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EFFECT OF ADSORPTION OF SURFACTANT MIXTURES ON WETTABILITY OF SINTERING DUST

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Abstract

In order to improve the wettability of sintering dust, we investigated the action mechanism of Triton X-100 (TX-100), which synergizes with Dodecyl Trimethyl Ammonium Bromide (DTAB). The settling times of nine different types of surfactants were measured, and the optimal ratio of cationic and nonionic surfactants to synergistically improve the wettability of sintering dust was determined from these measurements. The adsorption performance of the surfactants in the mixed solution and their effect on the wetting properties of sintering dust were investigated by sedimentation test, adsorption amount, Fourier transform infrared spectroscopy, and zeta potential determination. The results showed that a synergistic effect could be obtained when DTAB and TX-100 were mixed, and the DTAB: TX-100=2:2 composite solution with a concentration of 0.3% had a good wetting effect on the sintering dust. As the concentration of the surfactant mixtures increased, the content of hydrophilic functional groups and the absolute potential value of the surface of the sintering dust increased accordingly. Among them, DTAB was affected by alkyl interactions and had a greater adsorption affinity, and the hydrophobic tail of TX-100 was entangled with that of DTAB due to hydrophobic interactions and shared an adsorption site. This study contributes to the selection of surfactants for the efficient wetting of sintering dust and provides a theoretical basis for hydrometallurgy and dust control.

Keywords: *Sintering dust; Non-cationic surfactant; Dust suppression; Wetting; Synergistic mechanisms*

1. Introduction

The sintering process is currently a central process step in domestic steel production and also one of the main sources of metallurgical dust and sludge [1]. As the largest crude steel producer in the world, China’s crude steel production of 10.19 million tons in 2023 will generate at least 113,600 tons of sintering dust [2]. The sintering dust is usually returned to the sintering process as a component [3]. However, the potassium and sodium contained therein are in the form of chlorides with low melting and boiling points, are continuously enriched as they pass through the blast furnace body, leading to scaffold buildup in the furnace, that impairs the smoothness and stability of the blast furnace [4, 5]. In addition, potassium and sodium are vaporized into the flue gas as dust particles during high-temperature sintering, leading to an increase in the specific resistance of the electrostatic precipitator (ESP), affecting the capture efficiency of the dust by the ESP [6, 7]. Sintering dust is considered a hazardous waste, because it contain a certain amount of heavy metals, so it is necessary to strengthen the dust control of the sintering process.

The wettability of powders and agglomerates is an important influencing factor in many practical applications and processes such as wet treatment of sintering dust and dust reduction by water mist method, since the wetting of powders by droplets must first overcome the obstruction of the air-water interface [8, 9]. Hydrophobic functional groups such as C-H structures, benzene rings, aromatic hydrocarbons with benzene rings, aliphatic hydrocarbons with methyl groups, and methylene structures of carbonaceous macromolecules hinder the wetting process between the droplets and the solid powders [10, 11]. Unfortunately, Tang et al. have shown that the surface of sintering dust is covered with a hydrophobic shell layer of n-alkyl chains and aromatic groups, which makes the sintering dust highly hydrophobic and tends to aggregate and float on the water surface when added to it [12]. Since surfactants are ideal reagents for surface modification of mineral particles, the wettability of hydrophobic

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particles can be increased by adding surfactants to regulate surface tension, wettability, dispersibility, etc. [13, 14]. In recent years, numerous scientists have investigated the effect of surfactant additives on the wettability of hydrophobic particles such as coal dust and have achieved significant results [15-17]. However, most studies on sintering dust have focused on the recycling of valuable metals, and there have been fewer studies on the effect of surfactants on the wettability of sintering dust and their mechanism of action [18-20]. Improving the wettability of sintering dust not only improves alkali metal removal and increases potash production, but also reduces water consumption in the wet treatment of sintering dust and facilitates the practical application of diffusion of many liquids on solid substrates and the benign development of industrial processes, such as flotation and dust suppression.

Considering the different mechanisms of different types of surfactants, nine types of surfactants were selected for the wettability test, and the surfactants with excellent wetting effect in single-use were sequentially selected for compounding in different ratios. Meanwhile, the materials were analyzed by UV-visible absorption spectra, FTIR spectra and surface potentials to investigate the influence of the adsorption capacity of surfactants on the wetting properties of sintering dust. This work aims to obtain a new type of surfactant mixtures with high equilibrium adsorption capacity and remarkable wetting effect and to systematically reveal the synergistic mechanism of action among the surfactants. Based on the type of adsorption isotherm, the adsorption mechanism of the surfactant mixtures on the surface of sintering dust during the wetting process was summarized. This study can provide a strong theoretical basis to guide the control of sintering dust in engineering practice.

2. Material and methods

2.1. Materials and reagents

The sintering dust samples came from the sintering plant of Jiuquan Iron and Steel Company Limited in Gansu Province, China. A total of nine analytical grade surfactant reagents, three types from each group of anionic, cationic, and nonionic surfactants, as shown in Table 1, were cetyltrimethylammonium bromide, cetylpyridinium chloride, Dodecyl trimethyl ammonium bromide, sodium dodecyl sulfate, sodium dodecylbenzene sulfonate, sodium alcohol ether sulfate, fatty alcohol ethoxylate, Triton X-100 and coconut oil diethanolamine to increase the hydrophilicity of the sintering dust. The sintering dust was sieved with 200 mesh and deionized water was used for the entire experiment.

2.2. Wettability test

The settling test is usually used to analyze the effect of surfactants on the wettability of dust. It allows a visual comparison of the hydrophilicity and wetting effect of the dust within the surfactant solution [21, 22]. First, 100 ml of nine surfactant solutions at different concentrations (0.1 %, 0.2 %, 0.3 %, 0.4 %, 0.5 %) were prepared and stirred at room temperature (25 °C) at 100 rpm to ensure that all surfactants were dissolved. 0.1 g of sintering dust was weighed and carefully placed on the surface of the solution. The dust particles were considered fully wetted when they had all settled, and the shorter the settling time, the better the hydrophilic effect of the surfactant on the sintering dust. The four surfactants with the fastest settling speed were selected for the compound test and the wetting effect of the compound solution on the sintering dust was analyzed, with each test group being performed three times.

Table 1. *The surfactants used in the experiment*

Category	Reagent name	Abbreviate	Molecule formula
Cationic	Hexadecyl trimethyl ammonium Bromide	CTAB	$C_{19}H_{42}BrN$
	Cetylpyridinium chloride	CPC	$C_{21}H_{38}ClN$
	Dodecyl Trimethyl Ammonium Bromide	DTAB	$C_{15}H_{34}BrN$
Anionic	Dodecyl sodium sulfate	SDS	$C_{12}H_{25}SO_4Na$
	Sodium dodecyl benzene sulfonate	SDBS	$C_{18}H_{29}NaO_3S$
	Sodium alcohol ether sulphate	AES	$C_{14}H_{29}NaO_5S$
Non-ionic	P-iso-Octyl phenoxy polyethoxyethanol	TX-100	$C_{34}H_{62}O_{11}$
	Fatty alcohol polyoxyethylene ether	AEO-9	$C_{30}H_{62}O_{10}$
	Coconut Diethanol Amide	CDEA	$C_{16}H_{33}O_3N$

2.3. Adsorption experiment

To better understand the wetting process between the surfactant and the dust particles, an ultraviolet spectrophotometer UV-1901 was used to study the adsorption experiment. 0.1 g of sintering ash dust was added to 100 ml of surfactant solution at a concentration of 0.5%, and after the sintering ash powder settled freely, it was left to saturate the adsorption of the active agent molecules on the surface of the sintering dust for 30 min. The supernatant was collected for the absorbance measurements and the concentration of the surfactant solution was read from the standard curve operated in the 200-700 nm spectrum. All measurements were performed at a room temperature of 25 ℃.

The amount of adsorbed surfactant was determined based on the change in concentration of the surfactant solution before and after adsorption according. The adsorption capacity was calculated using Eqs. (1) [23].

$$\Gamma = \frac{(C_0 - C_e)\mathrm{V}}{\mathrm{m}} \tag{1}$$

Where Γ is the amount of adsorbed surfactant (g/g), C_0 and C_e are the concentrations of surfactant before and after the addition of sintering dust (g/L), V is the volume of surfactant solution (L), and m is the mass of sintering dust (g).

2.4. FTIR test

The infrared spectra of the sintering dust samples were measured by Fourier transform infrared spectroscopy (FTIR) and micro-infrared system. 0.1 g of sintering dust was immersed in different concentrations of compound solutions for 2 hours to completely adsorb the surfactant on the surface of the dust, and then pumped into an oven and filtered and dried at 40 ℃ for 12 hours. The dried sintering dust was processed by the potassium bromide tablet method, in which the sample was mixed with potassium bromide powder at a ratio of 1:100 and ground to distribute it evenly, and then placed flat in a mold and pressed with a powder pressing machine at a pressure of 10 MPa for 1 minute. Finally, the pressed tablets were analyzed by infrared spectroscopy. The spectral range was 400-4000 cm^{-1} with a resolution of 4 cm^{-1} and 32 scans were performed for each group of samples.

2.5. Zeta potential test

The ζ-potential measurements of surfactant solutions on sintering dust were performed with a Zetasizer Nano. An aqueous solution of mixed surfactants was mixed with sintering dust at a ratio of 0.001 g/ml and stirred at 100 rpm and 25 ℃ for 30 minutes. One ml of the solution was used for ζ-potential analysis. The pH was measured before each ζ-potential measurement.

3. Results and discussion

3.1. Wettability analysis of sintering dust

In the settling test, the settling time can be a good response to the effect of surfactant on the wettability of sintering dust.

3.1.1. The wetting effect of a single surfactant

Under the condition that no surfactant is added, the sintering dust exhibits considerable hydrophobicity and the settling time is more than 24 hours. As shown in Fig. 1, when the sintering dust is carefully placed on the surface of the aqueous solution, it spreads spontaneously in the environment, and its hydrophobicity causes the powder to be subjected to transverse capillary forces at the gas-liquid interface, resulting in the formation of an oily film on the surface of the solution, which isolates the water from the sintering dust [24]. The other, incompletely wetted sintering dust is agglomerated into lumpy particles, which further hinders the

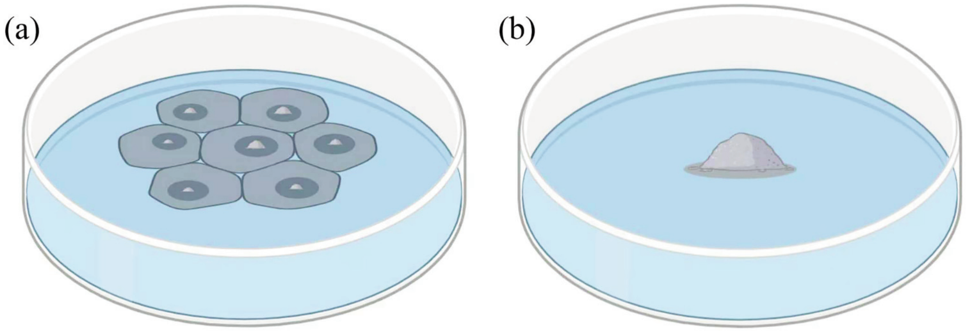


Figure 1. *The wetting process of sintering dust on liquid surfaces (a) Distilled water (b) 0.5% DTAB*

Table 2. *Wetting time of sintering dust for different surfactant solutions*

Abbreviation	Surfactant concentration (wt.%)				
	0.1	0.2	0.3	0.4	0.5
CTAB	14059s	12997s	11672s	11493s	11055s
DTAB	1260s	844s	572s	489s	471s
CPC	13424s	6729s	3766s	3451s	3369s
SDS	16584s	14693s	12887s	12537s	12394s
SDBS	11481s	10696s	9653s	9114s	8760s
AES	13282s	12194s	4795s	3429s	2455s
TX-100	5972s	1831s	1496s	1164s	802s
AEO-9	4563s	1984s	1464s	1243s	1136s
CDEA	14711s	11364s	9658s	8586s	8291s
Distilled water	> 86400s				

wetting effect of the liquid. This property not only hinders the comprehensive utilization of hydrometallurgy but also significantly impairs the effect of dust removal. Therefore, it is imperative to analyze the wetting effect of surfactants on sintering dust and improve its wettability.

As shown in Table 2, the time required for the complete settling of 0.1 g of sintering dust was determined at different concentrations of various surfactants. Basically, at a surfactant concentration of less than 0.2 by weight, the settling time of sintering dust decreases significantly with the addition of surfactants. When the concentration of surfactant is more than 0.2 wt.%, the decrease in settling time decreases, such as CPC for cationic surfactants, SDS for anionic surfactants, and CDEA for non-ionic surfactants, in the concentration range of 0.2 wt.% to 0.5 wt.%, the change in settling time tends to stabilize gradually. This is because the concentration of the surfactant has already reached the concentration of the critical micelles and a further increase in the solution only causes the formation of micelles and does not contribute significantly to the wetting process [25]. From the overall effect, the nonionic surfactants had the greatest influence on the wetting process of sintering dust, and this result may be caused by the fact that the hydrophilic groups of nonionic surfactants do not have strong electrostatic repulsion with each other, and therefore they are more easily adsorbed on the surface of the sintering dust, followed by cationic surfactants, and the anionic surfactants are the smallest. Finally, AEO-9, TX-100, DTAB, and AES (A, B, C, and D) were selected for the compounding test based on the settling time, and the rest of the surfactants had a long settling time under different mass concentration conditions, so it was meaningless to select them as wetting agents.

3.1.2. The wetting effect of mixed surfactants

The cationic and anionic surfactants were compounded with different nonionic surfactants in different ratios (4:0, 3:1, 2:2, 1:3, and 0:4) to observe the presence of synergistic effect and control the mass concentration of 0.5 wt.%. The results are shown in Fig. 2. The two surfactants were considered to be synergistic with each other if the required settling time of the surfactant mixtures solution was shorter compared to the single-use condition. If the wetting time of the surfactant mixtures was between the wetting times of the two surfactants, they were neither synergistic nor antagonistic. If the wetting time is longer than the wetting time of either single surfactant, they are considered to be antagonistic.

TX-100 and DTAB played an obvious synergistic effect, no matter in what proportion of the conditions

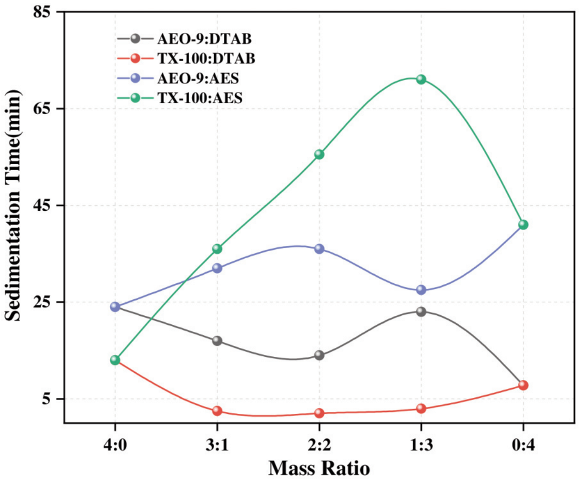


Figure 2. *Relationship between sedimentation time and different surfactant formulations*

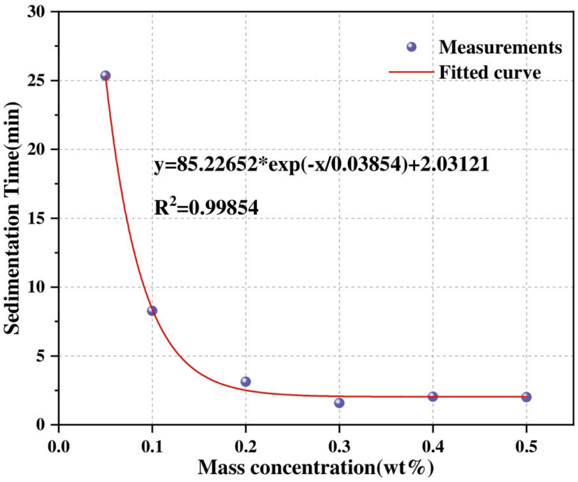


Figure 3. *Relationship between sedimentation time and the mass concentration of surfactant mixtures*

of intermixing, the settlement time is smaller than the single use of the case, especially in the 2:2 synergistic effect to reach the strongest, the settlement time is only 122 s, compared with a single use of 0.5wt.% DTAB settlement time of 471 s, the wetting performance increased by 74%, the sole use of TX-100 treatment of the settlement time was 802 s, and the wetting performance was improved by 84.8%. However, as a nonionic surfactant, AEO-9 had neither synergistic nor antagonistic effects on DTAB and AES, which was also true when TX-100 and AES were compounded in the ratio of 3:1, TX-100 and AES played an obvious antagonistic effect in the ratios of 2:2 and 1:3. Therefore, DTAB and TX-100 are selected to be mixed in a ratio of 2:2.

The fitted curves of the effect of surfactant mixtures on the wettability of sintering dust as a function of concentration are shown in Fig. 3. When the concentration of surfactant in the solution is lower than 0.1 wt.%, the settling time is rapidly shortened, and the decreasing trend of settling time gradually flattens out at higher concentration ranges (0.2 wt.% ~ 0.5 wt.%), and there is almost no decrease especially after 0.3 wt.%. Therefore, it can be inferred that the CMC of the surfactant mixtures is about 0.2wt.% to 0.3wt.%. When the concentration is less than 0.1 wt.%, the adsorption density on the surface of the sintering dust increases with the concentration of the novel surfactant, and after the critical micelle concentration is reached, micelles are formed in the solution, and the density of the adsorbed layer on the surface does not change much. When the mass concentration was greater than 0.3 wt.%, the increase in concentration had no significant effect on the settling time.

3.1.3. The synergistic effect of mixed surfactants

After complete wetting, the sintering dust was allowed to reach the saturated adsorption state after 30 min of standing, to obtain the equilibrium adsorption capacity of different surfactants, as shown in Fig. 4. For the case of different surfactants alone, the equilibrium adsorption capacity of cationic surfactant is obviously larger than that of anionic surfactant, so the sintering dust wetting performance is enhanced more by cationic surfactant, which is in line with the conclusions obtained in the sedimentation test. The reason for this phenomenon may be that the hydrophobic groups of the surfactant molecules adsorbed on the liquid surface extend into the air, and the hydrophobic groups of the surfactants are nonpolar groups, which show strong affinity with the hydrophobic groups of the sintering dust, such as aromatic hydrocarbons and aliphatic hydrocarbons [26]. In addition, the surface of sintering dust originally carries a positive charge, while the surface active part of the cationic surfactant carries a positive charge, and the effect of mutual repulsion of the same charge makes the hydrophobic group of the cationic surfactant adsorbed on the surface of the sintering dust, and the hydrophilic group goes outward, which strengthens the hydrophilicity of the sintering dust, so that the sintering dust wetted portion can have more contact with the active agent in the solution, thus increasing the possibility of adsorption [27].

It can also be concluded from Fig. 4 that the complex surfactant has stronger adsorption performance compared with the single surfactant. For example, the equilibrium adsorption amount reached 0.0513 g/g after the compounding of DTAB and TX-100, which increased by 58.8% and 105.2%, respectively, compared with the case of two

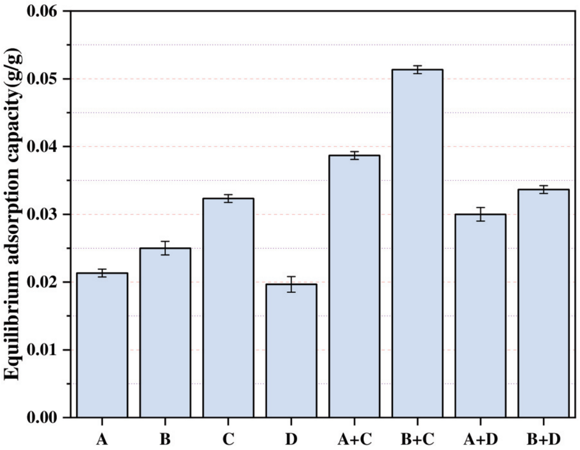


Figure 4. *Equilibrium adsorption capacity of different single and surfactant mixtures on the sintering dust surface*

surfactants used singly. This is mainly due to the hydrophilic groups of the same surfactant with the same kind of charge, thus generating electrostatic repulsion, so that in the adsorption process, the amphoteric surfactant is more uniformly distributed on the solid surface to form a hydrophilic film, with the increasing adsorption amount to reach the critical micellar concentration (CMC), adsorption amount is gradually saturated, and at the same time, the surface of the sintering dust is limited in the number of hydrophilic and hydrophobic sites, so the adsorption capacity is not able to adsorb too much of the same surfactant. At the same time, the surface of sintering dust has limited hydrophilic and hydrophobic sites, so it is unable to absorb too much of the same surfactant. Nonionic surfactant itself is not charged, and will not produce an electrostatic effect with amphoteric surfactant, nonionic surfactant molecules can penetrate the hydrophilic groups of amphoteric surfactant between the hydrophilic groups to reduce electrostatic repulsion, or with amphoteric surfactant to share the same hydrophobic sites. The synergistic effect of the two can make the solid surface can adsorb more surfactant molecules and further increase the adsorption amount [28].

3.2. Functional group analysis of sintering dust

The change in the wettability of sintering dust is due to the adsorption of long-chain hydrophobic groups of surfactants onto the surface of sintering dust, which may cause changes in the structure and content of functional groups on the surface of sintering dust. Therefore, the infrared spectra of the sintering dust wetted with different concentrations of complex surfactant solutions were determined and analyzed.

Compared with the original sample of sintering dust, the composite solution had no effect on the absorption bands and characteristic absorption peaks, but the peak area changed, indicating that the composite solution did not change the structure of the functional groups of the sintering dust, but only affected the relative content of the functional groups [29]. Based on the absorbance characteristics at different wavelengths in the infrared spectra, the structures of the four main functional groups, hydroxyl, aliphatic hydrocarbons, oxygen-containing functional groups, and aromatic hydrocarbons, were analyzed. The corresponding wave numbers were 3000-3600 cm^{-1} for hydroxyl groups, 2800-3000 cm^{-1} for aliphatic hydrocarbons, 1000-1800 cm^{-1} for oxygenated functional groups, and 700-900 cm^{-1} for aromatic hydrocarbons. Among the four main functional groups, hydroxyl and oxygenated functional groups are hydrophilic, while aliphatic hydrocarbons and aromatic hydrocarbons are hydrophobic, and the higher the content of the hydrophilic group, the higher the content of hydrophilic groups, the better the wettability of the sintering dust.

The measured FTIR spectral curves are shown in Figure 5. The infrared spectrum of the original sample of sintering dust showed an absorption peak at 875 cm^{-1} caused by the out-plane bending vibration of the monosubstituted aromatic ring, the absorption peaks at 1430 cm^{-1} and 1628 cm^{-1} indicated the presence of the aromatic ring, and the symmetric telescoping vibration peaks and antisymmetric telescoping vibration peaks of CH_2 were also more obvious at 2853 cm^{-1}and 2923 cm^{-1}, which is consistent with the conclusion of Tang's study, indicating that the existence of a hydrophobic shell consisting of n-alkyl chains and aromatic groups on the surface of the sintering dust [12, 30, 31]. The curves in the region of oxygen-containing functional groups are characterized by three peaks, the absorption peak between 1000-1300 cm^{-1} is due to the stretching vibration of the C-O bond, the absorption peak near 1400 cm^{-1} is due to the bending or deformation

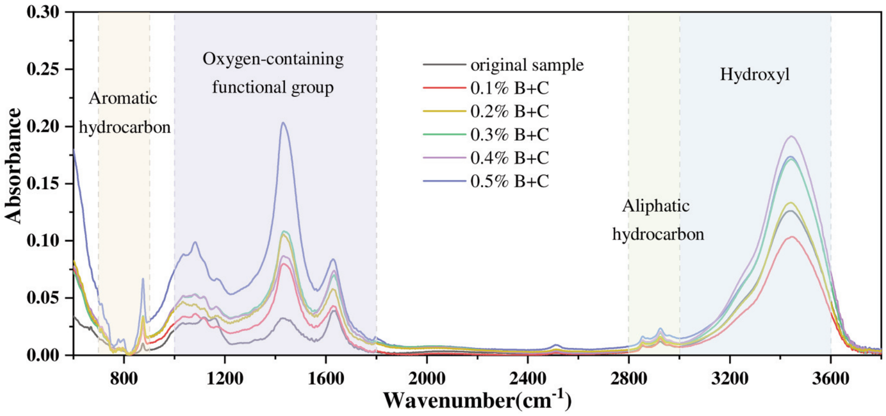


Figure 5. *FTIR spectra of sintering dust treated with different concentrations of surfactants*

***Table 3.** Absorption peak area of functional groups in sintering dust treated with surfactant mixtures with different concentrations*

Sintering dust treatment method	Functional group type			
	Hydroxyl	Aliphatic hydrocarbon	Oxygen-containing functional group	Aromatic hydrocarbon
Original sample	37.174	1.534	15.644	1.151
0.1%B+C	55.653	2.38	35.766	2.228
0.2%B+C	37.986	1.991	33.805	2.176
0.3%B+C	49.172	2.177	38.025	2.049
0.4%B+C	55.65	2.354	35.766	2.183
0.5%B+C	50.679	3.066	61.858	4.369

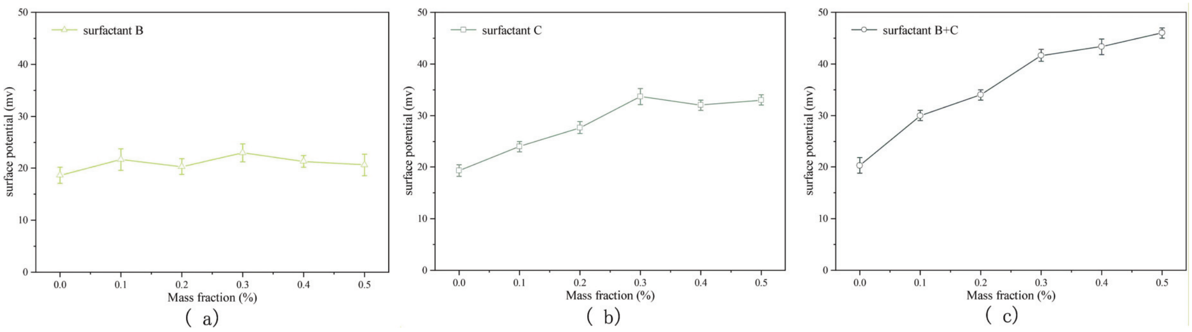
vibration of $-CH_2$ and $-CH_3$, and the absorption peak between 1600-1700 cm^{-1} is due to the stretching of the C=C bond. The peak intensities increased with the increase of solution concentration, in which the second peak intensity increased gradually and exceeded the other two peaks, which was caused by the increase in the stacking of the infrared absorption peaks of $-CH_2$ and $-CH_3$, and there was the possibility that TX-100 promoted the adsorption of DTAB. Additionally, hydroxyl group's absorption peak intensities increase with solution concentration as well as its possibility for hydrogen bonding formation with water.

The results of the absorption peak areas of the functional groups are shown in Table 3. The sintering dust treated with the surfactant mixtures showed different degrees of increase in the content of the four functional groups, which was produced by the adhesion of the functional groups in the composite solution. The changes in aliphatic hydrocarbon and aromatic hydrocarbon groups were relatively small, and both of them were positively correlated with the concentration of the solution. The content of hydrophilic groups on the surface of the sintering dust was significantly increased, and the higher the concentration of the surfactant mixtures solution was, the larger the increment of hydrophilic groups was, and thus the better the wettability of the sintering dust was.

3.3. Polymerization performance analysis of sintering dust

In the solution, the fine powder is subject to electrostatic force, it is very easy to produce spontaneous coalescence, showing strong agglomeration characteristics, forming secondary particles (agglomerates) with large particle sizes, which are difficult to be wetted. It is well known that sintering dust is charged under the action of electric field force, and the hydrophilic group of cationic surfactant is positively charged in aqueous solution, so the adsorption of surfactant can not only change the functional group content on the surface of sintering dust but also change its surface potential in solution.

It can be seen from Fig. 6 that with the increase of surfactant solution concentration, the hydrophobic functional groups adsorbed on the surface of sintering dust and the hydrophilic groups went outward, increasing the hydrophilicity of the sintering dust, and at the same time, changing its surface potential. The influence of nonionic surfactants on the surface potential of sintering dust is smaller than that of cationic surfactants, and there is almost no change.



(a) (b) (c)

***Figure 6.** Variation of the zeta potential of sintering dust with different surfactants. (a)TX-100 (b)DTAB (c)Mixed solution*

This is because the nonionic surfactant itself is not charged, and its adsorption arrangement with the sintering dust is more chaotic than that of the amphoteric surfactant, which cannot effectively affect the surface potential of the sintering dust [32]. With the increase of cationic surfactant concentration, the negatively charged hydrophobic group long chain entangled in the surface of sintering dust, while the hydrophilic group is positively charged outward, so the positive charge on the surface of the sintering dust increases, increasing the electrostatic interaction between the particles, which makes the fully wetted sintering dust detach from the agglomerates and settle, when the concentration of DTAB is more than 0.3%, it may be due to the adsorption saturation reached, and the surface potential of sintering dust's surface potential changed slowly and gradually stabilized.

The composite solution affects the surface potential to a greater extent than the single use of surfactant. When the particles are close to each other, they are subjected to the double layer repulsion and van der Waals mutual attraction, and the dividing line of particle dispersion stability in the aqueous phase is generally considered to be at +30mV or -30mV, and a higher zeta potential will make the particles repel each other so that the whole system has a higher stability. At the same concentration of 0.3%, the surface potential of sintering dust in the surfactant mixtures (B+C) was 41.62 mv, which was 23.98% higher than that of 33.57 mv when DTAB was used alone. This is due to the co-adsorption of nonionic surfactants, which reduces the electrostatic repulsion between the cationic surfactants adsorbed on the surface of sintering dust, so that DTAB can have a larger adsorption capacity at the saturated adsorption state compared with that when it is used alone, and it has a more significant effect on the surface potential of the sintering dust.

3.4. Wetting mechanism of surfactant on sintering dust

3.4.1. Adsorption isotherm

Adsorption isotherms can usually be combined with corresponding surface potentials to express the interaction of active agent molecules with solid surfaces and to analyze the adsorption mechanism. Figures 7 and 8 correspond to the adsorption of two surfactants, TX-100 and DTAB, respectively, for a single application at a constant temperature of 25℃, and all of them conform to the L-type adsorption isotherm.

The adsorption isotherms of the two surfactants on the sintering dust were fitted using Langmuir and Freundlich adsorption isotherm models, respectively. Langmuir adsorption isotherm assumes that the adsorbed molecules form a saturated monolayer on the surface, that the adsorbed molecules do not interact with one another and that they do not migrate in-plane, and that the adsorption energy is constant. The Langmuir equation can be represented as Eqs. (2):

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \tag{2}$$

Where q_e and max are the equilibrium and maximum adsorption capacity (mg/g), C_e is the concentration of the solute in solution when adsorption reaches equilibrium (mg/L), and K_L is the Langmuir constant (L/mg). Langmuir's constant is commonly used to assess the appropriateness of adsorption treatments, and its basic properties are expressed through the dimensionless equilibrium parameter, R_L, which is used to predict the affinity between the active agent molecule and the sintering dust, expressed as the Eqs. (3) [33]:

$$R_L = \frac{1}{1 + K_L C_0} \tag{3}$$

C_0 is the initial concentration of the active agent molecule (mg/L), which was calculated using 1500 mg/L. The value of R_L provides important information about the nature of adsorption, which can be verified by the type of Langmuir isotherm as irreversible (R_L=0), favorable (0<R_L<1), linear (R_L=1), or unfavorable (R_L ≥1). The values of R_L for TX-100 and DTAB were respectively 0.07827 and 0.03224, which are in the range of 0.003~0.333, conforming to the Langmuir isotherm, indicating that both surfactants are favorable in the adsorption process, and the R_L

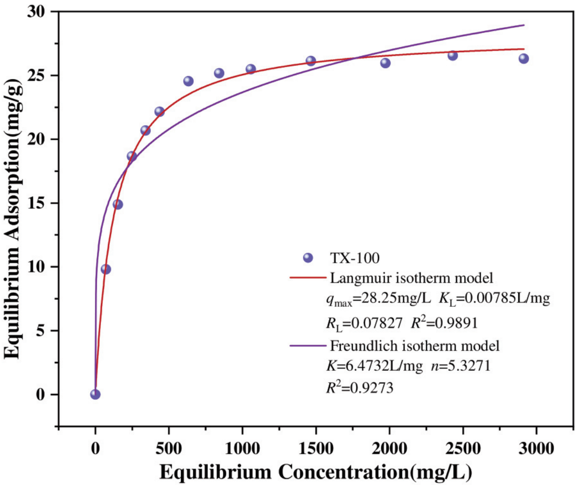


Figure 7. *Plot of equilibrium adsorption capacity (q_e) vs equilibrium concentration for the adsorption of TX-100 onto sintering dust*

value of DTAB is much lower, with a higher adsorption affinity with the surface of the sintering dust during the adsorption process.

The Freundlich adsorption isotherm is an empirical equation as shown in Eqs. (4). It assumes that the adsorption process is multilayer adsorption in a non-homogeneous phase system and that the adsorption at each adsorption site takes the form of individual adsorption conforming to the Langmuir adsorption isotherm, with an exponential decay in the energy distribution of the adsorption sites.

$$lnq_e = lnK_F + \frac{1}{n}lnC_e \tag{4}$$

Where K_F denotes the Freundlich isothermal adsorption coefficient (mg/g) related to the adsorption capacity and n is the Freundlich isothermal exponent that determines the isothermal nonlinearity, the higher the K_F value the more favorable the adsorption is, and for the favorable adsorption, the n value should be in the range of $1<n<10$ [34]. The K_F values of TX-100 and DTAB were 6.4732 and 11.4461 mg/L and n values were 5.3271 and 6.5759, respectively, which shows that both of them are favorable for adsorption.

Based on the R^2 values, the Langmuir model has a higher correlation coefficient, and the best-fitting model for both adsorption isotherms is Langmuir > Freundlich, which suggests that the interaction between surfactant molecules and sintering dust may be in the form of homogeneous monolayer adsorption on the surface of the sintering dust.

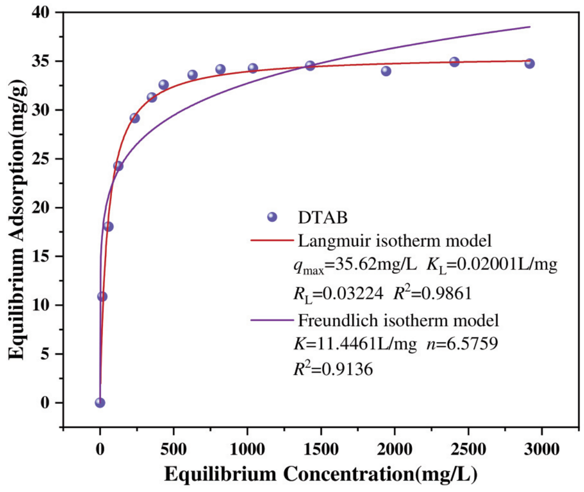


Figure 8. *Plot of equilibrium adsorption capacity (q_e) vs equilibrium concentration for the adsorption of DTAB onto sintering dust*

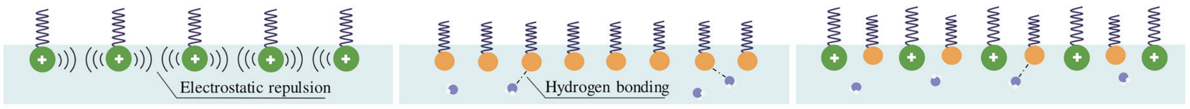
3.4.2. Gas-liquid interface adsorption layer

The arrangement of surfactant at the air-water interface can directly reduce the surface tension of the solution, thus reducing the energy barrier for dust particles to enter the droplet and improving the wetting efficiency. With the increase of surfactant concentration, the arrangement density at the air-liquid interface gradually increases, as shown in Fig. 9(a), the cationic surfactant has the same charge between them, there is electrostatic repulsion, and the adsorption layer arrangement density is relatively loose. While the nonionic surfactant itself is not charged, so there is no electrostatic interaction between the molecules, and its arrangement at the gas-liquid interface benefits from the hydrogen bonding with water molecules, and the arrangement density is higher, as shown in Fig. 9(b). However, as shown by the settling time, the wetting effect of cationic surfactants alone is better than when nonionic surfactants are used alone, probably because the HLB values of nonionic surfactants are usually smaller than those of cationic surfactants [35].

As shown in Fig. 9(c), since the adsorption mechanisms of the two surfactants at the gas-liquid interface are different, the nonionic surfactants can be interspersed and arranged between the cationic surfactants to reduce the electrostatic repulsion between them, and both of them produce a synergistic effect, which leads to a more compact adsorbent layer as a whole [36].

3.4.3. Solid-liquid interface adsorption layer

When the solid-liquid interface comes into contact with each other, the organic hydrophobic shell consisting of n-alkyl chains and aromatic groups reduces the surface energy of the sintering dust and hinders the wetting process, resulting in the formation of an oil film floating of the water. Adsorption of surfactants on sintering dust is physisorption, and there are a large number of hydrophobic sites on the hydrophobic shell, and there is a strong affinity with the hydrophobic group of surfactant, when the hydrophobic tail of surfactant adsorbed on the hydrophobic sites of the hydrophobic shell, the



(a) DTAB (b) TX-100 (c) B+C

Figure 9. *Adsorption state of surfactant molecules at the gas-liquid interface*

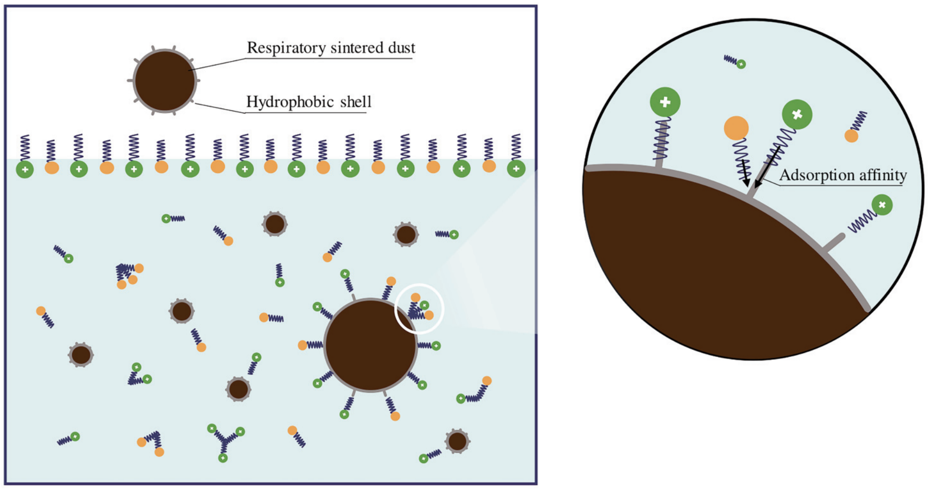


Figure 10. *Adsorption state of surfactant molecules at the solid-liquid interface*

hydrophilic head of the hydrophilic head outward, thus increasing the hydrophilicity of the sintering dust.

The adsorption process of both surfactants was favorable and conformed to the Langmuir model, whereas the stronger affinity of DTAB may be because its hydrophobic tail is a n-alkyl chain, which can interact with the alkyl group on the hydrophobic shell to form a hydrogen bond, whereas the presence of a benzene ring structure on the hydrophobic tail of TX-100 may interact weakly (π-π stacking) with the aromatic ring on the hydrophobic shell, so the more affinity DTAB adsorbs first [37]. When the adsorption site is saturated, the hydrophobic tails of the nonionic surfactant and the cationic surfactant are entangled and bonded because of hydrophobic interactions, which reduces the electrostatic repulsion between the cationic surfactants and further enhances the adsorption capacity on the hydrophobic shell, increasing the hydrophilicity. The wetting process of sintering dust in the compound surfactant solution is shown in Fig. 10.

4. Conclusion

The settling time of the surfactant mixtures solutions in different combinations and ratios was determined, and when DTAB and TX-100 were used in combination, there were synergistic effects under all conditions and the adsorption amount was higher than with the two alone. The best wetting effect was achieved with DTAB: TX-100=2:2 and an additional concentration of 0.3%, which reduced the settling time by 74% and 84.8%, respectively, and increased the adsorption capacity by 58.8% and 105.2%, respectively, compared with the two single-use cases.

The use of surfactant mixtures did not change structure of the functional groups of the sintering dust, but did change the relative content of functional groups, which was due to the adsorption of surfactants on the surface of the sintering dust. The content of hydrophilic groups increased significantly as the concentration of the surfactant mixtures increased.

The adsorption of surfactants conformed to the isothermal equation of Langmuir adsorption, and the cationic surfactant was more easily adsorbed on the surface of the sintering dust compared with the nonionic surfactant. When used in combination, the cationic surfactant adsorbed first, and after reaching the initial saturation, the hydrophobic tails of the nonionic surfactant and the cationic surfactant are entangled with each other due to hydrophobic interactions and share a common hydrophobic site, which reduces the electrostatic repulsion between the cationic surfactants and thus the adsorption density on the hydrophobic shell can be increased.

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Authors contributions

JianTao Ju (Writing - Review & Editing, Supervision, Methodology), Liule Wei (Writing - Original Draft, Data Curation), Qiang Bi(Conceptualization), YongWei Hu(Methodology)

Data availability

The data in this study involves the core production technology and original operational data of the enterprise. Strict confidentiality obligations must be *fulfilled, and the data cannot be disclosed to the public for the time being.*

Conflict of interest

No potential conflict of interest was reported by the author(s).

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UTICAJ ADSORPCIJE MEŠAVINA SURFAKTANATA NA KVAŠLJIVOST PRAŠINE IZ PROCESA SINTEROVANJA

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Apstrakt

Radi unapređenja kvašljivosti prašine nastale u procesu sinterovanja, ispitivan je mehanizam dejstva surfaktanta (površinski aktivne materije) Triton X-100 (TX-100), koji ostvaruje sinergijsko delovanje sa dodecil-trimetil-amonijum-bromidom (DTAB). Mereno je vreme taloženja za devet različitih tipova surfaktanata, na osnovu čega je određen optimalan odnos katjonskog i nejonogenog surfaktanta za sinergijsko poboljšanje kvašljivosti prašine iz sinterovanja. Adsorpcione karakteristike surfaktanata u mešovitom rastvoru i njihov uticaj na svojstva kvašenja prašine ispitani su sedimentacionim testovima, određivanjem količine adsorbovanih materija, FTIR spektroskopijom i merenjem zeta-potencijala. Rezultati su pokazali da se sinergijsko dejstvo ostvaruje pri mešanju DTAB i TX-100, te da je rastvor DTAB:TX-100=2:2, pri koncentraciji od 0,3%, imao dobar efekat kvašenja prašine iz sinterovanja. Sa porastom koncentracije mešavine surfaktanata povećavao se sadržaj hidrofilnih funkcionalnih grupa i apsolutna vrednost potencijala na površini čestica prašine. Pritom je na DTAB uticao alkilni međuodnos, što je rezultovalo većom adsorpcionom afinitetnošću, dok je hidrofobni rep TX-100 bio upleten sa hidrofobnim repom DTAB-a usled hidrofobnih interakcija, deleći isto adsorpciono mesto. Ova studija doprinosi izboru surfaktanata za efikasno kvašenje prašine iz procesa sinterovanja i pruža teorijsku osnovu za hidrometalurgiju i kontrolu emisije prašine.

Ključne reči: *Prašina iz sinterovanja; Nekatjonski surfaktant; Suzbijanje prašine; Kvašenje; Sinergijski mehanizmi*