Study on Enhancing the Slurry Performance of Coal–Water Slurry Prepared with Low-Rank Coal

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Graphical Abstract

Although coal–water slurry (CWS) with low-rank Shenhua coal has poor slurry performance, it is a good power coal with many advantages including low ash content and ease of incineration. This article establishes differences between the slurry performance of CWS prepared with low-rank Shenhua coal and medium-rank Shandong coal. Moreover, we examined the effects of coal powder gradation, water pre-adsorption, formulation of modified sodium lignosulfonate (SL-M) with other dispersants and stabilizer, and a combined preparation of coal samples on the apparent viscosity of CWS. Results showed that the existence of weak acid groups, strong water adsorption ability, and high-density mineral substances were the major factors that affected the slurry performance of low-rank Shenhua coal. Furthermore, when the average coal particle size was 26.19 μm, the apparent viscosity of CWS was lowest according to bimodal distribution. When low-rank coal was treated first with water pre-adsorption, the slurry performance of CWS was greatly improved and the apparent viscosity was only 1200 mPa·s when the solid concentration was 63%, showing an increase of 3%. Finally, when low-rank Shenhua coal was combined with medium-rank Shandong coal, apparent viscosity was enhanced.

Keywords Low-rank shenhua coal, medium-rank shandong coal, coal–water slurry (CWS), apparent viscosity, combined

1. INTRODUCTION

The requirement of a substitute for petroleum fuels has become more and more urgent due to the rapid increase in oil consumption and the crisis of energy depletion. Coal–water slurry (CWS), one kind of concentrated coal – water suspension containing 60–70% fine coal, 29–39% water, and about 1% additives (dispersants involved), also referred to
as coal–water fuel, has become an alternative choice to oil because of its high combustion efficiency, as well as the convenience of handling and transportation.\(^\text{[1–4]}\) For maximum efficiency as a fuel, the coal concentration (i.e., slurry performance) in CWS should be as high as possible, simultaneously maintaining its viscosity at the minimum level in order that it will be suitable for storage and transportation through pipelines.\(^\text{[5,6]}\)

For the successful utilization of CWS in commercial plants, there are several factors required of CWS, including slurry performance, rheological properties, stability during transportation, and coal particle size.\(^\text{[7–9]}\) Among these, slurry performance is a key factor which also affects the rheological properties and stability of CWS. The primary factors responsible for the optimum slurry performance of CWS depend on the physicochemical properties of coal, such as quality, particle size distribution, and additives, as well as the preparation process. Most of these factors are controlled by the interfacial characteristics of coal itself. Coal, being a heterogeneous mixture of carbonaceous and mineral substances, has varying surface chemistry based on its rank. Researches have shown that coal rank is one of the most important factors influencing the slurry performance of CWS.\(^\text{[10–15]}\) Normally, coal can be divided into three categories: high-, medium-, and low-rank, each with different physical and chemical properties. Therefore, the slurry performance of CWS can vary widely by rank of coal.

Although coal of a higher rank can be used to prepare CWS with better slurry performance, the high price and relatively low storage capacity of medium- and high-rank coal considerably restrict their application. Contrarily, low-rank coals such as lignite, non-caking coal, and long-flame coal, which are widely used to supply feed material for coal gasification or combustion, have attracted ever greater attention. For example, Shenhua coal has been extensively studied in regard to the preparation of CWS because of its low price and huge storage capacity; however, its high moisture content and high ratio of oxygen to carbon are two major drawbacks that can induce poor slurry performance of CWS. Thus, two key points in regard to the industrial use of CWS are to improve its slurry performance and decrease preparation cost.

In order to broaden the application of CWS and to lower its cost, an appropriate method is sought to improve the slurry performance of CWS prepared using low-rank coal. It was found that CWS prepared from low-rank coals had excellent combustion characteristics in a gas turbine.\(^\text{[10]}\) Das et al.\(^\text{[13]}\) modulated three varieties of non-coking coal (low-rank Indian coal) using three starch-based additives, and obtained a highly concentrated coal–water slurry with low viscosity. Tiwari et al.\(^\text{[17]}\) obtained a high concentration CWS, which was up to 69% of coal loading, from Indian coals using the newly developed naphthalene-toluene-based additive. Aktaş et al.\(^\text{[10]}\) prepared CWS of up to 60% solids with a low-rank British coal in the presence of a non-ionic surfactant, Triton X-405. They found that the viscosity of slurry with low ash content was significantly reduced by the addition of surfactant. Zhou et al.\(^\text{[18]}\) used four different chemicals to coat the surface of Shangwan coal and investigated the corresponding effects on slurry preparation. They found that using Span-40 for surface coating, the maximum coal concentration was increased from 58 to 61.5%. Li et al.\(^\text{[19]}\) investigated the influence of sulfonated acetone-formaldehyde (SAF) condensation on low-rank CWS, and found that SAF of molecular weight 31,800–36,800 and sulfonic group content of 3.53–3.64 mmol/g had a superior effect in reducing viscosity. However, to the best of our knowledge, to date, no systematic work has been reported on improvement in the slurry performance of CWS with low-rank coal, especially Chinese Shenhua coal.

In this work, the mechanism of poor slurry performance of CWS using low-rank Shenhua coal was investigated. Furthermore, the effects of grain size distribution of coal particles, pre-adsorption of water on coal particles, additives, and combining coals for the preparation of CWS on its apparent viscosity are reported and discussed.

2. EXPERIMENTS

2.1. Materials

2.1.1. Coal Samples and Preparation of CWS

CWS preparation was carried out with Shenhua bituminous coal from Shenfu, Shanxi Province in China. Table 1 shows the results of both proximate and ultimate analyses for Shenhua coal used in this work.

Before CWS preparation, Shenhua coal was firstly crushed in a jaw crusher to obtain product of particle size below 10 mm. The particles were then dried under vacuum at 378 K for 24 hour. Next, the crushed particles were comminuted in a ball mill (dry grinding) to yield coal powder which was screened through a 100-mesh screener (0.149 mm pore size) to obtain a powder of average particle size 30 µm; over 99.7% of the particles were below 0.1 mm.

<table>
<thead>
<tr>
<th>Coal sample</th>
<th>Ash content (wt%)</th>
<th>Deliming ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shenhua</td>
<td></td>
<td></td>
</tr>
<tr>
<td>low-rank coal</td>
<td>Raw coal</td>
<td>4.96</td>
</tr>
<tr>
<td></td>
<td>After de-ashing</td>
<td>1.69</td>
</tr>
<tr>
<td>Shandong medium-</td>
<td>Raw coal</td>
<td>8.60</td>
</tr>
<tr>
<td>rank coal</td>
<td>After de-ashing</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Preparation of CWS: First, the coal powder was slowly mixed with a known quantity of dispersant and deionized water in a pot. Next, the mixture was continuously stirred by a mixer during the addition of coal powder, and the slurry was stirred for a further 10 minute at 1200 rpm to ensure that uniform dispersal of the coal particles in the CWS. Finally, the slurry obtained was sampled for further study of its characteristics.

2.1.2. Synthesis of GSL-M Compound

For the preparation of Modified sodium lignosulphonate (GSL-M), deionized water and sodium lignosulphonate (SL) were mixed in a reaction flask equipped with a temperature-controlled electric heating device, a motor stirrer, and a reflux condenser. The temperature was then raised to 333 K, with stirring. Next, known quantities of formaldehyde, sulfonating agent (Na₂SO₃), and acetone were added to the solution. Finally, the mixture was cooled to room temperature after being allowed to react for a set time. The light yellow product thus obtained was GSL-M dispersant aqueous solution.

2.1.3. De-Ashing of Coal Samples

De-ashing of coal samples was performed using a muffle furnace (3-550, Dentsply, USA).

De-ashing procedure: First, the samples were treated with HCl and HF for de-ashing, then about 80 g of coal furnace (3-550, Dentsply, USA). De-ashing of coal samples was performed using a muffle furnace (3-550, Dentsply, USA).

De-ashing of samples: First, the samples were treated with HCl and HF for de-ashing, then about 80 g of coal powder were mixed with 600 mL acid solution (150 mL HCl + 150 mL HF + 300 mL deionized water). The mixture was then placed under a water bath at 353 K for 5 hour and finally the coal powder was filtered and dried.

Ash determination (slow ashing): First, 1 g of dried coal was placed in the muffle furnace at a setting temperature at 373 K. Coal samples were then heated to 773 K and kept at this temperature for 30 minute, followed by heating to 1123 K for 3 hour until the weight of all samples was constant. Finally, the product obtained was cooled for 5 minute in air and placed in a desiccator.

2.2. Methods

2.2.1. Inherent Viscosity and Relation to Molecular Weight

Inherent viscosity of SL-M samples was measured using an Ubbelohde viscometer (diameter 0.8 mm) at 25 ± 0.1°C. The dilution and extrapolation method was used for theoretical calculation. All pH values of SL-M sample solutions were adjusted to 7.0 ± 0.2.

Inherent viscosity is an important parameter of high polymers and is related to their molecular weight. The relationship between molecular weight, M and inherent viscosity, [η] is described by the Mark–Houwink equation:

\[ [\eta] = KM^z \]  

where K and z are constants specific to the solvent and temperature, respectively, used in measurement.

2.2.2. Apparent Viscosity Measurement

Apparent viscosity measurement was carried out using a rheometer (type RotoVisco 1, Haake Corp., Germany) with a Z43 measure cup and a Z41 rotor. Before measurement, the slurries were allowed to stand for 5 minute. Measurements were taken at a shear rate of 100 s⁻¹ from the “up run” curve. The temperature was kept at 25°C (±2°C). Because 99.7% of the particles were finer than 100 μm, the gap size of the Z41 rotor (1 mm) was sufficiently wide for reliable measurement.

2.2.3. Infrared Spectrum Analyses

Fourier transform infrared spectrometry (FTIR) with Auto system XL/i-series/Spectrum 2000 PE was used for infrared spectrum analysis. Low-rank Shenhua coal and medium-rank Shandong coal were dried under vacuum and measured amounts of powder obtained were mixed with potassium bromide (KBr) in a mortar box. After grinding, the mortar box was thoroughly cleaned with acetone. The ground powder and KBr were pressed using a tablet machine for subsequent infrared spectrum analysis. Spectra were collected within a scanning range of 400-4000 cm⁻¹. The FTIR spectrometer was first calibrated for background signal scanning with a control sample, and sample scanning was then conducted.

2.2.4. Measurement of Particle Size Distribution (PSD) of Shenhua Low-Rank Coal

The PSD characteristics of pulverized Shenhua low-rank coal used in CWS formulation were determined by an EyeTech laser particle size analyzer (Ankersmid, Holland). Automatic particle size analysis can be performed in the measuring range 0.1–3600 μm in suspension. The results are calculated on the basis of Fraunhofer theory.

3. RESULTS AND DISCUSSION

3.1. Slurry Performance of CWS Prepared with Shenhua Low-Rank Coal

3.1.1. Slurry Performance of CWS Prepared with Low- and Medium-Rank Coal Samples

In order to evaluate the effect of coal rank on the slurry performance of CWS, low-rank Shenhua coal and medium-rank Shandong coal were used to prepare CWS. SL-M was used as the dispersant at a dosage of 1.0 wt% (dry coal basis). Figure 1 shows the effect of solid content on the apparent viscosity of CWS for both coal types. It was observed that with increase in solid content, the apparent viscosity of both CWSs increased markedly. The apparent viscosity of CWS prepared by Shenhua and Shandong...
The apparent viscosity of CWS, was 925.6 and 890 mPa·s, and the solid content was 59% and 65%, respectively. This indicates that the slurry performance of CWS prepared with Shandong medium-rank coal was much better than that with Shenhua low-rank coal, by around 6%.

### 3.1.2. FTIR of Low- and Medium-Rank Coal Samples

Figure 2 shows the FTIR spectra of low-rank Shenhua and medium-rank Shandong coal types, with marked similarities (e.g., the presence of bands at 3400, 1300–1000, and 1600 cm\(^{-1}\), corresponding to –OH, C-O stretching modes (alcohols, phenols, ether, esters), and C=O (carboxylic), respectively). It is suggested that they possess similar groups on their surface. On the other hand, the spectra also demonstrated differences: (1) the peak at around 3400 cm\(^{-1}\), which was assigned to hydrogen bond-associated O-H stretching groups, was more pronounced with Shenhua low-rank coal, indicating that the content of O-H groups was higher than in Shandong medium-rank coal; (2) three peaks, at 650–900 cm\(^{-1}\), for Shenhua low-rank coal were more evident than for Shandong medium-rank coal, corresponding to C-H groups (aromatic rings), suggesting that there were more aromatic rings in low-rank Shenhua coal.

### 3.1.3. Surface Acidity of Low- and Medium-Rank Coal Samples

Figure 3 shows the effect of consumption of NaOH on the pH value of solutions of both coal types. It will be observed that the surfaces of both coals samples are acidic, with preliminary pH values of about 3.5 and 3.9, respectively, which was ascribed to oxygen-containing groups. When the surfaces of both coal types had the same pH value, more NaOH was used by Shenhua coal, indicating that more oxygen-containing groups in that type. Furthermore, the sharp increase in NaOH used by Shandong medium-rank coal demonstrated that the presence of strongly acid groups, while Shenhua coal was characterized by weakly acidic groups. When the surfaces of both types were neutralized, the amount of NaOH used by Shenhua coal was only slightly higher than that used by Shandong coal, illustrating similar total acidity. However, the species and quantities of acid groups on the surfaces of these two samples were quite different.

### 3.1.4. Ash Content of Low- and Medium-Rank Coal Samples

Many minerals are present in coal besides the basic elements C, H, O, N, and S. In order to determine the effect of minerals on apparent viscosity, the two coal samples were de-ashed as was depicted in Figure 4. It will be observed that...
the apparent viscosity of both samples after de-ashing increased markedly, leading to decreased slurry performance. The apparent viscosity of raw Shenhua low-rank coal was 801 mPa·s, while the delimed sample shows an apparent viscosity of 1290 mPa·s, an increase by 489 mPa·s; the corresponding values for delimed Shandong coal increased from 713 to 1403 mPa·s, an increase of 690 mPa·s. These findings suggest that the mineral content of both samples enhanced the decrease in apparent viscosity, with the effect being much greater in Shandong than in Shenhua coal.

Table 1 lists the ash content of both coal types after de-ashing, for Shenhua coal this decreased from 4.96% to 1.69% and the deliming ratio was 65.93%; the corresponding values for Shandong coal were 8.60% to 1.15% and the deliming ration was 86.63%. Figure 5 presents the IR spectra of both coal types after de-ashing. The bands at 874.63, 541.74, and 465.93 cm\(^{-1}\) for Shenhua coal after de-ashing (Figure 5a) and those at 1033.16, 539, and 470.75 cm\(^{-1}\) for Shandong coal after de-ashing (Figure 5b) either decreased or disappeared, indicating that the concentration of minerals in both coal types after de-ashing dramatically decreased.

3.1.5. Effect of Water Adsorption Performance of Low-Rank Shenhua Coal on Slurry Performance

The water adsorption capacity of coal is an important factor affecting the slurry performance of CWS, especially low-rank.\(^{[11,20,21]}\) Table 2 shows the water adsorption performance of both coal types. It will be seen that the preliminary water content of Shenhua coal was 1.30%; however, after water adsorption, this increased to 5.54%; the corresponding values for Shandong coal were 2.81% and 0.78%. This illustrates that under the same conditions, the slurry concentration of Shenhua coal decreased by 2% as compared with Shandong coal.

![FIG. 4. Effect of Shenhua low-rank and Shandong medium-rank coal after de-ashing on apparent viscosity of CWS.](image1)

![FIG. 5. FTIR spectra of Shenhua low-rank (a) and Shandong medium-rank coal (b) before and after de-ashing.](image2)

3.2. Methods to Improve the Slurry Performance of Shenhua Low-Rank Coal

3.2.1. Effect of PSD on Slurry Performance

The significance of particle size and distribution of coal used in CWS was put forward by Boylu et al.\(^{[12]}\) According to previous researches, the grinding and selection of optimum particle size distribution has proved to be an important aspect in all CWS technologies. In the current study, Shenhua low-rank coal was used as the sample with SL-M as dispersant, and the effect of solid content on the apparent viscosity of CWS in single modal distribution was investigated, as shown in Figure 6. Note that when mean coal particle size was 50.28 μm, apparent viscosity was lowest and slurry performance highest. This is because when water is added to coal, it enters the voids between
particles and can move freely since the volume fraction of coarse particles is high and the void between coal particles is much bigger, resulting in decreased apparent viscosity. On the other hand, with decrease in mean coal particle size, water fills the voids and consequently less water remains available between particles since the volume fraction of coal powder becomes smaller. Therefore, particle movement is hindered and apparent viscosity increases. However, since the density of coal is higher than 1, the larger the coal particles the more easily they are deposited, causing poor stability in CWS. Furthermore, larger coal particle size is disadvantageous to the full combustion of CWS, and thus a single modal distribution is infrequently used for CWS.

In order to find an appropriate gradation for fine and coarse coal particles, Shenhua low-rank coal was ground for 3 hour and then screened through a 100-mesh sieve. The fine particles thus obtained were graded with other Shenhua coal particles created under different grinding times in bimodal distribution. Figure 7 shows the effect of solid content on the apparent viscosity of CWS in bimodal distribution. It will be observed that with increase in solid content, the apparent viscosity also increased. Furthermore, when the average coal particle size of the graded sample was 26.19 μm, the apparent viscosity of CWS was lowest.

3.2.2. Effect of Water Pre-Adsorption of Shenhua Low-Rank Coal on Its Slurry Performance

The solid concentration of CWS were held constant at 60 wt%, and the effect of water pre-adsorption of Shenhua coal on apparent viscosity was examined (Figures 8 and 9). Figure 8 shows that when the preliminary water content was around 0.50–0.55%, the apparent viscosity of CWS was 1230 mPa·s. Furthermore, with increase in water content to around 5.34–5.38%, apparent viscosity fell to 710 mPa·s. With further increase in water content, the apparent viscosity of CWS remained almost constant. Therefore, the water content of coal samples was set at 5.5% and the effects of pre-adsorption of water by low-rank coal on the slurry performance of CWS were further investigated.

The raw Shenhua low-rank coal and water pre-adsorption-treated coal were considered as the coal samples, with FDN used as dispersant, and the effect of solid concentration on the apparent viscosity of CWS is shown in Figure 9. It will be seen that the apparent viscosity increased in both samples with increase in solid concentration, with that for water pre-adsorption-treated coal being lower than that of raw Shenhua coal. Furthermore, when the solid concentration was 60%, the apparent viscosity of CWS using water pre-adsorption-treated raw

<table>
<thead>
<tr>
<th>Coal sample</th>
<th>Dry solid content of coal (wt%)</th>
<th>Water content (wt%)</th>
<th>Free-water loss (g/20 g, dry basis)</th>
</tr>
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<tbody>
<tr>
<td>Shenhua low-rank coal</td>
<td>Raw coal</td>
<td>98.70</td>
<td>1.30</td>
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<tr>
<td></td>
<td>After de-ashing</td>
<td>94.46</td>
<td>5.54</td>
</tr>
<tr>
<td>Shandong medium-rank coal</td>
<td>Raw coal</td>
<td>99.22</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>After de-ashing</td>
<td>97.19</td>
<td>2.81</td>
</tr>
</tbody>
</table>

**FIG. 6.** Effect of solid content on apparent viscosity of CWS with Shenhua low-rank coal in single modal distribution.

**FIG. 7.** Effect of solid content on apparent viscosity of CWS with Shenhua low-rank coal in bimodal distribution.
Shenhua coal decreased from 1230 to 710 mPa \cdot s; at solid concentration 63%, the apparent viscosity was only 1200 mPa \cdot s, showing an increase of 3% in solid concentration as compared with that of raw Shenhua coal. This indicates that water pre-adsorption enhances the slurry performance of CWS using Shenhua low-rank coal.

3.2.3. Effect of SL-M Additive on Slurry Performance of CWS

3.2.3.1. Effect of SL-M with Other Additives on Slurry Performance of CWS. Since the use of nonionic additives for CWS incurs relatively high costs, in this study, the commercially available anion dispersants FDN and SAF were selected as the combination additives. Table 3 shows the effect of GSL-M and FDN in combination on the slurry performance of Shenhua low-rank coal. It will be noted that the apparent viscosity of CWS with SL-M as dispersant was far lower than that of CWS with FDN as dispersant. Furthermore, with increase in SL-M in the combined dispersant, the apparent viscosity of CWS decreased, indicating that there was no synergistic effect between SL-M and FDN.

Table 4 shows the effect of combined SL-M and SAF on the slurry performance of Shenhua low-rank coal. It will be seen that the apparent viscosity of CWS with SL-M as dispersant was slightly lower than that with SAF. When the mass ratio of SL-M and SAF was equal to 1, the apparent viscosity of CWS was lowest at 1045 mPa \cdot s, which was only slightly lower than that with SL-M (1060 mPa \cdot s). This also suggests that there was very little synergistic effect between SL-M and SAF.

3.2.3.2. Effect of SL-M and CMC Combination on the Apparent Viscosity of CWS. In order to prevent direct deposition of CWS, it is usually necessary to add stabilizer; however, this results in increased apparent viscosity. Research has shown that the polymeric anionic agent, sodium carboxymethyl cellulose (CMC) had a marked effect on the stability of CWS prepared from bituminous coal.\cite{22} In that study, SL-M was the additive and CMC the stabilizer, these having been added to study the effect of the synergism of SL-M and CMC (0–0.15%, dry coal base) on apparent viscosity, as shown in Table 5. Note that with increase in CMC (0 to 0.05%), the apparent viscosity of CWS markedly increased from 850 to 1126 mPa \cdot s, an increase of 32.5%. However, when the level of CMC was further increased (0.05 to 0.15%), the apparent viscosity of CWS increased only slightly. This occurred because

![FIG. 8](image-url) Effect of water content of coal on apparent viscosity of CWS with Shenhua low-rank coal.

![FIG. 9](image-url) Effect of solid content on apparent viscosity of CWS with Shenhua low-rank coal.

Shenhua coal decreased from 1230 to 710 mPa \cdot s; at solid concentration 63%, the apparent viscosity was only 1200 mPa \cdot s, showing an increase of 3% in solid concentration as compared with that of raw Shenhua coal. This indicates that water pre-adsorption enhances the slurry performance of CWS using Shenhua low-rank coal.

<table>
<thead>
<tr>
<th>Additive(s)</th>
<th>Solid content (wt%)</th>
<th>Additive (wt%)</th>
<th>Apparent viscosity (mPa \cdot s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDN</td>
<td>60</td>
<td>1.0</td>
<td>1230</td>
</tr>
<tr>
<td>SL-M</td>
<td>60</td>
<td>1.0</td>
<td>1060</td>
</tr>
<tr>
<td>m (SL-M): m(FDN) = 1:2</td>
<td>60</td>
<td>1.0</td>
<td>1209</td>
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<tr>
<td>m (SL-M): m(FDN) = 1:1</td>
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<td>m (SL-M): m(FDN) = 2:1</td>
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<td>m (SL-M): m(FDN) = 3:1</td>
<td>60</td>
<td>1.0</td>
<td>1096</td>
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</table>
CMC is a high-molecular weight chemical with both carbonyl and hydroxyl groups; with the addition of only a small amount of CMC, the viscosity of the CWS increases due to the high molecular weight of CMC. Meanwhile, CMC can form a net-like structure on the surface of coal particles, hindering the free movement of coal particles and resulting in an increase in the apparent viscosity of CWS.

### 3.2.4. Effect of a Mixture of Shenhua Low-Rank and Shandong Medium-Rank Coal on the Apparent Viscosity of CWS

The grinding process is also an important issue in regard to improvement in the solid concentration of CWS.\cite{23,24} In this part of the study, SL-M was used as dispersant and Shenhua low-rank coal was mixed with Shandong medium-rank coal to prepare CWS. Table 6 shows the results obtained in regard to slurry properties. As will be seen, the solid concentration of CWS using only Shenhua low-rank coal is low, but when mixed with Shandong medium-rank coal, this concentration increased. Among the four mixed coal samples, the slurry performance of CWS using mixture of Shenhua low-rank coal ground for 3 hour (screened with 100-mesh sieve) and medium-rank Shandong coal ground for 3 hour (screened with 100-mesh sieve) was optimum. The poorest slurry performance was shown by a mixture of Shenhua low-rank coal ground for 40 minute (screened with 70-mesh sieve) and Shandong

### Tables

#### Table 3

<table>
<thead>
<tr>
<th>Additive(s)</th>
<th>Solid content (wt%)</th>
<th>Additive (wt%)</th>
<th>Apparent viscosity (mPa·s)</th>
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<tr>
<td>SAF</td>
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#### Table 4

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<td>CMC (%)</td>
<td>Solid content (wt%)</td>
<td>Additive (wt%)</td>
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#### Table 5

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<th>Additive (wt%)</th>
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<td>Shenhua and Shandong coal types ground for 40 minute</td>
<td>Shenhua coal ground for 40 minute and Shandong coal ground for 3 hour</td>
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<td></td>
</tr>
<tr>
<td>Mixture ratio (m:m)</td>
<td>Solid content (%)</td>
<td>Apparent viscosity (mPa·s)</td>
<td>Solid content (%)</td>
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<td>Shenhua/Shandong</td>
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<td>1215</td>
<td>60.01</td>
</tr>
<tr>
<td>7:3</td>
<td>62.1</td>
<td>943</td>
<td>62.75</td>
</tr>
<tr>
<td>5:5</td>
<td>63.54</td>
<td>895</td>
<td>63.89</td>
</tr>
<tr>
<td>3:7</td>
<td>65.80</td>
<td>923</td>
<td>66.05</td>
</tr>
<tr>
<td>0:10</td>
<td>68.05</td>
<td>915</td>
<td>67.95</td>
</tr>
</tbody>
</table>
medium-rank coal ground for 40 minute (screened with 70-mesh sieve).

It was also observed that the slurry performance of CWS varied widely according to mixing ratios used. The slurry performance of CWS with Shenhua low-rank coal was greatly improved by the addition of Shandong medium-rank coal, with apparent viscosity was obviously decreased, and solid concentration was increased by about 5%. The preparation of CWS with mixed coal samples can broaden the range of coal types used and effectively extend the application field of CWS technology.

4. CONCLUSIONS

From the foregoing discussion, the following conclusions can be drawn.

(1) Differences between Shenhua low-rank and Shandong medium-rank coal in regard to water adsorption performance and mineral and carbonyl group content, among others, were investigated. The results show that the presence of many weakly acidic groups, strong water adsorption ability, and relative absence of high-density mineral were the major factors that affected the slurry performance of Shenhua low-rank CWS.

(2) CWS was prepared using Shenhua low-rank coal with SL-M as additive. The effect of grain gradation on the apparent viscosity of CWS was further examined. The results show that single modal distribution was not applicable for the preparation of CWS using low-rank Shenhua coal. Furthermore, when the average coal particle size was 26.19 μm, the apparent viscosity of CWS was the lowest with bimodal distribution.

(3) The effect of water pre-adsorption on the slurry performance of CWS prepared with Shenhua low-rank coal was determined. The results indicate that when the low-rank coal was previously treated by water pre-adsorption, the slurry performance of CWS was greatly improved; the apparent viscosity was only 1200 mPa·s when the solid concentration was 63%, showing an increase of 3% in solid concentration at the same apparent viscosity.

(4) The effect of combining SL-M with other additives and stabilizer on the slurry performance of CWS prepared with Shenhua low-rank coal was determined. The results show that there was no synergistic effect between SL-M and FDN. With increase in SL-M, the apparent viscosity of CWS decreased and the apparent viscosity of CWS with SL-M as dispersant was slightly lower than that with SAF. When the mass ratio of SL-M and SAF was equal to 1, the apparent viscosity of CWS was the lowest at 1045 mPa·s, which was only slightly lower than that with only SL-M (1060 mPa·s), suggesting that there was very little synergistic effect between SL-M and SAF. Furthermore, with increase in CMC (0 to 0.05%), the apparent viscosity of CWS increased markedly from 850 to 1126 mPa·s, an increase of 32.5%. However, when the level of CMC was further increased (0.05 to 0.15%), the apparent viscosity of CWS increased only slightly.

(5) The effect of combining Shenhua low-rank with Shandong medium-rank coal on the apparent viscosity of CWS was investigated. The results show that the apparent viscosity was improved. Among the four mixed coal samples, the slurry performance of CWS with a mixture of Shenhua low-rank coal ground for 3 hour (screened with 100-mesh sieve) and Shandong medium-rank coal ground for 3 hour (screened with 100-mesh sieve) was optimum. The slurry performance of CWS with a mixture of Shenhua low-rank coal ground for 40 minute (screened with 70-mesh sieve) and Shandong medium-rank coal ground for 40 minute (screened with 70-mesh sieve) was the worst.

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