Understanding the Role of Polyvinylpyrrolidone on Ultrafine Low-Rank Coal Flotation

Qiuyu Lin, Yujie Mei, Wei Huang, Bo Zhang, and Ke Liu*

ABSTRACT: Effective regulation reagents are essential in low-rank coal flotation for improving the floatability of ultrafine particles. Polymer regulators have great potential in the surface modification of ultrafine coal particles. A novel nonionic polymer, polyvinylpyrrolidone (PVP), is evaluated in this study to determine its effectiveness as a regulator in floating ultrafine low-rank coal. Laser particle size analysis is used to discern both the size distribution of coal particles and the change in size distribution. Contact angle tests are carried out to evaluate the wettability of low-rank coal. Surface functional groups of low-rank coal are analyzed by Fourier transform infrared spectroscopy, and the surface interaction energy is tested by X-ray photoelectron spectroscopy. The results show effective adsorption of PVP and demonstrate the effects of PVP at the coal surface. The adsorption of PVP changes the proportion of exposed carbon and oxygen-containing functional groups on the surface of low-rank coal, regulating the size distribution of low-rank coal particles in suspension. The success of polyvinylpyrrolidone as a regulator in low-rank coal flotation is demonstrated, and the mechanisms by which PVP can affect ultrafine low-rank coal flotation are elucidated.

1. INTRODUCTION

Low-rank coal consists primarily of lignite and sub-bituminous coals, and it accounts for the most significant proportion of the total coal reserves worldwide. Low-rank coal is notorious for its poor economic reprocessing and is almost without exception used as fuel for power plants. However, recent years have witnessed an increasing interest in low-rank coal reprocessing, with the purpose of improving its processability and leading to a higher economic appraisal and cash flow. Among the propositions for low-rank coal reprocessing, froth flotation is the popular choice due to its low operational cost and robust performance on an industrial scale. Coal flotation is a technique based on the differences in surface hydrophobicity between organic and mineral matter. When applied in low-rank coal reprocessing, separation performance deteriorates due to the inherent characteristics of low-rank coal: high surface roughness and oxygen content. Ultrafine particle size is also an important factor constraining the floatability of low-rank coal. As a rule, surface regulation methods are customarily employed for the betterment of low-rank coal flotation performance. Surface regulation is typically achieved with the aid of surfactants and regulators, which have attained noticeable industrial applications lately.

It has been reported that surfactant can trigger a synergistic effect with the collector on the coal surface and that it can play a critical role in low-rank coal surface regulation. Xia et al. have discovered that the hydrophobicity of coal can be improved by the addition of dodecyltrimethylammonium bromide (DTAB). DTAB, a typical surfactant, is a soluble microemulsifier that can also be utilized for surface modification. Marsalek et al. have established the relationship between temperature and cetyltrimethylammonium bromide (CTAB) adsorption on the coal surface. The temperature is found to be an important factor affecting surfactant adsorption and is used as a surface modification method. Harris et al. have summarized the improvement of hydrophobicity of low-rank coal by efficient adsorption of nonionic surfactants. This study discusses the advantages of nonionic surfactants both in stability and in high efficiency. Qu et al. have demonstrated the synergistic effect of surfactants and collectors on the coal and oil–water interface. Li et al. have calculated the energy of surfactant adsorbed on low-rank coal via molecular simulation modeling assisted with X-ray photoelectron spectroscopy (XPS) experimental analysis. Xia et al. have summarized the method of molecular simulation on low-rank flotation and its significance in analyzing the effect of surfactant. They have conducted an experimental investigation into the adsorption of cationic surfactant on low-rank coal.
coal on the level of atomic bonding energy. Wang et al.19 have optimized low-rank coal flotation through pH adjustment and inorganic salt ion addition. The above studies have opened up a wide area for further research of low-rank coal beneficiation, while also providing effective research paths for subsequent research scholars.

In recent years, researchers have focused on polymers as surfactants or regulators on mineral separation due to their particular chemical properties and affordability. Zou et al.20 have reported the role of hydrophobically modified P(AM-NaAA-C(16)DMAAC) on coal selective flocculation. Li et al.21 have researched the agglomeration of molybdenite fines by poly(ethylene oxide). Nasser et al.22 have analyzed the effect of polyacrylamide on fine kaolinite and the behavior regulation of kaolinite particles in suspensions. Researchers have studied the effect of polymer adsorption on fine mineral agglomeration,23 but the mechanism of polymer regulators on ultrafine low-rank coal in flotation still requires further study.

In this paper, as a novel mineral separation reagent, polyvinylpyrrolidone (PVP) is evaluated as a flotation regulator in low-rank coal beneficiation. A nonionic polymer, PVP, is used as a carrier of functional molecules in the pharmaceutical, food, and materials industries.24,25 Esumi et al.26 have reported the simultaneous adsorption of PVP and a cationic surfactant on silica. Utilizing electron spin resonance spectroscopy, it has been determined that the conformation and state of PVP are the most significant factors in process regulation. Sun et al.27 have reported the regulation effect of PVP on low-rank coal flotation,28 but the mechanism of polymer regulators on flotation still requires further study.

Table 1. Proximate Analysis and Ultimate Analysis of Coal Samples

|                  | proximate analysis/% | ultimate analysis/% |
|------------------|----------------------|---------------------|
|                  | Mkad | Ad | Vkad | FCKad | C | H | N | S | O*  |
| chemical results | 6.73 | 4.92 | 39.81 | 58.45 | 72.41 | 3.84 | 0.99 | 0.00 | 22.76 |

a M - moisture; A - ash; V - volatile; FC - fixed carbon; ad - air-dry basis; * by difference.

To study the flotation behavior of low-rank coal at ultrasound particle size, the SBC is crushed and the resulting coal particles are ground to ~0.074 mm. A laser diffraction particle size analyzer (LPSA, Beckman LS 13320, USA) is used to evaluate the particle size distribution. The results in Figure 1 show an average diameter \(D_{50}\) of 18.91 \(\mu\)m for SBC. The particulate grain size in the figure that is larger than 74 \(\mu\)m is due to agglomeration of fine particles in the flow channel of the laser particle size analyzer.

The reagents used in experiments are listed in Table 2. All the reagents used are from Shanghai Macklin Biochemical Co., Ltd., China. The partial macromolecule structure of PVP is shown in Figure 2.

Table 2. Reagent Information

|        | purity | molecule weight | abbreviation |
|--------|--------|-----------------|--------------|
| dodecane | ≥98%   | 170             | DD           |
| polyvinylpyrrolidone | 40000 | PVP              |
| 2-octanol | ≥98%   | 130             | 2-octanol    |

2.2. Flotation Experiments. Flotation tests of SBC were performed in a 140 mL flotation cell (RK/FD II, Wuhan Tankuang Co., Ltd.) using ultrapure water as a medium with the stirring speed fixed at 1800 rpm. In each flotation test, 20 g of SBC was added to the 140 mL flotation cell to prepare a coal slurry. The 0.14 mg/mL reagent dodecane (DD) was added as a collector, and the 0.089 mg/mL reagent 2-octanol
was then added as frother. After stirring and mixing, the coal slurry was floated and the froth product was collected, filtered, and dried. In the experiment with polyvinylpyrrolidone pretreatment, a 7 mg/L PVP solution was added to regulate the coal slurry before the addition of DD and 2-octanol. After the flotation test, all the collected samples were filtered, dried, and weighed to calculate the cumulative flotation recovery using eq 1:

\[ R_{real} = \frac{M_f}{M_t} \times 100\% \]  

(1)

where \( M_f \) is the weight of floated coalaf, \( M_t \) is the weight of total coal feedstock, and \( R_{real} \) is the tested cumulative flotation recovery.

Measurement of the error (y) in cumulative flotation recovery was calculated with \((n)\) tests, the experimental results \((R_{real} = \bar{x})\), and their average value \((\bar{x})\). The error (y) was calculated using eq eq 2:

\[ y = \sqrt{\frac{\sum (x - \bar{x})^2}{(n - 1)}} \times 100\% \]  

(2)

The value of \( y \) was set as the depth of error bars in the results and discussion part, and it was also used to analyze the validity of the obtained data.

2.3. Particle Size Analysis. LPSA was used to evaluate the change in particle size distribution of SBC; this analysis worked well using the wet method. For measuring the optical parameter, the real and imaginary part of the medium refractive index values were set to 1.8 and 0.8, respectively. Ultrapure water was used for sample dispersion. To correspond to the dosage of reagent and solid content in the flotation test, the 0.14 g/mL coal slurry with 7 mg/L PVP solution was stirred at a rotation speed of 600 r/min and prepared as the test sample. The sample was injected into the LPSA with a microsyringe and was subjected to constant agitation in the LPSA channel.

2.4. Contact Angle Measurements. The contact angle instrument (Kruss100, Germany) was used to analyze the contact angle of SBC. Before the contact angle measurement, SBC was dispersed in water to prepare the suspension, and then different dosages of PVP were added to the suspension. After shaking and mixing for 24 h, the solutions were concentrated, filtered, and dried in a vacuum chamber. The dried samples were extruded by a mechanical hydraulic tablet press (formed from packing of a die cavity) at a pressure of 20 MPa. Finally, the contact angle measurement was performed using the sessile drop method. The drop distance was controlled at 3 cm, and the droplet was 9 µL.

2.5. FT-IR Test. The Fourier Infrared Spectra Nicolet iS10 (FT-IR, Thermo Fisher Scientific, America) was set and recorded over the wavenumber range from 4000 to 600 cm\(^{-1}\). For the preparation of SBC with PVP treatment, 0.5 g of SBC was added to 50 mL of ultrapure water (with a resistivity below 18.2 MΩ·cm), while PVP was predissolved and added into the suspension. The suspension was mixed and shaken at 100 rpm for 24 h using a concussion instrument, and then the solution was filtered to harvest the solid samples. The solid samples were washed using ultrapure water at least three times and dried in a vacuum oven at 40 °C for 24 h.

2.6. XPS Analysis. To obtain binding changes of the coal surface before and after PVP treatment, X-ray photoelectron spectroscopy (XPS) was performed at 25 °C (ULVAC PHI 5000 VersaProbe III) with a monochromatic X-ray source. The Al K\(\alpha\) radiation (\(h\nu = 1486.6\) eV) and a light spot size of 200 µm were set. The spectra were recorded and stored at a pass energy of 26 eV in steps of 0.05 eV. The fitting process was performed with Multipak software and the binding energies were corrected by setting the C 1s hydrocarbon peak to 284.80 eV.

3. RESULTS AND DISCUSSION

3.1. Flotation. The flotation behavior of SBC and SBC with PVP pretreatment is shown in Figure 3; the flotation recovery has significant differences between the two samples. It can be seen in Figure 3 that the cumulative flotation recovery (R) of SBC with PVP pretreatment (indicated by the red curve in Figure 3) is always higher than that of SBC without PVP pretreatment (indicated by the black curve in Figure 3) during the first 5 min. In the first 5 min, the maximum measured R of SBC flotation without PVP is 42.82% (Table S1), while the test with PVP pretreatment is measured at 50.03% (Table S2). As a low-rank coal, SBC exhibits a poor flotation performance without PVP treatment. With the addition of PVP pretreatment, the cumulative flotation recovery of SBC can be increased by 7.21% in an absolute value and by 16.84% in relative terms.

The pretreatment of PVP yields a significant improvement of cumulative flotation recovery of low-rank coal, but quantitative indexes are still needed to explain the influence of PVP on the flotation rate. Here we introduce a flotation rate equation to evaluate the change of PVP pretreatment on the flotation rate. In previous studies, researchers have assumed...
that the flotation process can be described as a first-order reaction.\textsuperscript{33}

The first-order dynamics equation can be expressed as eq 3:

\[ R = R_{\text{max}} (1 - e^{-kt}) \]  

(3)

where \( R \) is the real floating rate, \( R_{\text{max}} \) is the maximum floating rate, \( k \) is the flotation fitted rate constant, and \( t \) is the flotation time.

The first-order dynamics equation assumes all mineral particles float at the same rate.\textsuperscript{34} However, in reality this is rarely the case. To describe a situation where the flotation products differ in floating rate, there are multiple stages with different flotation rate constants, and the flotation dynamics equation can be expressed as eq 4:

\[ R = \sum_{i=1}^{n} m_i (1 - e^{-k_i t}) \]  

(4)

where \( m_i \) is the fraction of component \( i \) and \( k_i \) is the rate constant of component \( i \). The most commonly used expression is Kelsall's model, which contains a fast floating fraction and a slow floating fraction. This is shown as eq 5:

\[ R = R_{\text{max}} - [R_{\text{fast}} \times e^{-k_{\text{fast}} t} + (R_{\text{max}} - R_{\text{fast}}) \times e^{-k_{\text{slow}} t}] \]  

(5)

where \( R_{\text{max}} \) is the maximum overall theoretical recovery, \( R_{\text{fast}} \) is the maximum recovery of the fast floating component, and \( k_{\text{fast}} \) and \( k_{\text{slow}} \) are the rate constant of the fast float and slow float components, respectively.

The SSQ function in the Excel Solver tool was used to analyze the fitting and iteration effect. The expression of SSQ is defined as eq 6:

\[ \text{SSQ} = \sum (R - \tilde{R})^2 \]  

(6)

where \( R \) is the real recovery and \( \tilde{R} \) is the fitted value. The Solver tool in Excel can be used for mathematical analysis of linear or nonlinear fitting, and the order of iteration is to find the optimum solution for the definitive problem. In Solver, constraints for eq 5 are added \((R_{\text{fast}} \leq 100, R_{\text{fast}} > R_{\text{slow}}, k_{\text{fast}} > k_{\text{slow}})\) and the SSQ formula eq 6 is added as the target cells to be minimized, so that the operation represents the true physical process with a fast and a slow stage. The iteration result shown in Figure 4 conforms to the assumptions; details can be found in the Supporting Information (SI, Figure S1 and Figure S2).

For the experiment with PVP pretreatment, the values of \( R_{\text{fast}}, R_{\text{slow}}, k_{\text{fast}}, k_{\text{slow}} \), and SSQ are 43.51, 8.28, 0.92, 0.90, and 6.91 (Table S2). For the experiment without PVP pretreatment, the values of \( R_{\text{fast}}, R_{\text{slow}}, k_{\text{fast}}, k_{\text{slow}} \) and SSQ are 35.28, 10.07, 0.73, 0.71, and 8.82 (Table S1).

We speculate that the poor flotation performance of SBC coals is attributed to the hydrophilicity and surface-exposed functional groups. Therefore, the influence of PVP pretreatment on the SBC coals has been investigated by XPS, FT-IR, and contact angle analyses as described in the following sections. The advantages of utilizing PVP are that there are no additional process and no more required energy input. However, one of the disadvantages of PVP in the experiment is its dissolution process, which requires a certain amount of time. Too short a time will result in the PVP floccule not unraveling, whereas too much time leads to excessive hydrolysis of PVP. The problem may be solved by modification of the polymer chain with the help of a reaction or other reagents. Chou et al.\textsuperscript{35} have found that PVP nanoparticles tend to be more stable in the presence of phosphoric acid, which may be a solution for improving the performance of PVP. The derivative reagents of PVP are being studied currently, and the test results can be updated after sufficient progress.

3.2. Particle Size. To analyze the effect of PVP on the particle aggregation behaviors of SBC, we evaluated SBC in PVP solutions with different concentrations. LPSA was used to measure the size distribution of the samples, and the results were shown in Figure 5. The results showed a change in particle size distribution when the concentration of PVP solution was set at 1, 7, and 15 mg/L. The \( D_{50} \) of samples with PVP treatment was larger than the SBC without PVP treatment (details in Figures S3—S10).

Particle size distribution was analyzed by LPSA through light diffraction and scattering of particles. Fraunhofer diffraction and Mie scattering theory were used to calculate the spatial distribution (light scattering spectrum) of particle size. The test process was not affected by temperature, sample viscosity, and density. The median size \( D_{50} \) parameter was used to represent the feature size of particles swarm.\textsuperscript{36}

The initial \( D_{50} \) of SBC without PVP treatment was 18.91 \( \mu \text{m} \) (Table S3), while after the PVP treatment of different concentrations \( D_{50} \) reached 24.66 \( \mu \text{m} \) (Table S5), 26.89 \( \mu \text{m} \) (Table S7), and 27.03 \( \mu \text{m} \) (Table S9). The particle size showed an increase of 30.41%, 42.20%, and 42.94%, respectively.

![Figure 4](http://pubs.acs.org/journal/acsodf)

**Figure 4.** Flotation results of SBC (red line, coal recovery after pretreatment of PVP; black line, coal recovery without PVP pretreatment).
With PVP addition, the increase in $D_{50}$ value established there is particles agglomeration. The collision adhesion of ultrafine particles could be affected by solution properties such as solution viscosity, surface tension, gas bubbles, and contents.37 All the conditions were controlled in the experiment, the only variable was the low dosage addition of PVP. It could be deduced that PVP affected the adhesion efficiency of ultrafine particles, and thus $D_{50}$ of SBC could be changed. Larger particle size was a factor that would also affect flotation. In flotation, ultrafine coal particles were gathered by collectors during the mixing and stirring process and were floated via bubbles induced in the water solution. The relationship between particle size distribution and flotation behavior had been studied, and the influence of polyvinylpyrrolidone was now been established.

3.3. Contact Angle. To test the role of PVP on the contact angle of SBC, 7 and 15 mg/L PVP solutions were employed to treat SBC. SBC treated by pure water was used as a blank control group (SBC-1), while the SBCs with PVP treatment samples were recorded as SBC-2 (7 mg/L PVP) and SBC-3 (15 mg/L PVP), respectively. Figure 6 showed the results of the contact angle tests, demonstrating the change between different PVP concentrations and the effect of increasing contact time.

**Figure 6.** Change of contact angle with the increasing contact time. Sample information: SBC-1 (0 mg/L PVP), SBC-2 (7 mg/L PVP), SBC-3 (15 mg/L PVP).

The contact angles at 1 s contact time for SBC-1, SBC-2, and SBC-3 were 37.3°, 38.5°, and 40.4°, respectively. It could be seen that PVP increased the contact angle of SBC, but the effect was slight. All the samples showed a specific retention time, which was worth investigating. It was observed that the contact angles of SBC-1, SBC-2 and SBC-3 had different decline rates with increasing contact time, and Figure 6 showed this trend. These data indicated that the coal surface was more hydrophobic after treatment with PVP.

Other researchers also reported the phenomenon where the declining trend of contact angle was a function of increasing time.38 PVP might influence the contact angle of SBC, and with increasing time the change was even more dramatic. Thus, we deduced that PVP played a role as a regulator in the surface modification of coal, which affected the contact angle of SBC. While a high content of the oxygen-containing group exposed we deduced that PVP played a role as a regulator in the surface molecular weight and polymer hydrolysis also needed to be considered in further research.

3.4. FT-IR. As shown in Figure 7, the FT-IR spectra shows the changes in SBC functional groups before and after the treatment with PVP, which establishes the interaction mechanism between PVP and low-rank coal. The characteristic peaks of PVP are shown by the orange curve concur with data reported by other researchers.39–41

The infrared absorption peaks of SBC with PVP treatment are shifted to 2851.42 and 2920.36 cm$^{-1}$, as compared with the initial peaks of SBC without PVP treatment at 2908.55 and 2975.77 cm$^{-1}$. These wavenumbers correspond to the antisymmetric and symmetric stretching vibrations of $\text{–CH}_2$, $\text{–CH}_3$, and aromatics in SBC.42–44 It has been reported that the hydrophobic force between the solid–liquid interface is affected by surface groups on the coal surface. The change of $\text{–CH}_2$, $\text{–CH}_3$, and aromatic peaks may be attributed to the interaction between PVP macromolecules and SBC. The change of oxygen-containing groups is also significant; the intensity of peaks of $\text{–Si–O}$ at 1040.78 cm$^{-1}$ decreases and shifts to 1031.25 cm$^{-1}$; PVP may partially cover the $\text{–Si–O}$ groups on the surface of SBC. The intensity of peaks near 1593.13, 1440.32, and 1662.57 cm$^{-1}$ increases, which may be due to the interchain forces and strain in five-member rings of PVP macromolecules.45,46 The peak at 1239.03 cm$^{-1}$ of SBC with PVP treatment shows higher intensity than that of SBC without PVP treatment, and the latter has a peak shift to 1217.28 cm$^{-1}$. This peak is assigned to the bending vibration of $\text{–C–O}$ and the $\text{–CH}_2$ ring wag mode. This peak shift indicates an interaction between a SBC hydroxyl group and the
lactam ring of PVP, specifically formation of hydrogen bonds.}\textsuperscript{46} The intensity of peaks in the range 3600—3200 cm\textsuperscript{-1} increases, corresponding to the broad infrared absorption of \(-\text{OH}\) in SBC after PVP treatment. It also shows that \(-\text{OH}\) groups are partially involved in hydrogen bonding with the carbonyl group or with the N atom in PVP macro-molecules.\textsuperscript{40,47} In conclusion, the surface groups of SBC are changed by the adsorption of PVP.

3.5. XPS. XPS wide sweep spectra were used to analyze the effect of PVP on the SBC surface at the level of element composition. As shown in Figure 8, the relative amount of C increased from 75.9\% to 77.6\% with addition of PVP (C is the main surface element in SBC). The initial carbon/oxygen ratio of SBC was 3.37 and the carbon/oxygen ratio of PVP was 6, demonstrating that the oxygen content of PVP was significantly lower than that of SBC. Therefore, the carbon/oxygen ratio increment of SBC (increased to 4.88 after PVP treatment) confirmed polar interactions between the lactam group of PVP and the hydrophilic sites (oxygen functional groups) at the surface of SBC.\textsuperscript{40,49} The relative amount of Si decreased from 1.6\% to 1.3\% and the N content reached 5.2\% after PVP treatment, which was additional strong evidence of polar interaction.

Figure 9 illustrates the C 1s peak fitting results for carbon species on the SBC surfaces before and after treatment with PVP. The results of fitting curves have a high degree of confidence. The peak at the binding energy of 284.80 eV (Figure 9a—c) corresponds to the chemical groups C—C and C—H and is maintained at 284.80 eV to value the shift of other peaks. The peaks at 285.82 eV (Figure 9a,b) and 285.79 eV (Figure 9c) correspond to C—O groups. The peaks at 286.94 eV (Figure 9a), 286.79 eV (Figure 9b), and 287.35 eV (Figure 9c) correspond to O—C=O groups.

Figure 8. XPS wide sweep spectra of coal before (a) and after (b) treatment with PVP (c).

Figure 9. Fitted XPS C 1s spectra results of SBC coal before (a) and after (b) treatment with PVP (c).
resonance; the same result is obtained from oxygen functional groups of SBC occurred on the SBC surface hydrogen bonds between the lactam group of PVP and the lactam group of PVP. This paper focuses on the role of PVP in ultra-low-rank coal flotation. SBC collected from Shaanxi and PVP-K30 are employed in this investigation. Due to the results from flotation, LPSA, contact angle, FT-IR, and XPS tests, we define PVP as a regulator. As a macromolecule rarely used in flotation, the characteristics of PVP and its effect on low-rank coal are worth further investigation. The main conclusions are summarized below:

1. Polyvinylpyrrolidone is an effective regulator in coal flotation due to its role in adjusting the contact angle of SBC and in the agglomeration of ultrafine coal particles. The larger the PVP dosage used, the longer duration time and lower decline rate for the contact angle of SBC. These effects are achieved with a low dosage of PVP. Hence, a low addition of PVP can significantly increase the flotation rate, thus improving the cumulative flotation recovery of SBC.

2. Polyvinylpyrrolidone is effectively adsorbed on the surface of SBC. The adsorption is demonstrated using FT-IR by the shift of infrared peaks and the presence of characteristic peaks. The variation of binding energy found via XPS also validates the effective interaction between PVP and SBC.

3. The adsorption of PVP on SBC is reflected in both elemental and binding energy variation. The regulation of the content of C—C, C==O, and −COO groups proved the selective shelter of PVP on the SBC surface. The peak intensity change observed from surface functional groups shows the mechanism of the interaction between PVP and low-rank coal.

The tests in this paper reveal that the poor flotation performance of SBC coals may be attributed to surface oxygenic functional groups and ultrafine particle size. However, the induction of PVP as a regulator in flotation did help with recovery and flotation rate, which may be attributed to the regulation of surface exposure and the enhanced collision adhesion efficiency of SBC. In conclusion, the poor flotation performance of SBC can be improved by PVP, and the change is likely due to the adsorption of PVP on SBC. The adsorption of PVP regulated the surface of coal and improved the agglomeration of ultrafine coal particles, which is beneficial for flotation performance. As macromolecules that are easy to be loaded or modified, polyvinylpyrrolidone and the derivative reagents are worth further research.

4. SUMMARY AND CONCLUSION

This paper focuses on the role of PVP in ultrafine low-rank coal flotation. SBC collected from Shaanxi and PVP-K30 are employed in this investigation. Due to the results from flotation, LPSA, contact angle, FT-IR, and XPS tests, we define PVP as a regulator. As a macromolecule rarely used in flotation, the characteristics of PVP and its effect on low-rank coal are worth further investigation. The main conclusions are summarized below:

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c06701.

Table S1, flotation result of the SBC and fitting calculation (without PVP); Figure S1, fitting degree observation (without PVP); Table S2, flotation result of SBC and fitting calculation (with PVP); Figure S2, fitting degree observation (with PVP); Table S3, size distribution of SBC; Table S4, size distribution of SBC (detailed information); Table S5, size distribution of SBC (1 mg/L PVP); Table S6, size distribution of SBC (1 mg/L PVP, detailed information); Table S7, size distribution of SBC (7 mg/L PVP); Table S8, size distribution of SBC (7 mg/L PVP, detailed information); Table S9, size distribution of SBC (15 mg/L PVP); Table S10, size distribution of SBC (15 mg/L PVP, detailed information) (PDF)

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Notes
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