

SOAPSTOCK-BASED SURFACE-ACTIVE REAGENT FOR COAL FLOTATION–GRAVITY BENEFICIATION

A.A. Kucharov^{1,2*}, F.M. Yusupov¹, S.U. Xalilov¹, R.A. Toshboboyeva¹, S.B. Sultonov¹,
M.M. Mamanazarov², L.A. Azimov², S.K. Yusupov¹, S.Y. Saparov², A.D. Dusmatova²

¹The Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan,
Tashkent, 100071, Uzbekistan

²Pharmaceutical Education and Research Institute, Tashkent, 100114, Uzbekistan

*e-mail: sciuzb@mail.ru tel: +998901247202

Received 18.05.2026

Accepted 03.07.2026

Abstract: This study investigates the synthesis and application of a soapstock oil-based surface-active reagent for the beneficiation of high-ash Angren brown coal. The reagent was prepared as a surface-active reagent by the alkaline reaction of soapstock oil with potassium hydroxide and other hydrocarbon-based oil and gas processing residues. The synthesized reagent was characterized by GC–MS, rheological analysis, FTIR, and SEM for beneficiation of Angren brown coal and was tested using the combined flotation–gravity separation technique. Rheological analysis showed that SFM-4 showed the most balanced rheological profile for coal and water dispersion. The FTIR and SEM results showed the presence of active surface sites and morphological changes which are favourable for surfactant adsorption. At 15° inclination angle, 18 rpm drum speed and 50 mL SFM-4 dosage, the ash content was 26.6%, coal yield was 56.4% and combustible recovery was 65.50%. These results demonstrate the potential of the synthesized reagent to improve brown coal beneficiation efficiency.

Keywords: coal beneficiation, brown coal, surface-active reagent, soapstock oil, flotation, gravity separation, GC–MS, rheology

1. Introduction

Coal is still one of the major primary energy resources for powering electricity generation and heat production in the industrial sector [1]. Coal demand is estimated to reach about 8.8 billion tonnes in 2024 in the world and more globally than 9 billion tonnes in the future. Although renewable energy technology is very advanced [2], coal remains an important part of the global energy sources [3], while waste-derived activated carbons are increasingly used for pollutant removal and sustainable environmental remediation [4]. However, lower-grade coal is not as suitable for use as high ash and moisture content, so the transportation and combustion losses are more intense [5], and thus more solid residues and atmospheric emissions are created. These are especially the case with brown coal [6], which has high mineral matter and moisture content. As such, the development of beneficiation technologies for high-ash brown coal must be improved to improve the quality of fuel and energy efficiency and reduce the environmental impact of coal use.

Coal beneficiation is mainly conducted by gravity separation, flotation, or combined separation [7]. Gravity separation is effective for coarse particles and is based on density differences between organic coal matter and mineral impurities [8]. However, fine particles are less efficient due to particle entrainment and incomplete liberation since they are of low density. Flotation is more appropriate for fine coal fractions, but the performance of the flotation depends on coal surface chemistry, particle size, reagent selectivity, pulp stability [9], and the hydrophobic-hydrophilic balance at the coal-water interface [10]. The hydrophobic coal particles will attach to air bubbles and disperse into the concentrate, while the hydrophilic mineral particles will remain in the aqueous phase [11]. In practice, this separation is often limited by oxidized coal surfaces, clay minerals, fine slime coating, high reagent consumption, unstable froth, and poor selectivity of commercial collectors and frothers [12]. As a result, a conventional reagent system may not be able to reduce ash content enough or produce high combustible losses, particularly in the beneficiation of heterogeneous brown coal.

Surfactant-based reagent systems are promising for improving coal beneficiation because they can improve the interfacial properties, particle dispersion [13], coal hydrophobicity, and bubble-particle attachment. However, past research efforts have been largely centered on separate flotation chemicals, collector-frother combinations, and adsorbing functional materials [14, 15]. Still, the correlation between chemical constitution, rheological properties, surfactancy, adsorption capacity, and flotation efficiency is inadequately understood in respect to new soapstock-based surfactants. In this study, a surface-active material was generated from soapstock oil, KOH, technical water, and secondary oil- and gas-processing residues and applied to Angren brown coal beneficiation [16]. The novel aspect of our work is that the synthesized reagent is evaluated by GC-MS, rheological analysis, FTIR, SEM, and beneficiation tests. The reagent-assisted process reduced coal concentrate ash content to 26.6%, the coal yield to 56.4%, and the combustible recovery to 65.50% under the optimum conditions of 15° inclination angle, 18 rpm drum rotation speed, and 50 mL SFM-4 dosage.

2. Experimental part

The Angren brown coal from Uzbekistan was selected as the principal raw material for conducting the tests on its beneficiation. It should be noted that this particular type of coal has a lot of coal processing waste, rich in minerals. These minerals include inorganic substances forming ash during coal combustion [17]. The sample was mechanically prepared and classified to obtain a particle-size fraction of 0–500 μm . The ash content was 35–60% and the moisture content 10–30%, indicating that the raw coal was heterogeneous. The surface-active substance (SFM) was produced using soapstock oil as the main organic feedstock, potassium hydroxide (KOH) as an alkaline modifier, distilled water for KOH dissolution and technical water for dilution of the finished product. The oil and gas-processing residues were added as hydrocarbon-containing components to make the reagent hydrophobic [18]. The distilled water was used to prepare laboratory solutions and coal–water suspensions. The pH was adjusted with standard acidic or alkaline reagents, and all materials were used without further purification [19].

The surface-active reagent was prepared by alkaline modification of soapstock oil with KOH. For 5 L of SFM, 0.9–1.9 L of soapstock oil was mixed with an alkaline solution prepared by dissolving 0.10–0.20 kg of KOH in 0.10–0.20 L of distilled water. The alkaline solution was gradually added to the soapstock oil under mixing at 20–30 °C. During the first hour, the mixture was stirred at 50–70 rpm to ensure effective contact between the oil phase and the alkaline modifier and maturation was carried out in 20–25 h. The final product was diluted with 3.0–4.0 L of technical water to obtain a liquid SFM suitable for coal beneficiation. The final pH was 7–9, and the product yield was 85–95%. Four SFM formulations were prepared with the same raw materials but different soapstock oil–alkali ratios. In the final volume of 5 L, soapstock oil content was increased from 0.9 to 1.9 L, while the KOH amount was increased from 0.10 to 0.20 kg. Distilled water used for KOH dissolution was varied from 0.10 to 0.20 L, and technical water was changed from 4.0 to 3.0 L to ensure that the final volume remained the same. Thus, SFM-1, SFM-2, SFM-3, and SFM-4 differed mainly in the relative amounts of soapstock oil and alkali.

A surfactant-water-coal dispersion was prepared at high shear (IKA RW 20 digital mechanical stirrer), as depicted in Fig. 1. The synthesized SFM-4 reagent was added in the aqueous phase and mixed until the surfactant solution was homogeneous. The oil-containing phase and coal particles were then gradually added with continuous stirring to form a stable coal-water-surfactant dispersion. A high shear mixing led to a uniform distribution of surfactant molecules at the coal-water interface and improved the contact between the surfactant and coal particles [20]. Used this dispersion in coal beneficiation experiments. The raw coal and treated samples were analyzed with FTIR spectroscopy (Bruker Tensor 27) to determine the functional groups on the surface [21], SEM (JEOL JSM-IT200) to determine the particle shape and surface texture [22], GC-MS (Shimadzu GCMS-QP2020) to determine the organic material of the generated reagent and coal extracted extractable fractions [23], and rheological tests to determine the viscosity characteristics of 1% SFM solution at 25 ± 2 °C. Beneficiation was conducted using flotation and gravity separation under controlled conditions,

including inclination angle, drum rotation speed and SFM-4 dosage. Quantitative measures of performance are necessary for assessing the relative efficacy of materials used in functional separation systems [24]. Furthermore, performance of the separation process was quantified in terms of ash, coal concentrate, ash removal, and combustible recovery efficiency [25]. All beneficiation experiments were repeated under the same operating conditions to check reproducibility. The ash content, coal yield, ash reduction, and combustible recovery were calculated as the mean of three independent measurements. All tests related to beneficiation have been conducted under identical operating conditions for validation purposes, and the figures stated herein reflect their average value.

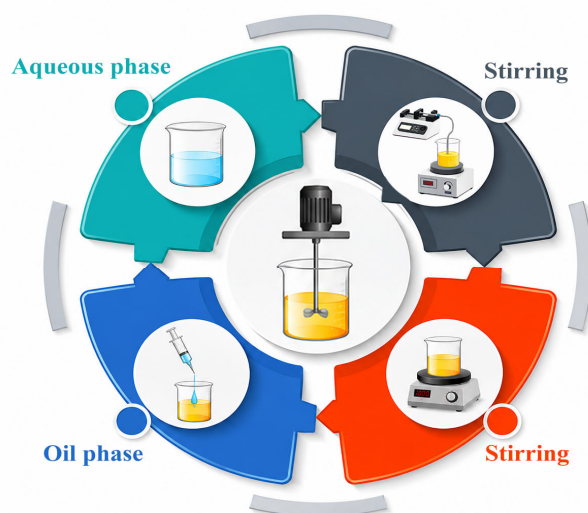


Fig. 1. Schematic illustration of high-shear preparation of the surfactant–water–coal dispersion used for coal beneficiation

Hence this methodology ensured reproducible experimental conditions and provided a reliable basis for relating the chemical composition, interfacial behavior, rheological properties [26], and beneficiation performance of the synthesized surfactant in coal upgrading.

3. Results and Discussion

The GC-MS total ion chromatogram of the synthesized reagent shows a complex composition, with the main peaks being located mostly in the retention time range of 3.7–18.0 min (Fig. 2). The strong peak at 4.79 min and a number of other peaks indicate that the product is not one single compound but rather a mixture of low- and medium-molecular-weight organic components. As the mass spectra of the main component of the material were identified, docosane ($C_{22}H_{46}$), whose characteristic fragment ions are found at m/z 43, 57, 71, 85 and 99 in long-chain saturated hydrocarbons, is known to be predominant. The presence of such hydrocarbon fragments is indicative of the hydrophobic character of the synthesized reagent, which is important for adsorption on the coal surface. In addition, possible polar functional fragments, supported by FTIR analysis, may contribute to interaction with the aqueous phase, and oxygen-containing sites on the coal surface, supported by FTIR analysis in the reagent structure, may exhibit amphiphilic behavior and will interact with the aqueous material. GC-MS results suggest that the synthesized reagent is hydrophobic hydrocarbon chains and surface-active structural fragments, which can facilitate its adsorption at the coal–water interface and modify the surface properties of coal particles during beneficiation.

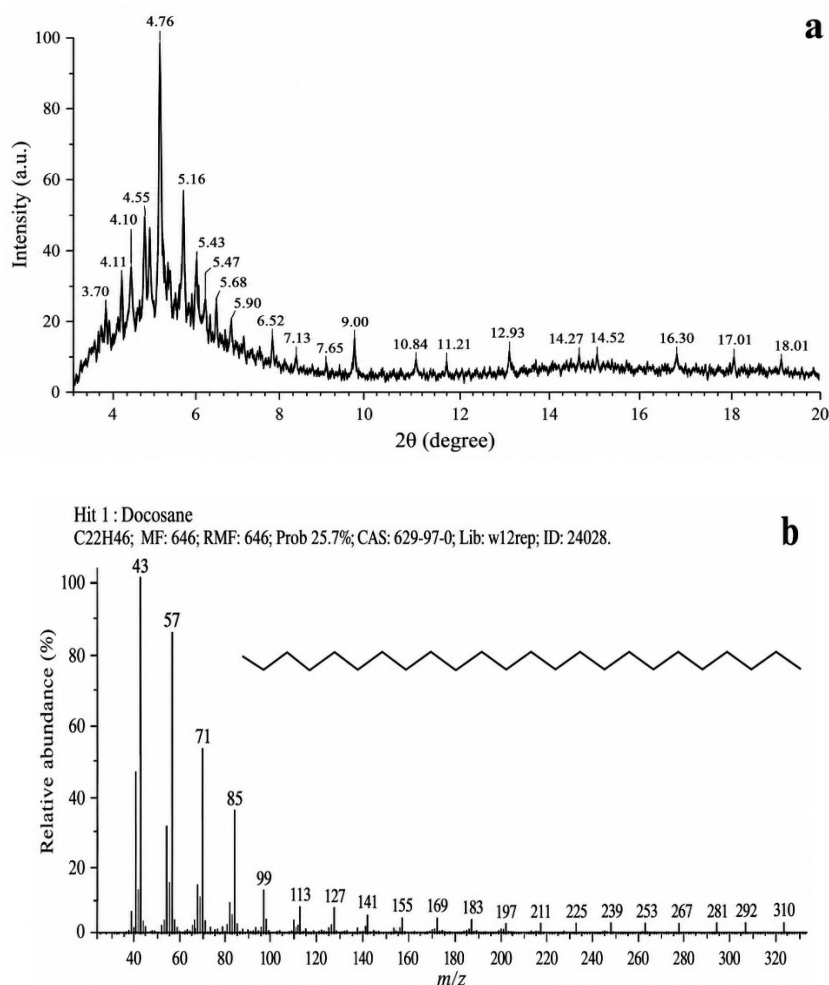


Fig. 2. GC–MS analysis of the synthesized surface-active reagent: (a) total ion chromatogram; (b) EI mass spectrum of docosane ($C_{22}H_{46}$).

The rheological behavior of 1% synthesized surfactant solutions with different oil-alkali ratios was investigated at $25 \pm 2^\circ\text{C}$. As shown in Fig. 3, all samples presented an increase in the apparent viscosity with increasing shear rate indicating non-Newtonian rheological behavior and the formation of structured surfactant aggregates in aqueous media. SFM-1 had the lowest viscosity profile, which increased from $0.425\text{ mPa}\cdot\text{s}$ at 7.2 s^{-1} to $2.339\text{ mPa}\cdot\text{s}$ at 1510 s^{-1} . This indicated good fluidity but relatively weak dispersion stabilization. SFM-2 showed a moderate viscosity and increased to $2.228\text{ mPa}\cdot\text{s}$ at 305 s^{-1} and remained almost constant at $2.227\text{ mPa}\cdot\text{s}$ at 1510 s^{-1} , indicating that the surfactant was stable in high shear. SFM-3 showed the highest viscosity at a high shear rate. The most balanced viscosity profile was found for SFM-4, from $0.365\text{ mPa}\cdot\text{s}$ at 7.2 s^{-1} to $2.792\text{ mPa}\cdot\text{s}$ at 1510 s^{-1} . This viscosity level is sufficient to stabilize the coal-water dispersion and still have good reagent distribution and contact with coal particles (Figure 3). Thus, SFM-4 was chosen as the most suitable formulation for further coal beneficiation experiments. FTIR spectrum of the raw coal sample and identified the functional groups of the surface that are involved in surfactant and coal surfactant interactions. As shown in Fig. 4, the bands from 2920 to 2850 cm^{-1} are aliphatic C-H stretching vibrations, which correspond to hydrocarbon fragments in the coal structure.

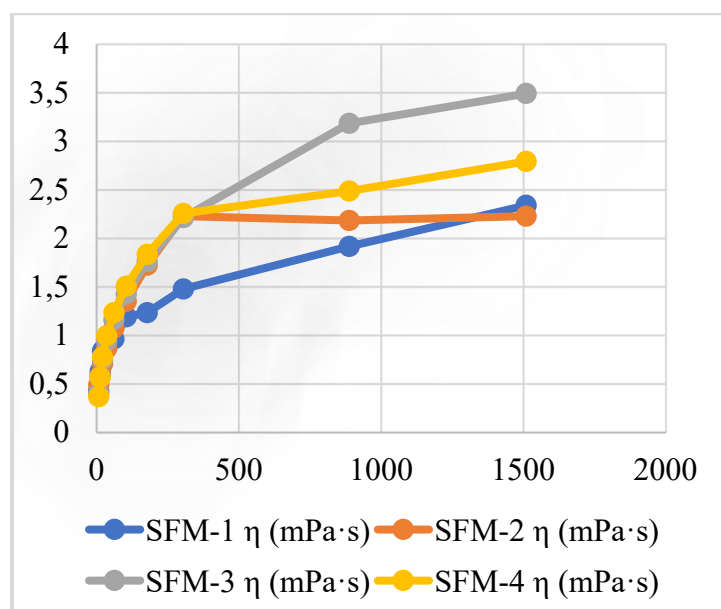


Fig. 3. Rheological viscosity profiles of 1% synthesized surfactant solutions with different oil–alkali ratios measured using an Anton Paar MCR rheometer at $25 \pm 2^\circ\text{C}$

The absorption band around 1580 cm^{-1} corresponds to aromatic C=C skeletal vibrations in the carbonaceous matrix. The peaks between 1030 and 1100 cm^{-1} indicate C-O stretching and oxygen-containing mineral components of the coal, and the bands below 800 cm^{-1} are aromatic C-H out-of-plane vibrations and inorganic mineral components. These results indicate that the coal surface contains hydrophobic aromatic/aliphatic and polar oxygen-containing sites. As indicated by the GC-MS of the synthesized reagent (Figure 2), long-chain hydrocarbon fragments of the surfactant can interact with hydrophobic coal domains, whereas its polar fragments may bind to oxygen-containing surface groups via hydrogen bonding or dipole-dipole interactions. These observations and rheological data (Figure 3) support the adsorption of the synthesized surfactant at the coal-water interface and explain its role in improving coal particle hydrophobicity during flotation.

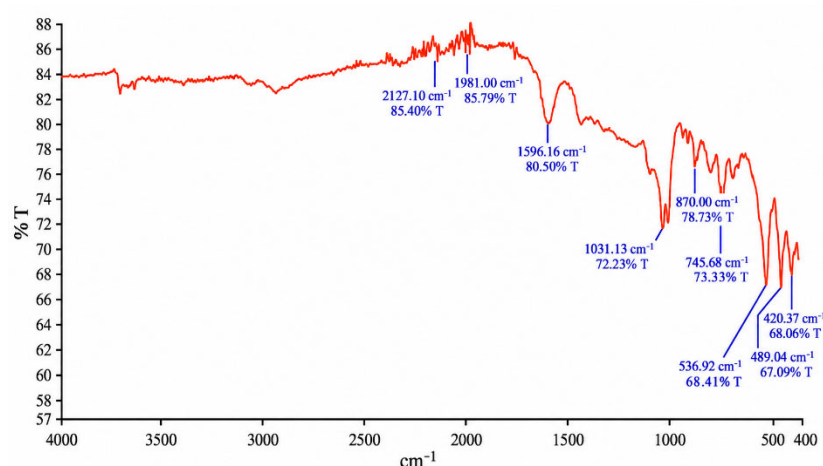


Fig. 4. FTIR spectrum of the raw coal sample used for surfactant-assisted coal beneficiation

Fig. 5 shows that upper panel is schematic the raw coal surface is irregular, compact, and partially covered by fine mineral particles, which may reduce flotation selectivity. After the surfactant is applied, the coal surface gets more dispersed and rough and is strongly adsorbed, implying weakly attached mineral impurities are removed. The beneficiated coal concentrate is cleaner and more porous, which is beneficial for bubble-particle attachment during flotation. This SEM result is in agreement with the GC-MS and FTIR results, for the hydrocarbon-rich surfactant can interact with

hydrophobic coal domains, and the polar groups can bind to oxygen-containing surface sites. Therefore, the synthesized surfactant improves the interfacial properties of coal particles and enhances the flotation performance.

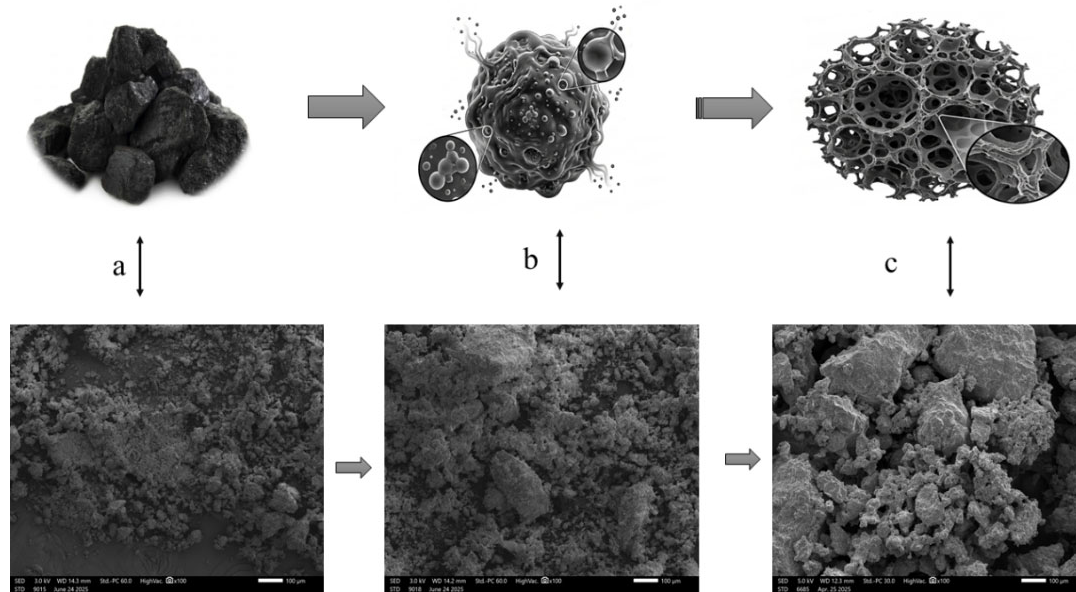


Fig. 5. Conceptual representation of surfactant-assisted coal beneficiation combined with SEM micrographs of coal morphology: (a) untreated raw coal, (b) coal particles after interaction with the synthesized surfactant, and (c) enriched coal concentrate after beneficiation

The beneficiation performance of coal using SFM-4 was evaluated under different inclination angles, drum rotation speed and reagent dosages (Table 1). The ash content of the concentrate was 37.6% to 26.1%, while the coal yield was 32.5% to 56.4%, thus demonstrating the influence of operating conditions on the separation efficiency. At low SFM-4 dosages of 20-29 mL, the ash content remained high (35.9 -37.6%), and the yield was not higher than 40.6%, indicating insufficient modification of the coal-water interface. Increasing the dosage to 40-50 mL significantly improved beneficiation efficiency. The best performance was obtained in Run 9 with a 15° inclination angle, 18 rpm drum speed and at an SFM-4 dosage of 50 mL and the ash content was reduced to 26.6%, coal yield was 56.4% and combustible recovery was 65.50%, respectively.

Table 1. Coal beneficiation performance under different separation conditions using SFM-4 as the synthesized surfactant reagent

Run	Angle, °	Drum speed, rpm	SFM-4, mL	Ash, %	Coal yield, %	Ash reduction, %	Combustible recovery, %
1	10	17	20	36.8	32.5	0.00	32.50
2	15	18	23	37.6	36.8	-2.17	36.33
3	20	18	26	36.1	34.2	1.90	34.58
4	10	17	29	35.9	40.6	2.45	41.18
5	15	18	32	32.8	47.9	10.87	50.93
6	20	17	35	30.7	44.1	16.58	48.36
7	10	18	40	28.5	49.2	22.55	55.66
8	15	17	45	27.9	52.6	24.18	60.01
9	15	18	50	26.6	56.4	27.72	65.50
10	20	18	53	26.8	51.0	27.17	59.07
11	10	17	56	26.2	45.8	28.80	53.48
12	15	18	59	27.4	50.3	25.54	57.78

13	20	18	65	28.4	46.5	22.83	52.68
14	20	17	70	27.5	43.9	25.27	50.36
15	10	18	75	26.1	35.1	29.08	41.04

Although Run 15 gave the lowest ash content of 26.1%, the coal yield decreased to 35.1% and combustible recovery decreased to 41.04%. Therefore, 50 mL SFM-4 was selected as the optimal dosage based on the combined balance of ash reduction, coal yield and combustible recovery. However, the results below confirm the effectiveness of the synthesized SFM-4 reagent in improving coal beneficiation performance, but there are limitations. Our work mainly focused on laboratory-scale flotation-gravity separation and analyzed the process using ash content, coal yield, and combustible recovery as the main performance indicators. More studies should be performed to understand the contact angle, zeta potential, froth stability, and reagent adsorption, and further beneficiation cycles to better understand the interfacial mechanism and process reproducibility. Pilot-scale experiments and comparison with commercial collectors or frothers are also required to assess the industrial applicability, economic feasibility, and environmental safety of the synthesized surfactant system.

Conclusions

In this study, soapstock oil-based surface-active material was synthesized and applied as a reagent for the beneficiation of Angren brown coal. GC-MS analysis showed that the reagent was hydrocarbon-rich and docosane ($C_{22}H_{46}$) was one of the main long-chain saturated hydrocarbons, which is hydrophobic in nature. The SFM-4 reagent was most characterized by the highest viscosity profile of all samples, from 0.365 mPa·s at 7.2 s⁻¹ to 2.792 mPa·s at 1510 s⁻¹, which enabled a stable coal-water dispersion with less viscosity. The FTIR and SEM analysis showed that the coal surface had hydrophobic carbonaceous and polar oxygen sites which provided a favorable environment of surfactant adsorption between the coal and water. The beneficiation experiments of Angren brown coal showed that SFM-4 was able to assist in the coal-water separation efficiency. At the optimum conditions of 15° inclination angle, 18 rpm drum speed and 50 mL SFM-4 dosage, the ash content decreased to 26.6%, the ash reduction to 27.72%, the coal yield to 56.4%, and the combustible recovery to 65.50%. The lowest ash content was achieved with higher reagent dosage, whereas the lower coal yield and combustible recovery show that excessive SFM dosage, reduced process selectivity and overall recovery. Thus, the synthesized SFM-4 reagent is a promising surface active system for the flotation-gravity beneficiation of high-ash brown coal. Future studies should focus on pilot-scale validation, contact angle and zeta potential, froth stability, reagent adsorption and comparison with commercial flotation reagents to validate its industrial application and environmental safety.

Acknowledgments

The authors acknowledge the Institute of General and Inorganic Chemistry of the Academy of Sciences of the Republic of Uzbekistan for laboratory support.

Conflicts of interest

The authors declare no conflict of interest.

References

1. Kumar B., Das B., Garain A., Rai S., Begum W., Inamuddin M., Mondal M.H., Bhattarai A., Saha B. Diverse utilization of surfactants in coal-floatation for the sustainable development of clean coal production and environmental safety: a review. *RSC Advances*, 2022, **Vol. 12(37)**, p. 23973-23988. DOI: [10.1039/D2RA02861A](https://doi.org/10.1039/D2RA02861A)

2. Patra A.S., Basu A., Biswas A., Das A., Anjoom S.J., Mukherjee A.K. Synergistic effect of polar group containing collectors and synthesized frother on flotation performance of oxidized coal. *International Journal of Coal Preparation and Utilization*, 2021, **Vol. 41(5)**, p. 307-320. DOI: [10.1080/19392699.2021.1883595](https://doi.org/10.1080/19392699.2021.1883595)
3. Sarma J., Rajkhowa S., Mahiuddin S. Upgradation of iron ore fines and slime by selective flocculation using surface-active agents, settling study, and characterization of the beneficiation waste for value addition. *Journal of Chemistry*, 2022, **Vol. 2022**, p. 1-13. DOI: [10.1155/2022/6451187](https://doi.org/10.1155/2022/6451187)
4. Salikhanova D., Muratov M., Usmonova Z., Abdikamalova A., Eshmetov I., Jumayeva D., Sagdullayeva D., Ismoilova M., Kadirova N., Eshmetov R. Engineering high-performance activated carbons from plum pit shells for efficient copper(II) removal: synthesis, structural characterization, and adsorption mechanisms. *Ecological Engineering & Environmental Technology*, 2026, **Vol. 27(6)**, p. 135–152. DOI: [10.12912/27197050/221291](https://doi.org/10.12912/27197050/221291)
5. Kucharov A., Xalilov S., Alikulova M., Mamrasulov T., Turayeva K., Imanova G., Saidova M., Farmonov N. Scientific analysis of the development of new types of flotation reagents used in coal enrichment. *EUREKA: Physics and Engineering*, 2025, **No. 2**, p. 32-39. DOI: [10.21303/2461-4262.2025.003742](https://doi.org/10.21303/2461-4262.2025.003742)
6. Xia Y., Yang Z., Zhang R., Xing Y., Gui X. Enhancement of the surface hydrophobicity of low-rank coal by adsorbing DTAB: an experimental and molecular dynamics simulation study. *Fuel*, 2019, **Vol. 239**, p. 145-152. DOI: [10.1016/j.fuel.2018.10.156](https://doi.org/10.1016/j.fuel.2018.10.156)
7. Kačur J., Laciak M., Durdán M., Flegner P. Investigation of underground coal gasification in laboratory conditions: a review of recent research. *Energies*, 2023, **Vol. 16(17)**, 6250. DOI: [10.3390/en16176250](https://doi.org/10.3390/en16176250)
8. Zalov A.Z., Shahverdiyeva A.F., Novruzova N.A., Ibrahimova Sh.A. Investigation of the oil-emulsifying and oil-dispersing properties of quaternary ammonium salts formed from triethanolamine with hexadecenoic and heptadecanoic acids, and their application as analytical reagents. *Chemical Problems*, 2025, **Vol. 23(2)**, p. 228-238. DOI: [10.32737/2221-8688-2025-2-228-238](https://doi.org/10.32737/2221-8688-2025-2-228-238)
9. Aleksandrova T.N., Kuznetsov V.V., Prokhorova E.O. Investigation of interfacial characteristics as a key aspect of the justification of the reagent regime for coal flotation. *Minerals*, 2025, **Vol. 15(1)**, 76. DOI: [10.3390/min15010076](https://doi.org/10.3390/min15010076)
10. Hornn V., Park I., Ito M., Shimada H., Suto T., Tabelin C.B., Jeon S., Hiroyoshi N. Agglomeration-flotation of finely ground chalcopyrite using surfactant-stabilized oil emulsions: effects of co-existing minerals and ions. *Minerals Engineering*, 2021, **Vol. 171**, 107076. DOI: [10.1016/j.mineng.2021.107076](https://doi.org/10.1016/j.mineng.2021.107076)
11. Cheng G., Zhang M., Lu Y., Zhang H., Lau E.V. New insights for improving low-rank coal flotation performance via emulsified waste fried oil collector. *Fuel*, 2024, **Vol. 357**, 129925. DOI: [10.1016/j.fuel.2023.129925](https://doi.org/10.1016/j.fuel.2023.129925)
12. Wang X., Cheng H., Ding D. Advances and prospects on flotation enhancement of difficult-to-float coal by emulsion: a review. *Minerals*, 2024, **Vol. 14(9)**, 952. DOI: [10.3390/min14090952](https://doi.org/10.3390/min14090952)
13. Zhang Q., Niu C., Bu X., Bilal M., Ni C., Peng Y. Enhancement of flotation performance of oxidized coal by the mixture of laurylamine dipropylene diamine and kerosene. *Minerals*, 2021, **Vol. 11(11)**, 1271. DOI: [10.3390/min11111271](https://doi.org/10.3390/min11111271)
14. Batjargal K., Guven O., Ozdemir O., Karakashev S.I., Grozev N.A., Boylu F., Çelik M.S. Frothing performance of frother-collector mixtures as determined by dynamic foam analyzer and its implications in flotation. *Minerals*, 2023, **Vol. 13(2)**, 242. DOI: [10.3390/min13020242](https://doi.org/10.3390/min13020242)
15. Yusupov F., Kucharov A., Baymatova G., Shukurullayev B., Yuldashev R. Development and study of adsorption properties of a new sulfur polyvinyl chloride cation exchanger for water treatment. *IOP Conference Series: Earth and Environmental Science*, 2023, **Vol. 1231**, 012027. DOI: [10.1088/1755-1315/1231/1/012027](https://doi.org/10.1088/1755-1315/1231/1/012027)

16. Augustyn A.R., Pott R.W.M., Tadie M. The interactions of the biosurfactant surfactin in coal flotation. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2021, **Vol. 627**, 127122. DOI: [10.1016/j.colsurfa.2021.127122](https://doi.org/10.1016/j.colsurfa.2021.127122)
17. Kucharov A., Xalilov S., Farxod Y., Toshboboyeva R., Bekturdiyev G., Turayeva K., Mamanazarov M., Temirov G. A comprehensive technological approach for the selective recovery of aluminum oxide and rare earth elements from coal processing. *EUREKA: Physics and Engineering*, 2026, **No. 2**, p. 13-24. DOI: [10.21303/2461-4262.2026.004149](https://doi.org/10.21303/2461-4262.2026.004149)
18. Niu C., Xia W., Li Y., Bu X., Wang Y., Xie G. Insight into the low-rank coal flotation using amino acid surfactant as a promoter. *Fuel*, 2022, **Vol. 307**, 121810. DOI: [10.1016/j.fuel.2021.121810](https://doi.org/10.1016/j.fuel.2021.121810)
19. Wang S., Xia Q., Xu F. Investigation of collector mixtures on the flotation dynamics of low-rank coal. *Fuel*, 2022, **Vol. 327**, 125171. DOI: [10.1016/j.fuel.2022.125171](https://doi.org/10.1016/j.fuel.2022.125171)
20. Saha B., Patra A., Das A., Basu A., Mukherjee A.K. Role of collector polarity and size on the low-rank fine coal flotation. *International Journal of Coal Preparation and Utilization*, 2023, **Vol. 43(2)**, p. 203-216. DOI: [10.1080/19392699.2022.2146103](https://doi.org/10.1080/19392699.2022.2146103)
21. Xu F., Wang S., Kong R., Wang C. Synergistic effects of dodecane-castor oil acid mixture on the flotation responses of low-rank coal: a combined simulation and experimental study. *International Journal of Mining Science and Technology*, 2023, **Vol. 33(5)**, p. 649-658. DOI: [10.1016/j.ijmst.2022.11.010](https://doi.org/10.1016/j.ijmst.2022.11.010)
22. Bao X., Liu J., Wang S., Chen D., Zhang D., Li J., Xing Y., Xu M. New insight into temperature effects on low-rank coal flotation using diesel as a collector. *ACS Omega*, 2023, **Vol. 8(17)**, p. 15479-15487. DOI: [10.1021/acsomega.3c00774](https://doi.org/10.1021/acsomega.3c00774)
23. Shahverdiyeva A.F., Zalov A.Z., Salamova N.V. Study of physical-chemical and colloidal properties of the quaternary ammonium salt obtained from heptadecanoic and octadecanoic acids with triethanolamine. *Chemical Problems*, 2026, **Vol. 24(2)**, p. 236-243. DOI: [10.65382/2221-8688-2026-2-236-243](https://doi.org/10.65382/2221-8688-2026-2-236-243)
24. Temirov G.B., Yusupov F.M., Yusupov S.K., Baymatova G.A., Kucharov A.A., Yodgorov N., Nuriddinova D.Z. Scientific dynamics and global contributions to anion exchange resin research (2000-2025): a comprehensive bibliometric study. *Rasayan Journal of Chemistry*, 2025, **Vol. 18(4)**, p. 2225-2232. DOI: [10.31788/RJC.2025.1849355](https://doi.org/10.31788/RJC.2025.1849355)
25. Zhang R., Xia Y., Guo F., Sun W., Cheng H., Xing Y., Gui X. Effect of microemulsion on low-rank coal flotation by mixing DTAB and diesel oil. *Fuel*, 2020, **Vol. 260**, 116321. DOI: [10.1016/j.fuel.2019.116321](https://doi.org/10.1016/j.fuel.2019.116321)
26. Kondratev S.A., Khamzina T.A. Assessment of collecting activity of physically sorbed reagents on the example of easily floatable coking coal sludge. *Journal of Mining Institute*, 2022, **Vol. 256**, p. 549-559. DOI: [10.31897/PMI.2022.52](https://doi.org/10.31897/PMI.2022.52)