conditions. Fig. 14 shows the RYP of bentonite dispersion containing different additives. As observed in Fig. 14(a), the RYP decreases gradually with increasing temperature. When the temperature reaches 150 °C, the RYP of bentonite dispersion with RM is less than that of pour bentonite dispersion, which indicates RM is useless. However, the RYP returns to that of pour bentonite dispersion at 160 °C. The comparison variation of RYP could be seen more directly in Fig. 14(b). Take AV, PV, YP and RYP into consideration, the experimental results indicate that carbon ash has the better stability in resistance to temperature than RM.

4. Conclusion

The effects of carbon ash on the rheological properties of water-based drilling fluids are investigated based on the Bingham-plastic model. Carbon ash could improve the rheological properties available, especially for the low solid content of water-based drilling fluids. The addition of carbon ash could result in the high YP and RYP but slight variation in viscosity. The density of

water-based drilling fluids decreases slightly with the addition of carbon ash. The density of bentonite dispersion decreases slightly whereas the filtrate loss and filter cake thickness increases dramatically as the addition of carbon ash increases. Furthermore, carbon ash has the excellent stability in improving the rheological properties, including the resistance to salt and temperature. The experimental results show that carbon ash is a potential additive for improving the rheological properties of water-based drilling fluids.

Acknowledgments

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