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INVESTIGATION OF SURFACTANTS AND FLOCCULATION PROCESSES IN COAL BENEFICIATION

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Abstract

This study represents an integral investigation of the joint effect of surfactants, flocculants, and Al^{3+}/SO_4^{2-} ions on the enrichment of 2BR-B2 and 2BOMSH-B2 varieties of brown coal. The study involves detailed examination of such aspects as dosage of flocculant (25–100 g/Mg), ion effects, agglomeration behavior, settling process kinetics, floc sizes, and transformation of mineral phase under experimental conditions with the help of X-ray fluorescence (XRF). In relation to colloid chemistry aspects, special attention is paid to such phenomena as interfacial interactions, electrical double layer compression, and bridging between particles. This makes the coagulation and separation processes much more efficient, since it is proved that the creation of stable and optimally-sized aggregates substantially increases the efficiency of mineral separation, whereas the excess of flocculant causes the formation of less stable heterophase systems. Thus, it is concluded that the control over colloidal destabilization and interfacial modifications are critical for enhancing the ash content and calorific value of coal.

Keywords: *coal beneficiation, surfactants, flocculation, coagulation, Al^{3+}ions, SO_4^{2-}ions, XRF analysis, colloidal systems*

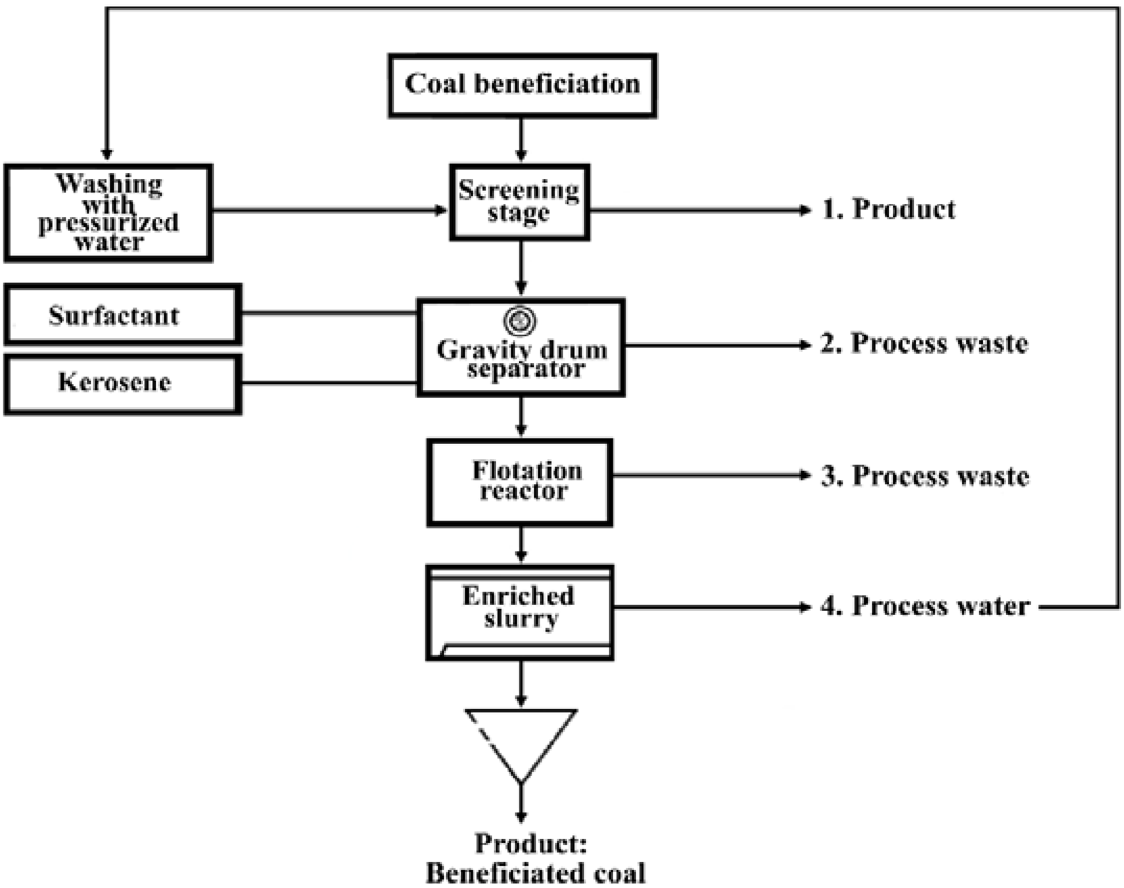
Introduction

Coal continues to be one of the main sources of energy in the world, especially in developing countries, whose contribution in terms of energy composition is considerable (Ejtemaei, M., Ramli, S., Osborne, D., & Nguyen, A. V., 2019). The moisture and ash content present in the low-rank coal lowers the efficiency of the coal, resulting in higher levels of emission of gas pollutants and particulates when burning (Kucharov, A., Xalilov, S., & To'Rayeva, X., 2024). Consequently, the need to improve the physicochemical nature of the coal through processes of beneficiation has taken center stage in recent times for reasons of environmental protection and energy efficiency, involving the removal of ash-forming minerals and increasing the heating value of the coal (Kocharov, A.A., Mamanazarov, M.M., Atabekova, D.L., & Toshbobayeva, R.A., 2024). Various methods of coal beneficiation have been investigated over the years, with special emphasis on the use of surfactants to enhance flotation performance via modification of interfacial properties and bubble-particle attachment (Song, S., 2008). Moreover, recent research proved that using coagulant ions, including Al^{3+}, together with anions, such as SO_4^{2-}, positively influences the process of particles agglomeration and improves the ability to remove minerals from the fuel material (Kucharov, A., Xalilov, S., Farxod, Y., Toshboboyev, R.N., Bekturdiyev, G., Turayeva, K., ... & Golib, T., 2026). However, the impact of interaction between surfactants, colloid system and inorganic ions requires additional investigation, especially the dependencies among flocculant concentration, the degree of ionic influence, distribution of particle sizes and general efficiency of beneficiation process (Eshmetov, R., Salikhanova, D., Jumaeva, D., Eshmetov, I., & Sagdullaeva, D., 2022). Kinetics of agglomeration, densification of aggregates, and their sedimentation have to be examined as well (Zhou, F., Yan, C., Wang, H., Zhou, S., & Liang, H., 2017).

Research method

The beneficiation procedure involved an integrated multi-stage technique, depicted in Fig. 1 below, which relied on both physical and surface chemistry approaches to increase mineral content removal. First, raw samples of brown coal (2BR-B2 and 2BOMSH-B2) underwent hydraulic washing to facilitate elimination of impurities loosely adhered to the particles' surface (Laskowski, J. S., & Yu, Z., 2000). Further, a size classification (screening) step ensured that an adequate particle size distribution was obtained for effective processing at a next stage (Zeng, H., Tang, H., Sun, W., & Wang, L., 2022).

Figure 1. *Integrated coal beneficiation process with washing, classification, gravity separation, and surfactant-assisted flotation*

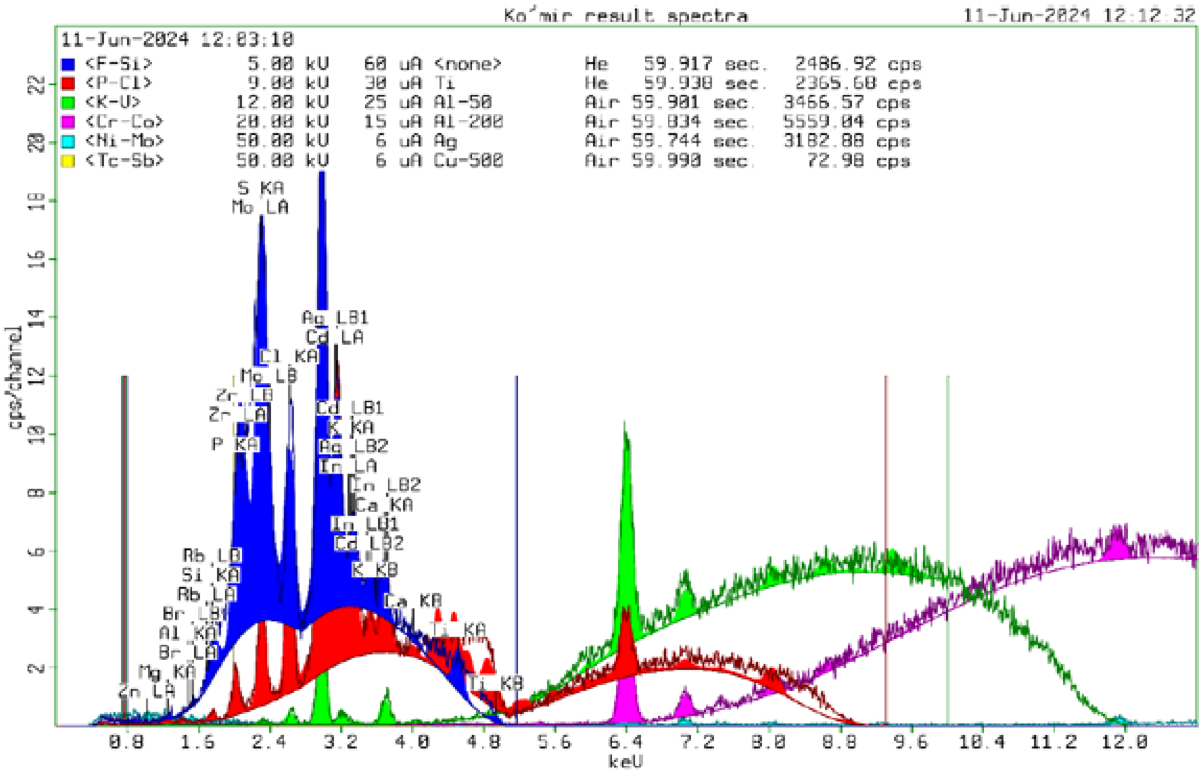


Gravitational separation entailed the use of a gravitational drum separator to achieve separation of heavier fractions using density differences between organic components of coal and minerals (Niu, C., Xia, W., Li, Y., Bu, X., Wang, Y., & Xie, G., 2022). For better selectivity, surfactant-assisted flotation was performed in a flotation reactor with a mixture of surfactants and kerosene acting as a collector, thus increasing hydrophobicity of coal particles while rejecting hydrophilic mineral components (Wang, Y., Wei, D., Qin, W., Jiao, F., Luo, X., & Pan, Z., 2023). Flocculants together with inorganic ions such as Al^{3+} and SO_4^{2-} were added to promote agglomeration of fine mineral particles due to their electrostatic charges neutralization and polymer bridging (Qurbonov, A., Kucharov, A., & Yusupov, F., 2024).

Result and discussion

The XRF spectrum of the raw coal sample (Figure 2) clearly shows that the composition of the minerals is largely dominated by the aluminosilicates due to strong intensity signals of both Si (36.55 cps) and Al (17.31 cps). At the same time, the Fe content (101.22 cps) clearly implies the involvement of iron-based minerals, which serve as active centers for surface reactions. Thus, it can be concluded that the ash-forming material consists mainly of quartz and aluminosilicate minerals containing iron phases. In this case, the interaction forces are dominated by electrostatic repulsion caused by the negative charge of the particles, thus providing stability of the suspension.

Figure 2. *XRF spectrum of raw coal showing major (Si, Al, Fe) and trace elements*



It can be seen from the comparative XRF results presented in Table 1 that there was a significant reorganization of minerals, demonstrating the transformation through the process of coagulation. The first thing that comes to mind is the increase in Fe intensity, which rises from about 101 cps to ≥150 cps (Δ50 cps).

Kinetics of flocculation shown in Figure 3 show high sensitivity to dosage used during the initial stage of settling. In particular, within 1–2 minutes after initiation of the process, maximum settling velocities were achieved at 17–18 cm/min for 25 g/Mg dosage and 19–20 cm/min for 100 g/Mg dosage. Thus, fast aggregation of dense and bulky flocs occurred during the early stages of flocculation.

Table 1. *Comparative XRF intensities (cps) of coal before and after Al^{3+}/SO_4^{2-} treatment showing mineral phase redistribution*

Element	Sample 1 Intensity (cps)	Sample 2 Intensity (cps)
Si	36.5	30–32
Al	17.3	22–25
Fe	101	≥150
S	49.1	70–80
Ca	12.9	15–18
Ti	0.79	1.5–2.0
Mo / Ag / Zr	4–9	≥15–25

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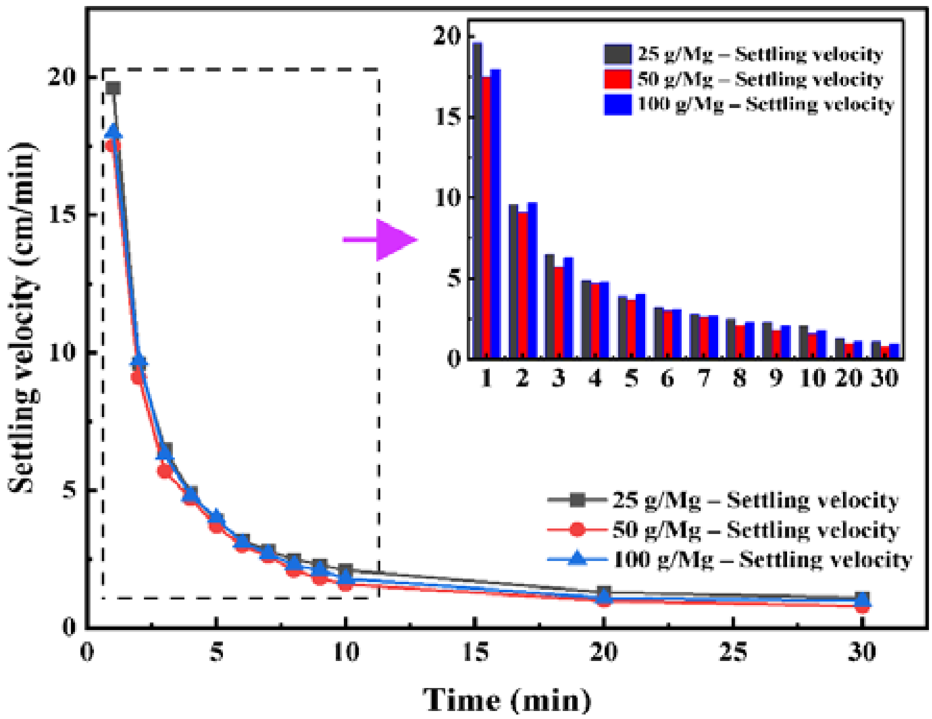
Figure 3. *Effect of flocculant dosage (25, 50, and 100 g/Mg) on the settling kinetics of coal suspension, showing the temporal evolution of settling velocity and the transition from rapid floc formation to consolidation-controlled sedimentation*



Consistent rise in the value of settling velocity with the increase in dosage shows that higher dosage leads to stronger interparticle interactions and thus to creation of larger and more efficient settling units with larger settling diameters (Fig. 3). As evident from Table 2, the beneficiation procedure results in considerable improvement in the physicochemical and energetic parameters of 2BR-B2 and 2BOMSH-B2 brown coals. Primarily, this is achieved due to efficient de-mineralization of the material and reconstruction of its organic skeleton. For example, there is a pronounced decrease in the content of ash

(Ad) from 35–60% to 20–35%, which corresponds to the reduction by 25 percentage points, which implies effective separation of inorganic minerals, including aluminosilicates and iron-containing compounds.

While acknowledging the obvious advancements that have been achieved, one cannot overlook the lack of proper zeta potential analysis, long-term stability assessment, and scale-up confirmation, which necessitates future research into establishing quantitative relationships between colloidal behavior and practical efficiency at an industrial level, investigating other combinations of surfactants and flocculants, and fine-tuning the processing parameters.

Table 2. *Comparative physicochemical properties of 2BR-B2 and 2BOMSH-B2 brown coals before and after beneficiation, highlighting the reduction of ash-forming components and enhancement of fuel quality indicators*

Physicochemical properties name	Symbol	Unit of measurement	Before enrichment		After enrichment	
			2BR-B2	2BOMSH-B2	2BR-B2	2BOMSH-B2
Moisture content	W_t	%	20–40	20–40	15–40	15–40
Ash content	A_d	%	35–60	35–60	20–35	20–35
Particle size	d	mm	1–100	1–100	Briquette	Briquette
Volatile matter formation	V^{daf}	%	32–50	35–45	44–55	40–55
High heat of combustion	Q_S^{daf}	MJ/kg	15.5–25.4	15.4–23.8	28.6	29.7
Low heat of combustion	Q_i^{daf}	MJ/kg	6.9–12.8	8.9–13.6	15.9	15.7

Conclusion

These results confirm that the simultaneous use of surfactants, flocculants, and Al^{3+}/SO_4^{2-} ions provides for a great rise in effectiveness of brown coal processing with regard to selective coagulation and mineral separation. Indeed, considerable decrease in ash percentage (from 35% to 60% to 20% to 35%) and calorific power (28–30 MJ/kg) confirm this achievement. Moreover, the examination of the dynamics of settlement of particles and their size distribution demonstrates that the optimal dosage of flocculant (~50 g/Mg) allows for obtaining stable and homogenous aggregates, while excessive dosages create a structurally heterogeneous system. The obtained XRF data prove the effectiveness of this technology in terms of the electrostatic interaction between particles and bridging mechanism.

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