

Received June 09, 2020; reviewed; accepted September 26, 2020

## Effect of particle properties on rheology of low-concentration coal suspensions

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**Abstract:** In wet coal preparation, the products of some processes are transported as low-concentration suspensions. Their rheology is greatly affected by the properties of the coal particles that result from the formation and weathering during preparation. In this study, the properties of coal particles, including volumetric properties (i.e., solids content, granularity, and clay mineral fraction) and surface characteristics (i.e., dynamic potential, degree of coalification, and degree of surface oxidization), were studied to determine their effects on the apparent viscosity of low-concentration coal suspensions. With increasing solids content and smaller particle size in the suspension, the interactions between the coal particles became stronger due to the increased particle content, thus increasing the coal suspension's apparent viscosity. Adding clay minerals to the suspension gradually changed its composition and structure and increased its viscosity. The dynamic potential of the coal particles and inter-particle electrostatic repulsive forces were reduced with the addition of  $\text{Ca}^{2+}$  ions, and the coal particles collided and aggregated, which increased the apparent viscosity of the suspension. For coal with a low degree of coalification or coal had been oxidized by a hydrogen peroxide solution, the suspension of the hydrophilic coal particles was associated with a lower apparent viscosity than that of highly hydrophobic solids, which tended to aggregate and form flocculent masses.

**Keywords:** apparent viscosity, coal suspension, particle property, hydrophobicity, effective volume

### 1. Introduction

Rheology is the scientific discipline that studies the flow and deformation of matter resulting from the relative movement of particles in a body (Markus, 1960). For suspensions, the presence of solid particles in the liquid makes the study of its rheological properties more complicated. The rheology of suspensions is a complex function of the physical and chemical properties of the particles and the processes that occur at the scale of the suspended particles (Mueller et al., 2010). Some of the physical properties of particles affecting rheology are volume fraction, particle shape, deformability, sensitivity to thermal agitation, and buoyancy (Mahaut et al., 2008).

Resource industries, including mineral and coal mining and the sand mining of oil, are the world's largest producers of waste. Much of this waste is produced as a fine particle suspension that is pumped to a storage area. Rheological knowledge could be applied to drastically reduce the volume of waste currently produced and stored, and, hence, reduce the negative social and environmental impacts of these industries (Boger, 2009).

The study of rheology in resource industries, especially in mineral processing, is of particular significance. Many processes in wet beneficiation, including dense medium separation, flotation and sedimentation, and dehydration, are conducted in the form of suspensions, the viscosity of which has a significant impact on the treatment effect. Viscosity is one of the two most critical parameters for dense medium separation; it is dependent on the medium's density, size, shape, and volume concentration and can be modified through the use of dispersant agents (Shi, 2016; Mabuza et al., 2005). For flotation, the suspension contains pulp and froth phases, and the viscosity of both phases can affect the flotation.

High pulp viscosity can also change the hydrodynamics within the flotation cell, which can negatively affect the sub-processes necessary for efficient flotation, such as gas dispersion, particle suspension, bubble-particle collision, attachment, and detachment (Bakker et al., 2009; Shabalala et al., 2011). The flotation of a particular mineral can be increased by changing properties such as the quantity and particle size distribution of the suspended particles, the type of flotation reagents, and the surface properties of the minerals. However, for the flotation of minerals with high clay contents, the yield stress and apparent viscosity are not sufficient to predict the flotation behavior because the negative effect of clay minerals on flotation depends primarily on the clay's inter-particle interactions (Cruz and Peng, 2016). The froth rheology, including the collection, further concentration, and transportation of the target minerals, is another critical parameter affecting the flotation performance (Farrokhpay, 2012; Li et al., 2018a; Li et al., 2018b). The flotation performance is related to the hydrophobicity of the minerals (Shi and Zheng, 2003), the frother type (Huangfu et al., 2018), and the surfactant type (Urdiales et al., 2018; Li et al., 2016), among other parameters. After the flotation process, the concentrates must be settled and dehydrated. The strong particle interactions in the froth inhibit particle settling (Zhang et al., 2018a), and salt can accelerate the settling velocity of particles that detach from the froth (Zhang et al., 2019). The rheology of the mineral suspension during preparation is highly dependent on the properties of the mineral particles.

Among mineral resources, the study of coal in suspension is complicated by factors including its composition, structure, and degree of carbonization, coupled with the mudification, weathering, and oxidation that occur during its storage, transportation, and preparation. Many studies have focused on the adjustment of the viscosity of the coal water slurry by adding additives (Wang et al., 2019; Zhu et al., 2017; Chen et al., 2019; Konduri and Fatehi, 2018), by changing the surface properties of the coal using microwave pre-treatment (Sahoo et al., 2017; Ren et al., 2017; Meikap et al., 2005), by using secondary fluids and additional particles (Chen et al., 2019), or by pre-absorbing water into the coal (Zhang et al., 2016). However, in wet coal preparation, the products of some processes are transported as low-concentration suspensions. Therefore, in this study, the properties of coal particles, such as volumetric properties (solids content, granularity, and clay mineral fraction) and particle surface characteristics (dynamic potential, degree of coalification, and degree of surface oxidization), were studied for their effects on the apparent viscosity of low-concentration coal suspensions.

## 2. Materials and methods

### 2.1. Materials

Four kinds of coal—Zhalainuo lignite (ZLNE), Majjaliang long flame coal (MJL), Malan coking coal (ML), and Zhaozhuang anthracite (ZZ)—and kaolin and bentonite minerals were used in this study. The results of the proximate and ultimate analyses performed for the four coal samples are listed in Table 1, and the properties of the two minerals are listed in Table 2. All samples were processed and stored in a 298 K dryer. The suspensions contained mixtures of the coal samples and deionized water and were stirred for 5 min to ensure homogenization before the viscosity measurements.

Table 1. Proximate analysis of various coal samples

| Coal sample | Proximate analysis/wt. % ad <sup>a</sup> |       |                 |                           |
|-------------|--|-------|-----------------|---------------------------|
|             | Moisture                                 | Ash   | Volatile matter | Fixed carbon <sup>b</sup> |
| ZLNE        | 3.15                                     | 11.20 | 44.92           | 40.73                     |
| MJL         | 1.19                                     | 33.09 | 25.42           | 40.30                     |
| ML          | 0.27                                     | 13.05 | 23.55           | 63.13                     |
| ZZ          | 0.23                                     | 20.10 | 10.29           | 69.38                     |

<sup>a</sup> Air-dry basis

<sup>b</sup> By difference

### 2.2. Viscosity measurement

The apparent viscosity measurements were performed at 298 K using an NDJ-9S rotational digital viscometer (Shanghai Pingxuan Scientific Instrument Co., Ltd., China).

Table 2. Properties of kaolin and bentonite minerals

|                   | Kaolin    | Bentonite       |
|-------------------|-----------|-----------------|
| Main mineral type | kaolinite | montmorillonite |
| Content/%         | 78.0      | 62.6            |
| Particle size/mm  | < 0.075   |                 |

Four different coal samples, ZLNE, MJL, ML, and ZZ, were chosen to study the effect of the degree of coalification on the apparent viscosity of the coal suspension, and the MJL was also used in other studies. The raw MJL was screened into five size ranges of granules (0.5–0.25 mm, 0.25–0.125 mm, 0.125–0.075 mm, 0.075–0.045 mm, and below 0.045 mm) to study their effects on the apparent viscosities of the suspensions. Unless otherwise stated, the coal samples in other measurements were milled and sieved into particles of less than 0.075 mm. To study the surface property changes,  $\text{CaCl}_2$  was added to adjust the dynamic potential of the coal surface. Oxidation using hydrogen peroxide solutions was performed to determine the coal types with different numbers of oxygen functional groups, which is relevant to the hydrophobicity of the coal. Two kinds of clay minerals, which had different structures and properties, kaolin and bentonite, were used to compare their effectiveness in increasing the viscosity of the suspensions.

### 2.3. Characterization

The FTIR spectra of the samples were recorded on a Bruker Tensor 27-spectrometer over the range of 4000–500  $\text{cm}^{-1}$ . The surface morphology of coal was measured with the scanning electron microscope (ZEISS MERLIN Compact). The wetting heat of the coal particles immersed in water was measured using a C80 micro-calorimeter (Setaram, France). Before testing, the coal samples were dried for 2 h at 348 K. Approximately 0.1 g of the tested sample was sealed inside a cell and then separated from 2  $\text{cm}^3$  of deionized water with an aluminum foil membrane. After mixing the coal sample with the water, the wetting heat of the process was measured at 303 K until the system reached equilibrium.

## 3. Results and discussion

### 3.1. Effect of the solids content on the apparent viscosity of the coal suspension

The MJL sample with particle sizes less than 0.075 mm was used to study the changes in the apparent viscosity of the suspensions with different solids contents; the values plotted at different shear rates are shown in Fig. 1. The results obtained indicate that the apparent viscosity of the coal suspension decreased with increasing rotational velocity (shear rate) at different solids contents, suggesting that the coal suspension was a non-Newtonian fluid possessing shear-thinning properties. Further, the apparent viscosity of the suspension increased with increasing solids content.

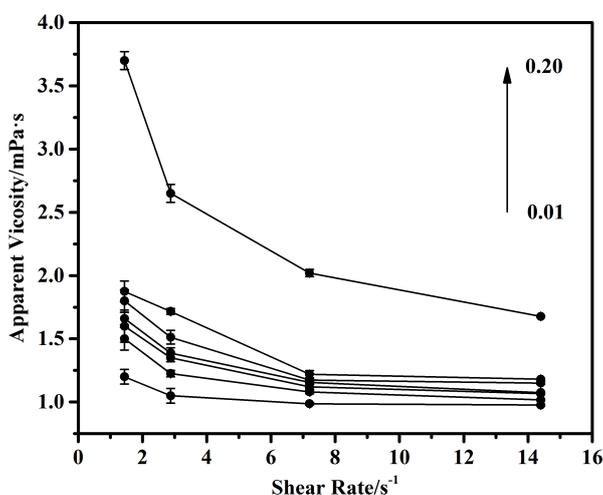


Fig. 1. Rheological curves recorded for the coal suspensions with different solid contents

The interaction between coal particles can be expressed by the Woodcock equation (Woodcock, 1997):

$$\frac{h}{d} = \left( \frac{1}{3\pi\phi} + \frac{5}{6} \right) - 1 \quad (1)$$

where  $h$  is the average distance between the particles (nm),  $d$  is the particle size (nm), and  $\phi$  is the solids content. The distance between the particles is significantly affected by the solids content of the suspension. The higher the solids content, the greater the number of particles per unit volume, and the lower the inter-particle distance. Once the suspension starts flowing, its particles tend to collide with each other and increase the internal friction of the suspension. The shear movement between the suspension layers is strongly affected by the increased particle resistance during movement and the formation of electrical double layers on the particle surfaces. These electrical double layers overlap each other, decreasing the inter-particle distance and leading to the increased magnitude of the electrostatic repulsion force. Therefore, it can be concluded that the interaction force between coal particles (and, therefore, the apparent viscosity of the suspension) increases with an increase in its solids content.

In this study, the solids content of the suspension varied between 0.01 and 0.20, corresponding to the semi-dilute regime, and the resulting plot of the relative apparent viscosity is shown in Fig. 2. Einstein's formula cannot describe the obtained dependence; the corresponding equation for the fitting curve is  $\eta_r = 1.11 + 0.95\phi + 14.57\phi^2$  (correlation coefficient = 0.992).

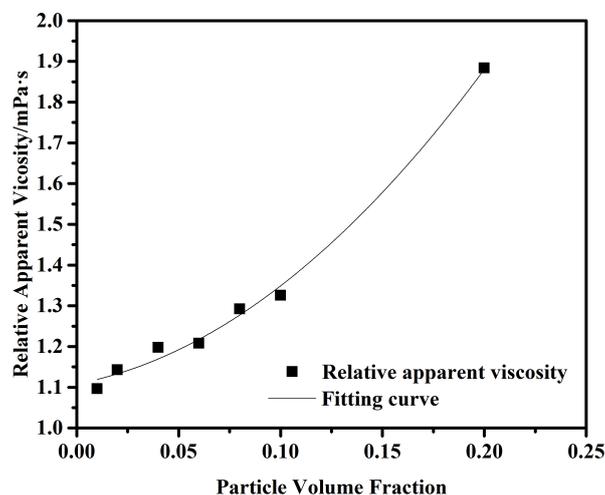


Fig. 2. Relative apparent viscosity of the coal suspension in the semi-dilute regime

### 3.2. Effect of granularity on the apparent viscosity of the coal suspension

Particle size also affects the apparent viscosity of the coal suspension, which, in this study, was determined at a solids content of 0.08 and shear rate of  $14.4 \text{ s}^{-1}$ . The viscosity values obtained for each grain size of the MJL raw coal sample are shown in Fig. 3. The apparent viscosity of the suspension containing coal particles smaller than 0.045 mm was substantially higher than that of the 0.5–0.25 mm coal particles. The apparent viscosity in the 0.5–0.25 mm particle size range was 0.90 mPa·s, which is extremely close to the 0.8937 mPa·s viscosity of deionized water under the same testing conditions (298 K) due to the high settling rate of the large coal particles. The terminal velocity of free settling in a suspension can be calculated using Stokes' formula (Collins et al., 1983):

$$v_0 = B \frac{d^2(\delta - \rho)g}{18\mu} \quad (2)$$

where  $v_0$  is the terminal velocity of the free particle settling (cm/s),  $B$  is the coefficient that takes into account the grain shape,  $d$  is the particle size (cm),  $\delta$  is the particle density ( $\text{g/cm}^3$ ),  $\rho$  is the density of water ( $\text{g/cm}^3$ ),  $g$  is the acceleration due to gravity (usually  $981 \text{ cm/s}^2$ ), and  $\mu$  is the viscosity of water at 298 K (P). Under the same conditions, the free settling rate of particles increases with increasing particle size. The free settling rate of the 0.5–0.25 mm coal particles was 1.45 cm/s. These particles completely settled during the apparent viscosity measurement of the suspension, indicating that the suspension's apparent viscosity was very close to that of deionized water. The free settling rate decreased with

increasing particle size; as a result, the larger coal particles only partially settled during the viscosity measurements.

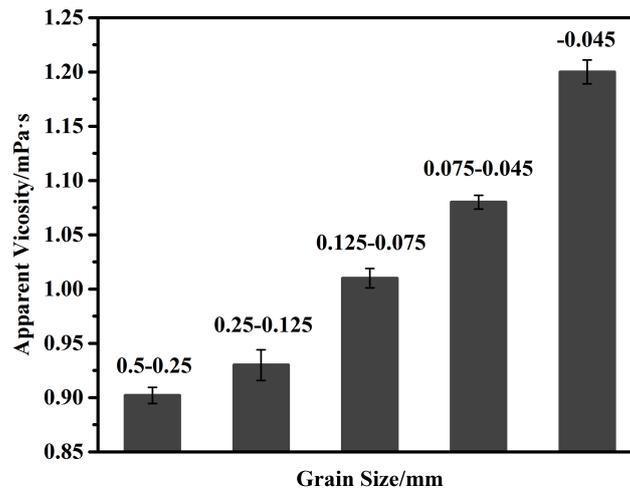


Fig. 3. Apparent viscosities of the coal suspensions with various grain sizes

As shown in Fig. 3, the apparent viscosity of the suspension increased with decreasing coal particle size because of the increase in the number of particles at the same solids content (0.08). The phenomenon is observed more distinctly at extremely small particle sizes (below 0.01 mm), because smaller particles have a relatively large specific surface area and, thus, a greater number of the water molecules adsorb on the particle surface. Therefore, the apparent viscosity of the suspension increased due to the increase in the effective particle volume of the suspension.

### 3.3. Effect of the clay mineral content on the apparent viscosity of the coal suspension

The clay minerals kaolinite and bentonite are typically present in coal and are excellent examples of marked differences in rheological responses. In this study, kaolin and bentonite were added to the MJL samples at concentrations of 0, 10, 30, and 50 wt.%. The particle sizes of the MJL, kaolin, and bentonite were all less than 0.075 mm, and the studied suspensions had solids contents of 0.08. As shown in Fig. 4, the apparent viscosities of the coal suspensions containing clay minerals decreased with increasing shear rate, indicating that the samples possessed shear-thinning properties; the fluid type of these suspensions was identical to that of the MJL suspension. The apparent viscosities of the obtained samples increased with increasing blending ratios of kaolin and bentonite. When the concentrations of the clay minerals were low—both less than 10%—the apparent viscosity of the coal-kaolin mixture was both higher than that of the coal suspension. When the blending ratio reached 50%, the apparent viscosity of the coal-bentonite mixture became significantly higher than that of the coal-kaolin mixture due to the different structures and forms in the suspensions.

Kaolinite has a two-layered (1:1) silicate structure containing Si-O tetrahedral sheets and Al-(O,OH) octahedral sheets together with water species existing in the form of -OH groups (Fernandez et al., 2011). Kaolinite has low chemical reactivity; it does not have interlayer materials and does not exhibit interlayer expansion or swelling in water (Theng, 2012). Montmorillonite has a (2:1) dioctahedral silicate structure containing water molecules and exchangeable cations between the layers and can expand when added to water, resulting in extensive interlayer surface area. The rheology of the two clay suspensions is significantly different due to their structures and characteristics, and the two clay minerals undergo a gradual change in structure with changing clay concentrations. Kaolin suspensions demonstrate a loosely packed card-house structure at low concentrations and can show continuous structural changes to the more compact ordered structures at high concentrations (Loginov et al., 2008). Montmorillonite forms fine flocculated masses (flocs) in suspension at low concentrations and gels at high concentrations (> 4%) (Janek and Lagaly, 2003). Conversely, when the clay particle concentration is sufficiently high (1% for many Na montmorillonite dispersions), the diffuse ionic layers around the silicate layers or particles restrict their translational and rotational motion, significantly increasing the

viscosity (Michot et al., 2009). When clay minerals are added to a suspension, its composition and structure gradually change. The kaolin impacts the apparent viscosity of the coal suspension less with increasing concentration as compared to the bentonite.

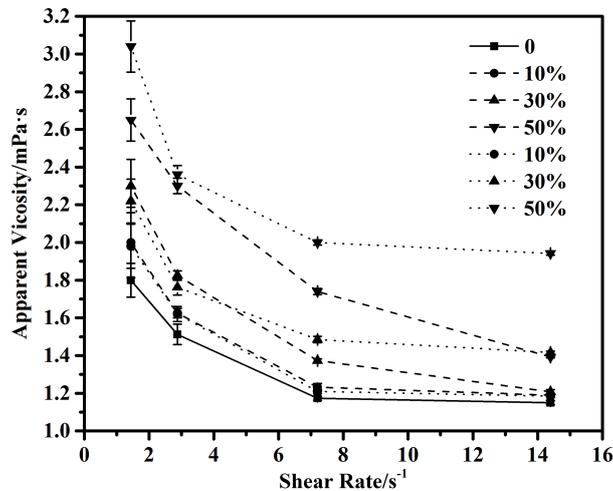


Fig. 4. Apparent viscosities of the coal suspensions with different contents of kaolin (dash line) and bentonite (dot line)

### 3.4. Effect of dynamic potential on the apparent viscosity of the coal suspension

Due to the particular surface properties of coal particles, they form a double layer in suspension, which is related to their dynamic potential. When opposite charges are present in the suspension, the double layers on the particle surfaces become compressed, changing the strength of the inter-particle interactions.

Pure deionized water cannot be used for the industrial processing of coal. Tap water contains relatively high amounts of metal ions (such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ , and  $\text{Na}^+$ ); as a result, various ions exist in the coal suspension. In this study, the coal particles' dynamic potential, which corresponds to the thickness of the double layers, was varied by adding  $\text{CaCl}_2$ . Taking MJL sample as example studied the correlation between the coal particles' dynamic potential and the apparent viscosity of the suspension. The MJL sample with particle sizes less than 0.075 mm and deionized water were used to prepare the suspension. The apparent viscosity was measured at a solids content of 0.08 and shear rate of 14.4  $\text{s}^{-1}$ . The dependence of the suspension's apparent viscosity on the  $\text{Ca}^{2+}$  concentration is shown as the black line in Fig. 5, while the red line depicts the dynamic potential of the coal particles in suspension as a function of  $\text{Ca}^{2+}$  concentration. The results reveal that, with increasing  $\text{Ca}^{2+}$  concentration, the dynamic potential of the particles decreased, and the apparent viscosity of the suspension increased. The adsorbed  $\text{Ca}^{2+}$  ions resulting from the addition of  $\text{CaCl}_2$  could efficiently neutralize the negative charge that occurred on the surface of the coal particles in the aqueous suspension. The electric double layer became compressed, and the electrostatic repulsive force between the coal particles decreased. Further, the presence of  $\text{Ca}^{2+}$  ions could weaken the hydration of coal particles, leading to their collision and aggregation and, thus, increasing the apparent viscosity of the suspension, especially for particles smaller than 0.01 mm. With the addition of  $\text{Ca}^{2+}$ , such particles could form flocs that subsequently grow and overlap to create a network structure that increases the floc-to-floc shear interactions. Therefore, as the dynamic potential of the coal particles decreased due to the addition of  $\text{Ca}^{2+}$ , the apparent viscosity of the suspension increased. Likewise, the apparent viscosities of ZLNE, ZZ and ML suspensions increased as the dynamic potential increased by adding  $\text{CaCl}_2$ .

### 3.5. Effect of the degree of coalification on the apparent viscosity of the coal suspension

The diversity of coal-forming materials and the complexity of their formation processes result in significantly different properties for various coals. Suspensions of four different coal samples (ZLNE, MJL, ML, and ZZ) with particle sizes below 0.075 mm and solids contents of 0.08 were investigated.

Their apparent viscosities are plotted as functions of shear rate in Fig. 6. All tested coal suspensions possessed shear-thinning properties and were non-Newtonian fluids, and their viscosities increased in the ascending order of ZLNE, MJL, ZZ, and ML. The heats of wetting of the coal samples are shown in Table 3 and can be listed in descending order as ZLNE, MJL, ZZ, and ML, meaning that they could be arranged from hydrophilic to hydrophobic in the same order.

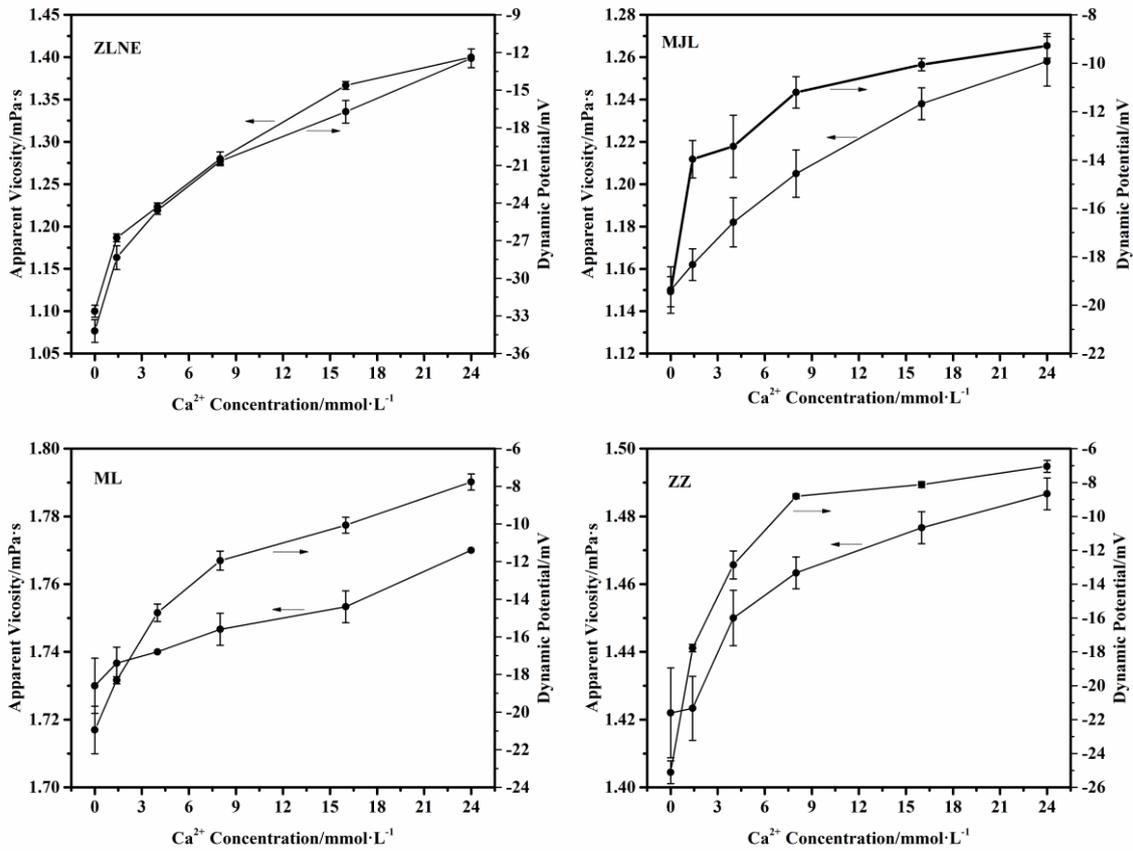


Fig. 5. Apparent viscosity and dynamic potential of the coal particle suspension plotted as a function of  $Ca^{2+}$  concentration

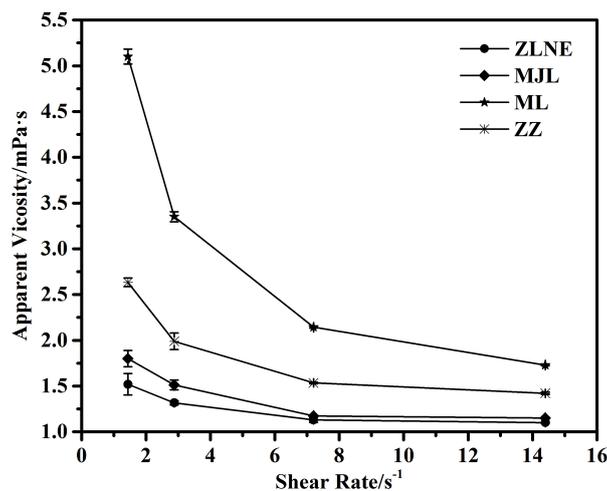


Fig. 6. Apparent viscosities of various coal suspensions plotted as functions of the shear rate

Table 3. Heats of wetting determined for various coal samples

| Sample                            | ZLNE   | MJL   | ML    | ZZ    |
|-----------------------------------|--------|-------|-------|-------|
| Heat of wetting/ $J \cdot g^{-1}$ | -60.11 | -8.09 | -0.79 | -2.37 |

After the coal particles were added to the aqueous solutions, water molecules densely arranged on their surfaces and assumed specific orientations. The hydration of the coal surface and formation of the hydration film depended strongly on the hydrophilic and hydrophobic characteristics of the coal particles, and the thickness of the adsorbed water layer was greater for the hydrophobic materials than for the hydrophilic ones. Highly hydrophobic solids tend to aggregate and form flocs with water-filled voids due to the long-range attraction between the hydrophobic macroscopic surfaces (Kékicheff, 2019; Mukherjee et al., 2015; Turov and Mironyuk, 1998). Both of these effects lead to an effective volume larger than the total effective volume and an increase in the coal suspension's viscosity.

### 3.6. Effect of coal surface oxidation on the apparent viscosity of the coal suspension

Under natural conditions, coal oxidizes slowly, causing changes in its surface properties. The experimental oxidation is usually performed under mild conditions to simulate the natural oxidation process and control the degree of coal oxidation. Generally, a positive correlation exists between the hydrophilicity of a coal sample and the number of oxygen-containing functional groups on its surface. Thus, hydrogen peroxide solutions with different concentrations can be used to obtain products with different numbers of functional groups and hydrophilic strengths. The apparent viscosity of a coal suspension is strongly correlated with the hydrophilic-hydrophobic properties of the coal surface. In this study, hydrogen peroxide solutions with concentrations of 0, 5, 10, 15, 20, 25, and 30 wt.% were selected for the oxidation of the coal suspension samples with particle sizes below 0.075 mm and solids contents of 0.08. As shown in Fig. 7, after oxidizing by the hydrogen peroxide solutions, different degrees of ravines or bumps appeared on the coal particle surfaces. Moreover, some covalent bonds on the coal surface (such as R–OH and R–O–R) were broken by H<sub>2</sub>O<sub>2</sub> species to form –COOH, C–O–C, and R–OH hydrophilic functional groups (Mae et al., 1997). As shown in Fig. 8, the region of 4000–3100 cm<sup>-1</sup> was attributed to the OH stretching in kaolinite, phenols, alcohols and carboxylic acid. The hydroxyl intensity in the oxidized coals was comparatively higher than raw coal. The total amount of oxygen-containing functional groups on the coal sample surfaces was measured by chemical titration. As shown in Table 4, the number of oxygen-containing functional groups increased with increasing hydrogen peroxide species concentrations.

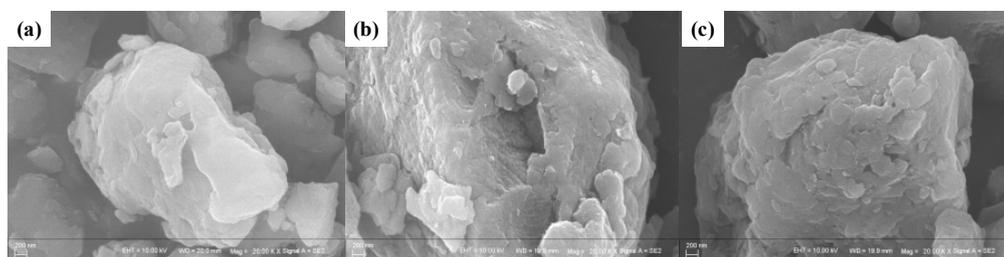


Fig. 7. Scanning electron micrographs of MJL oxidized by (a) 0, (b) 15 and (c) 30 wt.% hydrogen peroxide solution

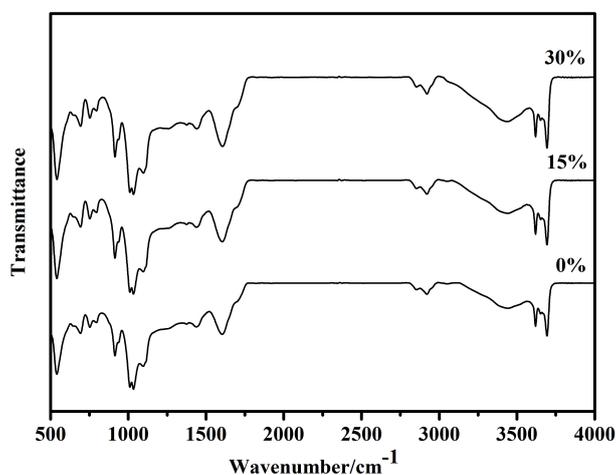


Fig. 8. FT-IR spectra of MJL oxidized by (a) 0, (b) 15 and (c) 30 wt.% hydrogen peroxide solution

As shown in Fig. 9, the apparent viscosities of these oxidized coal sample suspensions were lower than that of the raw coal suspension. The higher the hydrogen peroxide solution concentration was, the smaller the apparent viscosity of the suspension of the oxidized coal sample.

Table 4. Amounts of the oxygen functional groups on the surfaces of the coal samples oxidized under various conditions

| Coal samples   | Raw coal | Concentration of hydrogen peroxide solution/wt. % |      |      |      |      |      |
|--|----------|---|------|------|------|------|------|
|  |          | 5   | 10   | 15   | 20   | 25   | 30   |
| Total amount of oxygen-containing functional groups/mmol g <sup>-1</sup> | 0.97     | 1.05  | 1.13 | 1.23 | 1.37 | 1.51 | 1.55 |

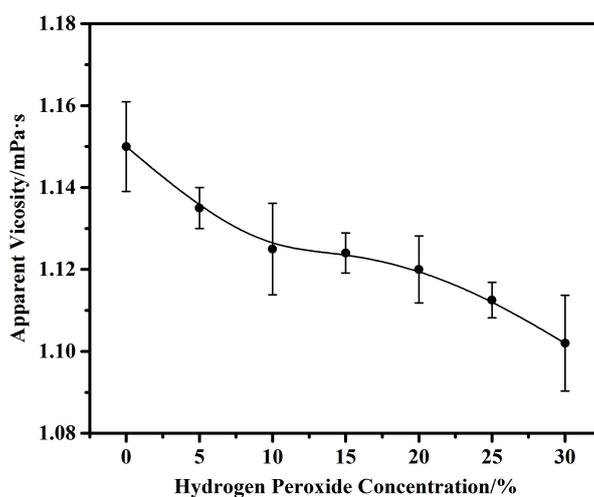


Fig. 9. Apparent viscosities of the suspensions of the coal particles oxidized by the hydrogen peroxide solutions with different concentrations

### 3.7. Discussion

In this study, several properties of coal particles were selected, including solids content, granularity, fraction of clay minerals, dynamic potential, degree of coalification, and degree of surface oxidization, to study their effects on the apparent viscosity of low-concentration coal suspensions. The first three properties can be termed volumetric properties, and the other three can be classified as the particles' surface characteristics. In suspension rheology, solids concentrations are expressed as a volume fraction (Laskowski, 2001). The volume fraction measured using dry samples is a parameter that depends on the solids' particle size distribution and particle shape. Therefore, increased solids content, decreased particle size, and increased clay minerals all lead to an increased volume fraction. When dispersed in water, coal particles in a suspension with a high-volume fraction are prone to collide due to the decreased distance between the particles, which is directly manifested as an increase in the internal friction and apparent viscosity of the suspension. Notably, the suspended clay minerals could swell and form fine flocs, or even gels, they show a packed card-house structure; the clay minerals could partially or entirely coat the coal particles, increasing the apparent viscosity of the suspension. These effects vary with the type and content of clay minerals. It is general knowledge that the surface electrical phenomena of minerals in aqueous media originate from ion preferential dissociation (or dissolution), ion preferential adsorption, and ion lattice substitution, forming electrical double layers at the interface. When the electric double layer is compressed, the electrostatic repulsive forces between the coal particles decrease, leading to particle collision and aggregation, and thus increasing the apparent viscosity of the suspension. For coal particles with hydrophobic surfaces, a long-range attraction exists between these surfaces, and the attractive forces exceed the van der Waals force by two orders of magnitude. The electrostatic response could explain the differences between the hydrophobic and

hydrophilic surfaces. Highly hydrophobic coal particles in suspension tend to aggregate and form flocs with water-filled voids, increasing the viscosity of the suspension.

In wet coal preparation, some processes, including flotation, settlement, and dewatering, involve low-concentration suspensions. The rheological behavior of the suspension can be considered when evaluating the processing performance. Flotation is well-known as the most common process in mineral separation for recovering valuable minerals from gangue. The pulp rheology, froth rheology, and froth stability are of importance in evaluating flotation performance, which is affected by factors such as the reagent chemistry and concentration, air flowrate, density of the slurry, particle hydrophobicity, and particle size distribution. The viscosity of the suspension increases with decreasing particle size and increasing particle concentration, which increases the liquid film draining resistance and stabilizes the froth (Ip et al., 1999). Particles with intermediate hydrophobicity are also conducive to froth stability. However, the efficiency of flotation is higher at a certain particle size than that at fine or coarse particle sizes because unstable froths decrease flotation recovery, and too-stable froths decrease the concentrate grade. Moreover, two kinds of clay minerals, kaolin, and bentonite, both increase the apparent viscosity of the suspension and have detrimental effects on concentrate grade and recovery in flotation. However, the apparent viscosity alone cannot predict the flotation behavior of a suspension with a high clay content; two suspensions having similar rheograms does not imply similar detrimental effects on flotation because these two clay minerals have different structures at high concentrations (Cruz et al., 2015). Further, the dynamic potential of the particles may also affect flotation performance. Some studies have shown that, when adding  $\text{CaCl}_2$  to shorten the bubble-particle attachment time and increase froth stability, the smaller the dynamic potential was, the more beneficial it was to improving the combustible recovery (Ozdemir, 2013; Zhang et al., 2018b). The properties of the coal particles have similar effects on the performance of suspension settlement and dewatering processes. Particles with low dynamic potential or highly hydrophobic surfaces collide and aggregate due to decreased electrostatic repulsive force or long-range attraction, leading to the increased apparent viscosity of the suspension but more efficient settling and dewatering, consistent with the conclusions of other researchers (Hassas et al., 2014). However, particles with high solids concentrations, small size, and high clay mineral content could be well-dispersed in the suspension due to increased electrostatic repulsion forces, causing the apparent viscosity of the suspension to increase; by contrast, these particles are not conducive to efficient settling or dewatering. To summarize, the apparent viscosity of the suspension could be a reference parameter to characterize the interaction between particles but is not the only parameter that determines the processing effects.

#### 4. Conclusions

Several properties of coal particles, including volumetric properties (solids content, granularity, and clay mineral fraction) and surface characteristics (dynamic potential, degree of coalification, and degree of surface oxidization), were selected to study their effects on the apparent viscosity of low-concentration coal suspensions.

As the solids content of the suspension increased, the distance between its particles decreased, which increased the probability of particle collision and, therefore, the internal friction and apparent viscosity increased. The gravity of the large coal particles weakened their interaction. The effect of the size of fine coal particles on the apparent viscosity of the suspension was identical to that produced by increased solids content. The apparent viscosity of the coal suspension was also affected by the clay mineral content. As compared with bentonite, increasing the kaolin concentration had less impact on the apparent viscosity of the coal suspension, owing to the differences between the structures of kaolinite and montmorillonite minerals. The dynamic potential of the coal particles increased after the addition of  $\text{Ca}^{2+}$ , which decreased the inter-particle electrostatic repulsive force, while the presence of  $\text{Ca}^{2+}$  ions weakened the particles' hydration. As a result, the coal particles tended to collide and aggregate, causing an increase in the apparent viscosity of the suspension. For coal with a low degree of coalification or coal that was oxidized by a hydrogen peroxide solution, the suspension with hydrophilic coal particles was associated with lower apparent viscosity. Highly hydrophobic coal particles tended to aggregate and form flocs with water-filled voids due to the long-range attraction between the hydrophobic macroscopic surfaces, which increased the suspension's viscosity.

## Acknowledgments

This research was supported by International Cooperation and Exchange of the National Natural Science Foundation of China under agreement number 51820105006, National Natural Science Foundation of China under agreement number 51674174, International Cooperation in Science and Technology of Major Research Plan of Shanxi Province under agreement number 201803D421104 and Science and Technology Research Foundation for Young Scholars of Shanxi Province under agreement number 201803D421104.

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