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Effects of sewage sludge on rheological characteristics of coal–water slurry

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ABSTRACT

The coal–sludge slurry (CSS) containing coal, sewage sludge and water was prepared to study the effects of sewage sludge on rheological characteristics of the CSS. The yield stress, thixotropy and rheological type of CSS were investigated and compared with those of coal–water slurry (CWS). The results showed that the yield stress of CSS appears at the shear rate range from 0.05 to 0.14 s^{-1}. For CSS with the naphthalene sulfonate sodium formaldehyde condensate as dispersant and the sludge/coal mass ratio of 10:100, the yield stress can reach to 22.9 Pa. The thixotropy was quantitatively described by the thixotropy loop area, and sewage sludge can obviously improve the CWS thixotropy. The non-Newtonian behavior of CSS was characterized by a progressive decrease in viscosity with increasing shear rate at the shear rate range from 5 to 180 s^{-1}. By the analysis of FTIR, SEM and optical microscope, hydrophilic functional groups and colloidal structure of sewage sludge play the key roles on the different rheological characteristics of CSS and CWS.

1. Introduction

Since energy and environmental protection become an important global issue, the efficient utilization of coal can play a very vital role on future energy policy. Coal–water slurry (CWS) [1,2] gasification as clean coal technology is an important method to tackle energy maintenance and developmental problem in the 21st century. One of the problems concerned is the stable feeding of CWS to the gasifier. During the past 20 years, feedstock technique of pumping CWS has been the focus of attention by energy researches in many countries [3–5]. The slurry is transported over long distances of several hundred kilometers, which creates severe problems such as settling of solids, wear of the conduit by erosion, and huge power requirements for the whole transport process [6]. Therefore, a detailed understanding of the rheological characteristics of CWS is a prerequisite for its optimum and safe processing. CWS is a complex and high concentrated suspension (solid mass content usually $\geqq$60 wt.%) mixed with water and coal powders. Many authors concluded that the rheological characteristics of CWS would be varied with coal content, coal particle size distribution and additives, etc. [7–10].

A new sewage sludge disposal method is to prepare coal–sludge slurry (CSS), which could instead of coal–water slurry (CWS) in the entrained-flow gasifier to realize the co-gasification of sewage sludge and coal [11]. The coal–sludge slurry is prepared by mixing the sewage sludge, coal powders, water and dispersant. This process does not require pre-dried sewage sludge because a certain quantity of water is needed during CWS gasification. In the process of co-gasification, the water and calorific value of sewage sludge can be adequately utilized. Sewage sludge addition to CWS forms a ternary mixture, which is composed of rigid coal particles, deformable sewage sludge and flowing water. The rheological characteristics of CSS become different to those of CWS, and are also of special significance. In this paper, several kinds of CSS and CWS were prepared. The rheological characteristics of CSS were investigated by Malvern Bohlin CVO rotating-type rheometer, and compared with those of CWS.

2. Experiment

2.1. Materials

Shenfu coal from Inner Mongolia and the sewage sludge from Shanghai Longhua wastewater treatment plant in China, were chosen for the study. The characteristics of the coal and sewage sludge are given in Table 1.

The coal was first crushed to obtain a sub-5 mm product, then comminuted in the ball mill to produce an optimum particle size distribution (PSD). The PSD of coal and sewage sludge was listed in Table 2.

2.2. Methods

2.2.1. Coal–sludge slurry preparation

The milled coal and sewage sludge were mixed slowly in a stainless steel vessel containing 1% (dry coal basis) of the additive

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Table 1
Proximate analysis and ultimate analysis of Jincheng coal and sewage sludge.

Sample	Proximate analysis w (%)				Ultimate analysis w_d (%)				Q_d (MJ kg^{-1})
	M_{ar}	A_d	V_d	FC_d	C_d	H_d	N_d	S_d	
Shenfu coal	7.17	6.58	39.70	53.72	69.20	4.72	0.86	0.49	28.36
Sewage sludge	81.88	28.53	63.14	8.33	45.28	6.84	3.88	0.88	16.73

M_{ar} refers to moisture on received basis; A_d, V_d and FC_d refer to ash, volatile and fixed carbon on dried basis; ultimate analysis is also on dried basis; Q_d refers to higher heating value.

Table 2
Particle size distribution of the test samples.

Size (μm)	Volume under (%)	
	Jincheng coal	Sewage sludge
<350	100	100
<200	89	97
<150	85	96
<100	75	94
<75	67	93
<50	52	90
<40	45	87
<30	37	82
<20	26	72
<10	14	46

and deionized water. The mixture was continuously stirred by a mechanical agitator at 1000 rpm for approximately 20 min to ensure homogenization. About 200 ml coal–sludge slurry was prepared and allowed to stand for 5 min to release entrapped air before taking any measurements. The solids loading of all the CWS and CSS was 60 wt.%.

It has been found by the authors [11] that NaOH modifying sewage sludge can improve the solids loading of CSS. When sewage sludge needed to be modified, 10% NaOH (dry sewage sludge basis) was added to the sewage sludge, which was named modified sewage sludge [12]. The sludge was agitated and then allowed to stand for 0.5 h in air before being used.

2.2.2. Determination of slurry properties

Rheological property measurements were performed using rotating-type rheometer (model Malvern Bohlin CVO). The rheometer consists of a cup centered on a turntable with a rotor concentrically suspended within it. When taking any measurements, the sample was placed in the gap between the inner rotor and outer cylinder. The temperature was controlled at 25 °C. The results, which were automatically recorded by computer, can reveal the relationship between the shear rate and the shear stress, and the shear rate and apparent viscosity, respectively.

3. Results and discussion

3.1. The effect of sewage sludge on the yield stress of CSS

When naphthalene sulfonate sodium formaldehyde condensate was used as dispersant, the shear stresses of CWS and CSS were determined at the shear rate range from 0 to 1.0 s^{-1}.

As it is seen from Fig. 1, CWS and CSS exhibit different behaviors. The shear stresses of CWS increase progressively with increasing shear rate. For CSS, the shear stresses tend to increase initially up to a certain shear rate and thereafter decrease with further increasing shear rate, finally they increase again. The peak appears at about 0.138 s^{-1} when the shear rate is very close to zero, there is no relative motion among particles. At a certain shear rate, the shear stress becomes big enough to break the CSS structure. At the same time, relative motion among particles occurs, and the shear stress of CSS begins to decrease. The shear stress at this shear rate is defined as the yield stress. So, the yield stresses of CSS are the shear stresses at the shear rate 0.138 s^{-1}. For the CSS with the rate of sewage sludge and coal 100:10 and 100:5, the yield stresses and shear stresses are 23.0 and 4.7 Pa, respectively. For the CSS with modified sewage sludge, the yield stresses decrease.

To investigate the effect of dispersant on the yield stress of CSS, two kinds of CSS were prepared without dispersant and with humic acid as dispersant, respectively. The yield stresses of CSS were also determined, which were depicted in Fig. 2.

It is obvious from Fig. 2 that all kinds of CSS have yield stresses. The yield stresses of CSS without dispersant are bigger than those of CSS with dispersant. Inside CSS, many interactions coexist, such as coal particle–coal particle, sewage sludge–sewage sludge, coal particle–sewage sludge, dispersant–coal particle, dispersant–sewage sludge, and so on. Because of those interactions, a kind of spatial structure forms. The spatial structure strength can be reflected by the yield stress. Among different CSS's, the yield stress of CSS without dispersant is the biggest, and the shear rate value is the closest to zero which is about 0.05 s^{-1}. So, the CSS has the strongest spatial structure without dispersant. Datin Fatia Umar [13] stated that dispersant can reduce the yield stress and apparent viscosity of CWS. The dispersant can also reduce the yield stresses of CSS.

3.2. The effect of sewage sludge on CSS thixotropic property

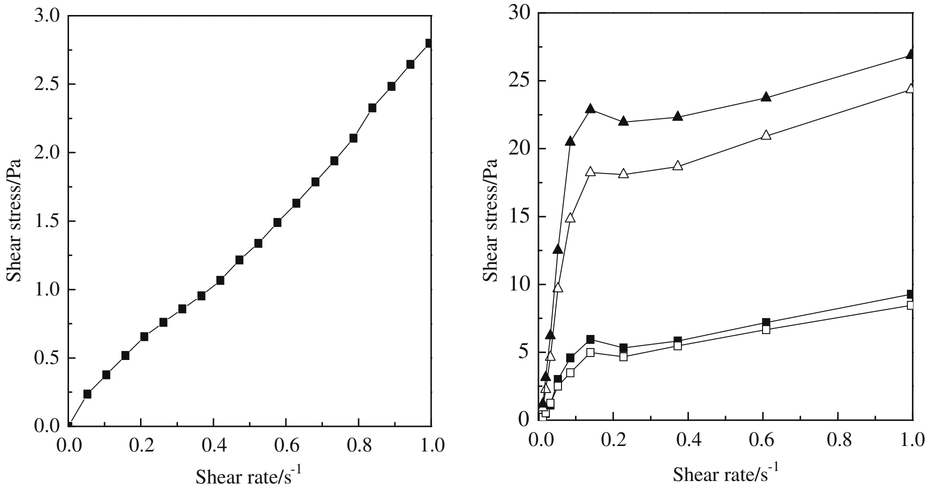
The slurries should keep stable spatial structure in order to prevent particles from setting at static condition. And during in the process of atomization and transport, the spatial structure should be broken in order to reduce viscosity. The thixotropy of slurry can meet the demands of two different conditions [14,15]. The thixotropic property of CSS were expressed by the thixotropy loop. The thixotropy loops of CWS and CSS with naphthalene sulfonate sodium formaldehyde condensate as dispersant were depicted in Fig. 3. It is obvious that there is a loop between upper and lower lines at the shear rate from 5 to 180 s^{-1}. The area of thixotropy loop was calculated by computer automatically. All the thixotropy loop areas of CWS and CSS were listed in Table 3.

As observed from Table 3, the thixotropy loop area of CSS is much more than that of CWS. Among different kinds of CSS, the thixotropy loop area of CSS without dispersant is the biggest, and the thixotropy loop area of CSS with NSSF is the smallest. The NSSF and HA as dispersants have positive effects on reducing the thixotropic property. The thixotropy loop area of CSS with modified sewage sludge is smaller than that with sewage sludge. The sewage sludge plays key role on increasing viscoelasticity of CSS.

3.3. The effect of sewage sludge on the rheological type of CSS

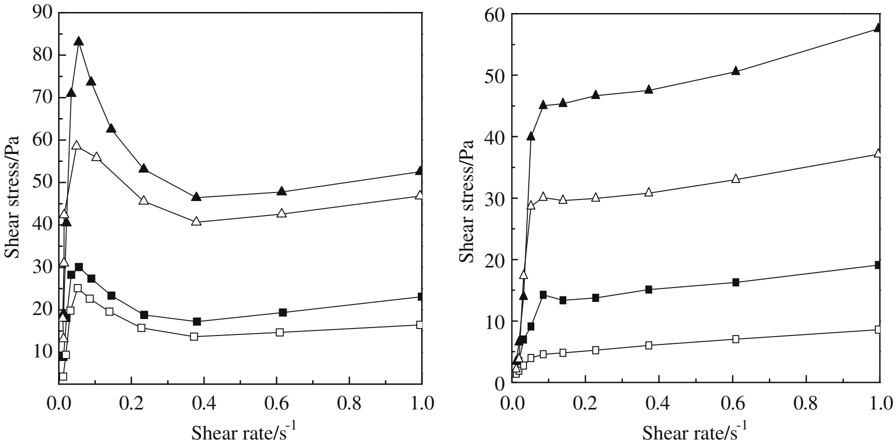
Rheological curves of CWS and CSS with naphthalene sulfonate sodium formaldehyde condensate as dispersant are shown in Fig. 4.

All CSS exhibit similar behaviors. At shear rate range from 5 to 180 s^{-1}, slurries exhibit non-Newtonian behavior, as characterized



(a) CWS (b) CSS

Fig. 1. The effect of sewage sludge on yield stress of CWS. ▲ Coal: sewage sludge = 100:10; △ coal: modified sewage sludge = 100:10; ■ coal: sewage sludge = 100:5; □ coal: modified sewage sludge = 100:5.



(a) no dispersant (b) humic acid as dispersant

Fig. 2. The effect of dispersant on the yield stress of coal–sludge slurries. ▲ Coal: sewage sludge = 100:10; △ coal: modified sewage sludge = 100:10; ■ coal: sewage sludge = 100:5; □ coal: modified sewage sludge = 100:5.

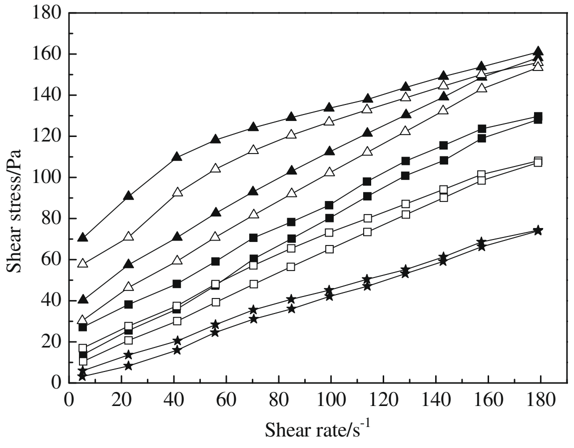


Fig. 3. Thixotropic behavior of coal–sludge slurries. ★ CWS; □ coal: modified sewage sludge = 100:5; ■ coal: sewage sludge = 100:5; △ coal: modified sewage sludge = 100:10; ▲ coal: sewage sludge = 100:10.

by a progressive decrease in viscosity with increasing shear rate. This type of fluid behavior is typical for suspensions of micro-particles [16,17]. In high-density coal–sludge slurries, inter-particle interactions become significant, leading to the formation of spatial structures, which are subsequently broken down by shear to result in shear-thinning. Comparing with CSS, the apparent viscosity of CWS exhibits almost no change with increasing shear rate.

It is obvious from Fig. 5 that the CSS without dispersant or with HA as dispersant show the same rheological type as the CSS with NSSF as dispersant. They are all non-Newtonian behavior. From 5 to 80 s^{-1}, the apparent viscosity reduces rapidly, and it decreases slowly from 80 to 180 s^{-1}.

3.4. FTIR spectra of sewage sludge and coal

The surface functional groups of sewage sludge and coal were analyzed by FTIR, and the spectra of Shenfu coal, sewage sludge and modified sewage sludge are depicted in Fig. 6.

From FTIR spectrums in Fig. 6, a strong absorption peak at about 3400 cm^{-1} is caused by the stretching vibration of –OH. Two absorption peaks at 2920 and 2851 cm^{-1} are due to the stretching

Table 3
The area of thixotropy loop of different coal–sludge slurries.

	The area of thixotropy loop				
	CWS	CSS			
		100:5	100:5 (modified)	100:10	100:10 (modified)
No dispersant	673	1812	1587	3023	2543
NSSF	542	1247	1034	2367	1954
HA	592	1542	1210	2667	2485

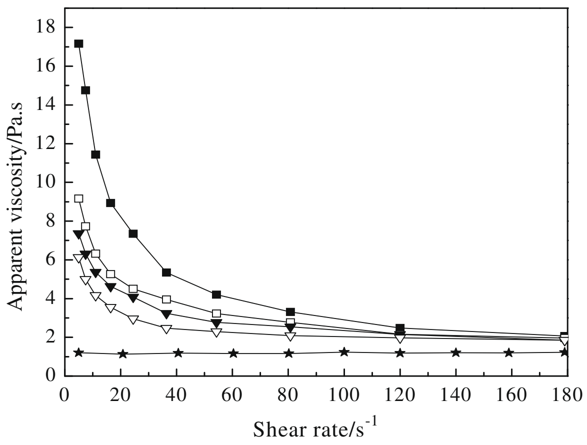


Fig. 4. The rheological properties of CWS and coal–sludge slurries. ★ CWS; ■ coal: sewage sludge = 100:10; □ coal: modified sewage sludge = 100:10; ▼ coal: sewage sludge = 100:5; ▽ coal: modified sewage sludge = 100:5.

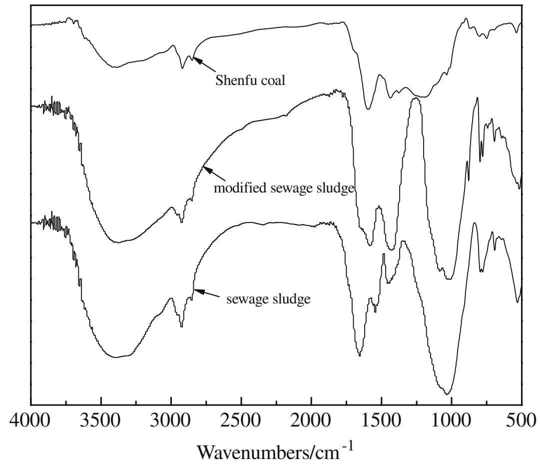
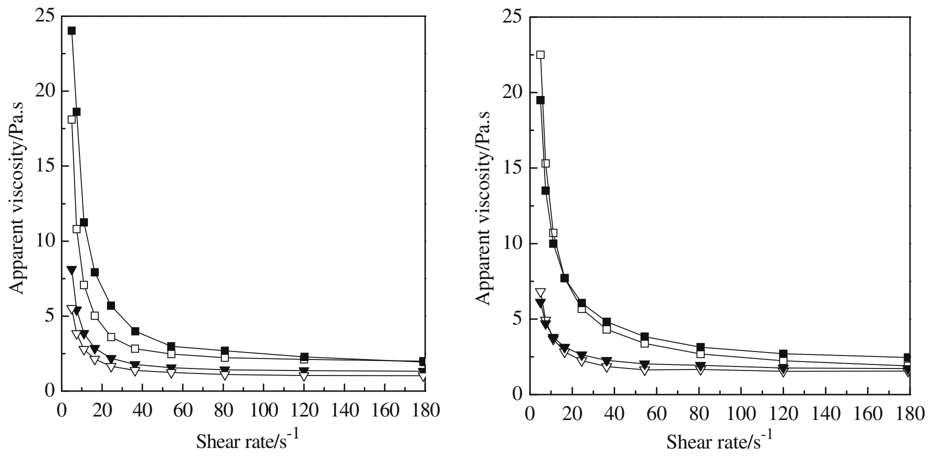


Fig. 6. FTIR spectra of samples.

vibration of $-CH_2-$ and $-CH_3$, respectively. A strong absorption peak at 1650 cm^{-1} is due to –C=O...H. At 1600 cm^{-1}, the absorption peak of C=C is strong. At 1200 cm^{-1}, two absorption peaks are caused by stretching vibration of C–O–C. The wide and strong absorption peak at 1050 cm^{-1} is because of stretching vibration of –C–O. At the range of 900–700 cm^{-1}, the peaks are caused by aromatic rings.

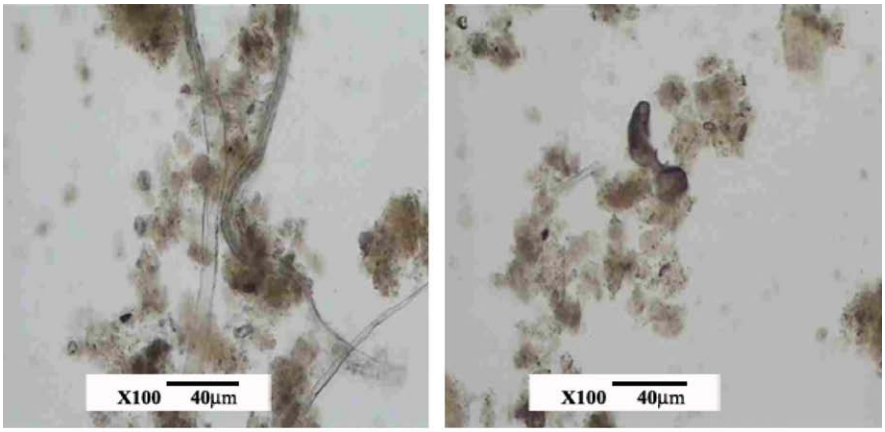
From what has been discussed above, it is obvious that the surface of Shenfu coal is dominated by hydrophobicity, which is the property of $-CH_2-$, $-CH_3$, C=C and C–O–C functional groups. The surface of sewage sludge is composed of hydrophilic functional groups, such as –OH, –C–O and –C=O...H. Comparing with sewage sludge, the functional groups on modified sewage sludge surface have no obvious changes.

After sewage sludge addition to CWS, on the one hand, coal particles combine with sewage sludge through van der waals force. On the other hand, the polar functional groups on surface of sewage sludge and coal particles form the "bridge" by hydrogen bonding and therefore, the strong spatial structure inside coal–sludge slurry emerges. May be, this is the main reason why the sewage sludge can enhance the yield stress of CWS.

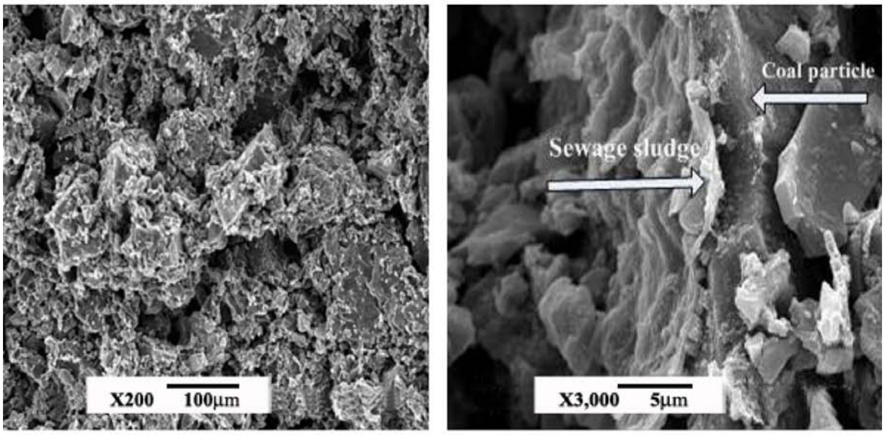


(a) no dispersant (b) HA asdispersant

Fig. 5. The effect of dispersant on rheological properties of coal–sludge slurries. ■ Coal: sewage sludge = 100:10; □ coal: modified sewage sludge = 100:10; ▼ coal: sewage sludge = 100:5; ▽ coal: modified sewage sludge = 100:5.



(a) Sewage sludge images



(b) SEM of dried coal-sludge slurry

Fig. 7. Structure of sewage sludge and dried CSS.

3.5. The structures of sewage sludge and coal–sludge slurry

Fig. 7a presents the 100 times magnified images of sewage sludge which are taken by optical microscope (Nikon E200). Fig. 7b shows the photos of CSS (sun dried) taken by scanning electron microscope (SEM).

As observed from Fig. 7a, sewage sludge is the integration of finer particles, which look like colloid. These particles have heavy hydrophilic property. After sewage sludge addition to CWS, the interaction of sewage sludge and coal particles plays the dominant role on the properties of CSS. It is obvious from Fig. 7b that sewage sludge fills the interspaces among the coal particles, and a kind of spatial structure forms. When the CSS is forced by shear rate, the water in sewage sludge particles releases, and apparent viscosity reduces. The sewage sludge has rapid recovery rate of deformation, which is responsible for stronger thixotropy of CSS than CWS.

4. Conclusions

In this study, the effects of sewage sludge on CWS rheological characteristics have been investigated. Experimental investigation revealed that CSS exhibits different properties to CWS in the aspects of yield stress, thixotropy and rheological type. The yield stress appears at the shear rate close to zero. Dispersant addition can reduce the yield stress of CSS. The thixotropy of CSS can be expressed by the thixotropy loop area, which is bigger than that of CWS. The CSS exhibit non-Newtonian behavior, as characterized by a progressing decrease in viscosity with increasing shear rate. After sewage sludge being modified by NaOH, the rheological characteristics of CSS have no obvious changes. The spatial structure can be formed by sewage sludge combining with coal particles inside slurries, and the sewage sludge have some colloidal like properties, which can explain the rheological differences between CWS and CSS.

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