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Preparation and Performance Analysis of a Spray Dust Suppressant for Coking Coal Dust

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Abstract: Coking coal dust has strong hydrophobicity, and it is difficult to combine with droplets in the air and settle. In order to improve the ability of droplets to collect coking coal dusts, a spray dust suppressant for coking coal dusts was studied. Based on monomer optimization and compounding experiments, two types of surfactant monomers, fatty alcohol ether sodium sulfate (AES) and sodium dodecyl benzene sulfonate (SDBS), were selected as the surfactant components for the dust suppressant. Meanwhile, the surfactant monomers were combined with four inorganic salts and the reverse osmosis moisture absorption of each solution was measured. By combining the results of both reverse osmosis moisture absorption and the water retention experiments, $CaCl_2$ was selected as the inorganic salt auxiliary component for the dust suppressant. Finally, the best concentration combination of the three components were obtained using orthogonal experiments, i.e., AES (0.05%), SDBS (0.03%), and $CaCl_2$ (0.6%). The dust suppressant solution constituted by this scheme had a high moisture absorption and great performance.

Keywords: Coking coal; Dust; Spray; Dust suppressant; Surfactant; Inorganic salt additive.

1. Introduction

Different amounts of dusts are generated in different processes of mines, such as coal mining and transportation. The suspended dusts in the air pose a serious threat to the health of workers and the safety of mines (Xu et al., 2019a; Ahmed et al., 2017; Zhou et al., 2018a; Wang et al., 2019g; Hua et al., 2020). According to the National Occupational Diseases Statistics Report issued by the National Health Commission of China, in recent years, the new cases of pneumoconiosis in China are mainly distributed in the coal mining and non-ferrous metal mining industries. The new pneumoconiosis cases in coal mining industry account for 40% of the total reported number of cases (Zhang et al., 2020; Vedal, 1997; Li et al., 2002; Bao et al., 2020; Yin et al., 2019). Therefore, it is urgent to take effective dust control measures to reduce the dust concentration in coal production sites (Nie et al., 2017a, b; Peng et al., 2019).

At present, dust reduction via spraying is the main technology for dust control in underground coal mines (Dey, 2012; Wang et al., 2019e, f; Han et al.; 2020a; Zhou et al., 2019). However, due to the large surface tension of ordinary spray water and the strong hydrophobicity of coal dust, the dust-reduction efficiency of spraying is generally low in coal mines (Wang et al., 2020a; Xu et al., 2018; Han et al., 2020). Some researchers have used surfactants in water to reduce the surface tension of water, thereby improving the wetting performance of the spray water (Yang et al., 2007; Tessum et al., 2017). Studies have shown that surfactants can significantly reduce the surface tension of water, and its reducing effect is related to the type and concentration of surfactants (Wang et al., 2019d; Omane et al., 2018). Tessum et al. (2014) investigated the trapping efficiency of charged dust particles by the droplets of different surfactant solutions. The experimental results showed that the type of surfactant can affect the trapping efficiency of charged particles. Non-ionic surfactants had a higher dust-trapping efficiency. Yang et al. (2014) found that the surface-active ions from the anionic surfactants were usually negatively charged and repelled the negatively-charged surface of coal dusts, which was not conducive to the adsorption of surfactant particles on the surface of coal dusts. As a result, the wetting ability of anionic surfactants was much poorer than non-ionic surfactants.

In addition, some researchers have worked on the research and development of new types of dust suppressants (Yan et al., 2020; Zhou et al., 2019; Fan et al., 2018; Hu et al., 2019). Tong (2013) and Jiang et al. (2013) concluded that the wetting performance of solution to coal dust can be improved by proper compounding through theoretical analysis and experiments. Li et al. (2010) developed a new type of dust suppressant by surfactant compounding method, and obtained the optimal concentration through orthogonal test. Experiments showed that the dust reduction efficiency of the new dust suppressant was 20% higher than that of clean water. Kilaua and Pahlman (1987) found that the addition of a metal inorganic salt to a surfactant solution can further improve the wetting properties of the surfactant solution. Subsequently, He et al. (2008), Du and Zeng (2002) studied the change in surface tension of surfactant solutions under the action of metal salts. Wu (2001) and others used experiments and theoretical analysis to study the effect of inorganic salt additives on the wetting performance of anionic surfactant solutions. The results showed that the addition of Na_2SO_4 to the anionic surfactant solution greatly improved the wetting ability of the solution. Li et al. (2016) compared the wettability of the sodium dodecyl sulfate (SDS) compound solution with 5 different additives and for the coal dusts through surface experiment, tension experiments, contact angle experiments, and reverse osmosis experiment.

As a type of bituminous coal, coking coal has stronger hydrophobicity than other types of coal dust, and it is difficult to combine with droplets. Thus the dust-capture effect of the traditional spraying technologies is extremely poor. In previous studies, the development of dust suppressants specifically for coking coal was rarely reported. In addition, in the formulation of dust suppressants, inorganic salts were rarely added as water-retaining agents and additives. In this study, two surfactant monomers were selected as the surfactant components of the dust suppressant for coking coal dusts through the monomer optimization and compounding experiments. At the same time, through the compounding of the surfactant monomer and the inorganic salt, the reverse osmosis moisture absorption of each solution was measured. By combining the results on the reverse osmosis water retention, an inorganic salt was selected as the auxiliary component of the dust suppressant. Finally, the optimal concentration combination of the three components was obtained by orthogonal experiments to obtain the formulation of a spray dust suppressant for coke coal dusts.

2. Materials and methods

2.1 Materials

Coking coal samples used in the experiment came from Shanxi Wanfeng Coal Mine. The coking coal of Shanxi Wanfeng Coal Mine had poor wetting performance, a large contact angle (88.76°), and was difficult to be wetted by water (Liu, 2006; Wang et al., 2019c; Zhou et al., 2018b; Luo et al., 2016). The coal sample was crushed by the pulverizer for 1 min, and sieved by a 150-mesh standard industrial sieve. The coal dust sample was dried in a vacuum dryer at the temperature of 80°C for 480 minutes. Then the coal dust sample was put into a sealed bag for later use. The industrial analysis indexes and characteristic particle sizes of the coal dusts samples are shown in Table 1. Figure 1 shows the contact angle and particle size distribution of coal dust samples.

Table 1. Industrial analysis and characteristic particle size of coal dust samples.

Coal quality	Mad(%)	Aad(%)	Vad(%)	FCad(%)	D_{10}(μm)	D_{50}(μm)	D_{90}(μm)
Coking coal	2.56	12.72	14.94	69.78	1.950	19.82	76.89

Note: Mad is air-dried base moisture; Aad is air-dried base ash; Vad is air-dried base volatile content; FCad is fixed carbon content; D_{10}, D_{50}, and D_{90} are characteristic particle sizes of coal dust, which represent particles smaller than this particle The particle size accounts for 10%, 50% and 90% of the total volume of all particles, respectively.

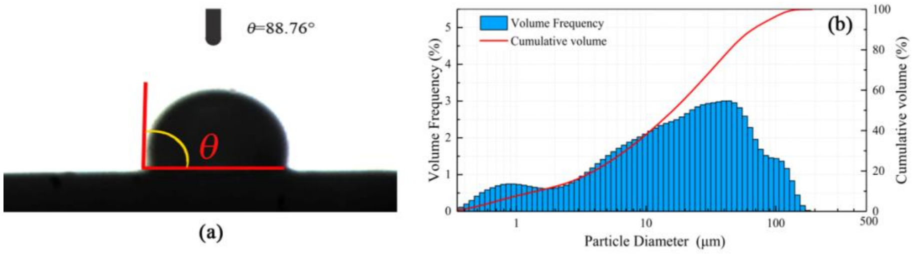

Fig. 1. Contact angle and particle size distribution of coal dust samples: (a) contact angle; and (b) particle size distribution.

If the spraying suppressants directly applied to the operation site of coal mine, it will directly contact the body of the coal mine workers. Thus there are strict requirements for the selection of surfactants. The selection of spraying suppressants for dusts should follow the principles including non-toxic, harmless, non-corrosive, and easily soluble in water; meanwhile, the selected suppressants should be economical and easy to transport. Based on the above principles, through market research and field investigation, 10 types of surfactants were preliminarily screened, as shown in Table 2.

Table 2. Types and specifications of surfactant.

Types	Reagent	Abbreviation	Molecular formula	Grade
Anionic	Fatty alcohol ether sulfate	AES	$C_{14}H_{29}NaO_5S$	AR
	Sodium lignosulfonate	SLS	$C_{20}H_{24}Na_2O_{10}S_2$	AR
	Sodium dodecyl benzene sulfonate	SDBS	$C_{18}H_{29}NaO_3S$	AR
Non-ionic	Polyoxyethylene sorbitan monooleate	Tween-80	$C_{64}H_{124}O_{26}$	CP
	Fatty alcohol polyoxyethylene ether	AEO-9	$RO(CH_2CH_2O)9H,R=12$	AR
	Polyoxyethylene sorbitan monolaurate	Tween-20	$C_{58}H_{113}O_{26}$	AR
Zwitterionic	Cocamidopropyl betaine	CAB-97	$C_{19}H_{38}N_2O_3$	AR
	Dodecyldimethylamine oxide	OB-2	$C_{14}H_{31}NO$	AR
Cationic	Cetyltrimethylammonium bromide	CTAB	$C_{19}H_{42}BrN$	AR
	Dodecyl dimethyl benzyl ammonium chloride	1227	$C_{21}H_{38}ClN$	AR

In the formulation of the dust suppressant, we can not only choose multiple surfactants for compounding, but also add some hygroscopic inorganic salts as additives to further improve the wetting and water retention properties of the solution (Tang et al., 2016; Kumar and Mandal, 2016). Hygroscopic inorganic salts and surfactants have different effects. Some can play a synergistic effect, and some can have an antagonistic effect. In this experiment, four types of hygroscopic inorganic salts, i.e., NaCl, $CaCl_2$, Na_2SO_4, and Na_2SiO_3, were selected. The effect of each inorganic salt and surfactant was analyzed, and the inorganic salt with optimal performance was selected.

2.2 Experimental scheme

2.2.1 Preparation scheme

(1)Surface tension experiments were used to investigate the ability of ten surfactant monomers to reduce the surface tension of the solution. At the same time, the contact angle and reverse osmosis experiments were used to investigate the performance of 10 types of surfactant monomer solutions in wetting coal dusts. A total of six surfactant concentrations were tested in the experiment, i.e., 0%, 0.00005%, 0.0005%, 0.005%, 0.05% and 0.5%. According to the experimental results of surface tension and wetting performance, 6 surfactant monomers were selected.

(2) The above selected 6 types of surfactant monomers were tested by a binary compounding experiment, and a reverse osmosis experiment was used to examine the performance of the compounded solutions, thereby obtaining an

optimal compounding scheme. In the binary compounding experiment, the concentrations of the six monomer surfactants were all set to 0.05%.

(3) Four inorganic salts were used to prepare the solutions with a mass fraction of 1%. The surfactant monomer in the preferred compounding scheme in step (2) was used to prepare a 0.05% solution. Then the surfactant monomer solution and the inorganic salt solution were binary compounded, and the wetting performance of the compounded solution was investigated by reverse osmosis experiment. Four types of inorganic salt solutions with equal mass and concentration were respectively added to the coal dust, and the water retention properties of the four types of inorganic salts were investigated. Based on the results of water retention and reverse osmosis experiments, an inorganic salt was selected as the auxiliary component of the dust suppressant.

(4) The three-factor three-level reverse osmosis orthogonal test was performed using the two surfactant monomers and one inorganic salt selected in the above binary compounding experiment. In addition, based on the ranges of the three factors and the comprehensive average of each level, the dust suppressant configuration scheme with better dust suppression effect for coking coal was obtained. The manufacturing process of dust suppressant is shown in Figure 2.

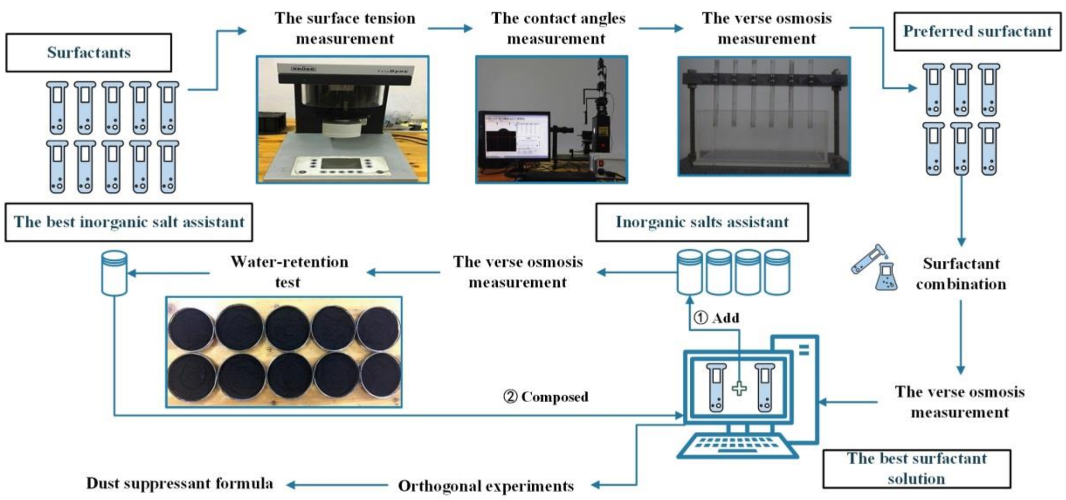

Fig. 2. Flow chart of the dust suppressant.

2.2.2 Parameter measurement method

(1) Surface tension experiment: The surface tension of the surfactant monomer and the compound solution was measured using a German Kruss K20 surface tension meter. The surface tension of all solutions was measured at 25°C. The hanging piece method was used in the experiment. During the measurement, first the platinum piece was placed and maintained vertically on the experimental table, and then the instrument was rotated to make the platinum piece coincide with the water surface. Then the minimum tensile force required for the platinum piece to leave the aqueous solution was measured.

(2) Contact angle experiment: 400 mg of pulverized coal was added to the mold, and the mold was placed in a desk-top powder tableting machine. A molding pressure of 50 MPa was applied and maintained for 1 minute to make a cylinder test piece with smooth surface and a thickness of about 2 mm. The contact angle of the solution in the coal dust sample was measured by the CA100B contact angle measuring instrument. Three test pieces were measured 3 times for each solution to obtain the average value.

(3) Reverse osmosis experiment: The self-designed reverse osmosis device was used to measure the moisture absorption performance of coal dust samples. First, 3 g of coal sample was put into a glass test tube with a diameter of 10 mm. The glass test tube was sealed with filter paper and weighed. Then the glass test tube was placed into a water tank, and the water was added to submerge in the glass test tube. After 2 hours, the glass test tube was taken out of the

tank and reweighed, then the water absorption by the coal dusts was calculated.

(4) Water retention experiment: The four inorganic salts, i.e., NaCl, $CaCl_2$, Na_2SO_4, and Na_2SiO_3, were used to prepare 1% solutions. 10 g of dry coking coal dust was placed in a petri dish, and 10 ml of each prepared solution was added and stirred. Then the petri dish was dried naturally at room temperature. The petri dish was weighed every 12 hours, and the moisture content of coking coal was calculated. The calculation method of the moisture content is shown in Equation (1).

$$\eta = \frac{m_2 - m_1}{m_1} \times 100\% \tag{1}$$

Where η is the moisture content, m_1 is the mass of the coal sample before wetting, m_2 is the mass of the coal sample after wetting.

3. Optimal selection of surfactants

3.1 Surface tension experiment

Table 3 shows the surface tensions of the ten surfactants used in the experiment under different mass fractions.

Table 3. Surface tension of 10 surfactants at 5 different mass fractions.

NO.	c_m(%)	AES	SLS	SDBS	Tween-80	AEO-9	Tween-20	CAB-97	OB-2	CTAB	1227
1	0	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3	71.3
2	0.00005	49.2	67.9	57.7	57.5	49.9	61.0	49.6	55.5	58.3	63.6
3	0.0005	47.5	62.0	47.8	49.1	43.9	49.2	43.0	46.8	47.6	56.2
4	0.005	30.3	55.1	27.9	44.2	30.9	38.1	36.3	31.1	39.8	49.7
5	0.05	29.1	51.4	27.8	43.5	30.5	36.5	35.4	30.0	36.6	47.0
6	0.5	30.3	48.9	27.6	39.9	30.1	35.4	35.1	29.4	35.0	45.6

The experimental results in Table 3 showed that the addition of a surfactant in water can reduce the surface tension of the solution to varying degrees. The amphiphilic structure of the surfactant molecules caused their positive adsorption on the surface of the aqueous solution, which significantly reduced the surface tension of the solution. The measurement results showed that for most coal dusts, the critical surface tension was about 45 mN/m (Wu, 2001). As can be seen from Table 3, the critical surface tension of some surfactants also exceeded 45 mN/m at the highest concentration (0.5%). For example, the critical surface tension of SLS was 48.9 mN/m and the critical surface tension of 1227 was 45.6 mN/m. Therefore, these two surfactants were not conducive to the wetting of coal dustsin coal mines and can be preliminarily ruled out.

Table 3 also shows that when the mass concentration of the surfactant in the solution is very low, the surface tension decreases sharply with the increase of the mass concentration. In addition, after the mass concentration reaches a certain value, the surface tension tends stable, and the concentration corresponding to the stable surface tension is defined as the critical micelle concentration (CMC) (Wang et al., 2020b; Jin et al., 2019). This is mainly because when the concentration of the amphiphilic molecules in the aqueous solution reaches a certain value, the interface adsorption reaches saturation, the amphiphilic molecules form colloidal aggregates in the aqueous solution, and the surface tension of the solution no longer decreases (Ma et al., 2004). In order to obtain the CMC value of each surfactant, the changing rates of the surface tensions of 10 types of surfactants were obtained in different concentration ranges, as shown in Figure 3.

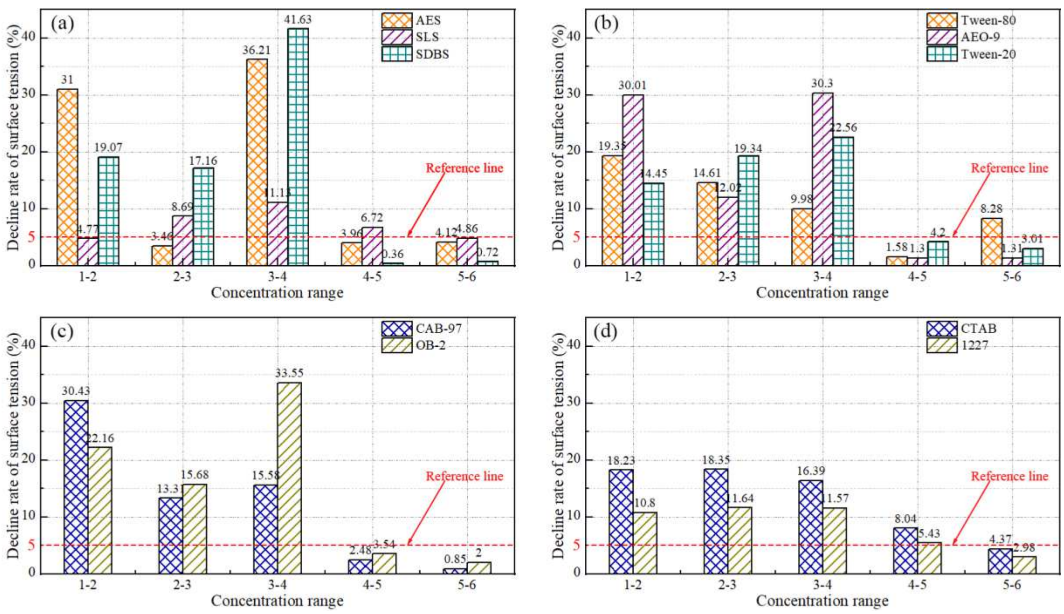

Fig. 3. Changing rates of the surface tensions of 10 surfactants in different concentration ranges: (a)a-SAA; (b)n-SAA; (c)z-SAA; (d)c-SAA.

Figure 3 shows that except for the non-ionic surfactant, Tween-80, thechanging rates of the surface tensionof the other nine surfactants are below 5%in the concentration range of 0.05% to 0.5%. The result proved that the CMC of Twee-80 was significantly higher than other surfactants. At the highest concentration, the corresponding surface tension valueof Twee-80 was close to 40 mN/m, which was close to the critical surface tension value of coal dust. Thus Twee-80 should not be selected as the dust suppressant. It can also be seen from Figure 3 that the CMC values of the six surfactants, i.e., AES, SDBS, Tween-80, AEO-9, Tween-20, CAT-97, and OB-2, are about 0.005%, while the CMC values of SLS, CTAB, 1227 are about 0.05%. From the experimental results on surface tension, three types of surfactants, SLS, 1227 and Tween-80, could be preliminarily excluded.

3.2 Wetting performance experiment

The wetting performance of a surfactant solution is closely related to its type and mass concentration. Figure 4 shows the contact angle and reverse osmosis moisture absorption of 10 types of surfactant solutions at different mass concentrations.

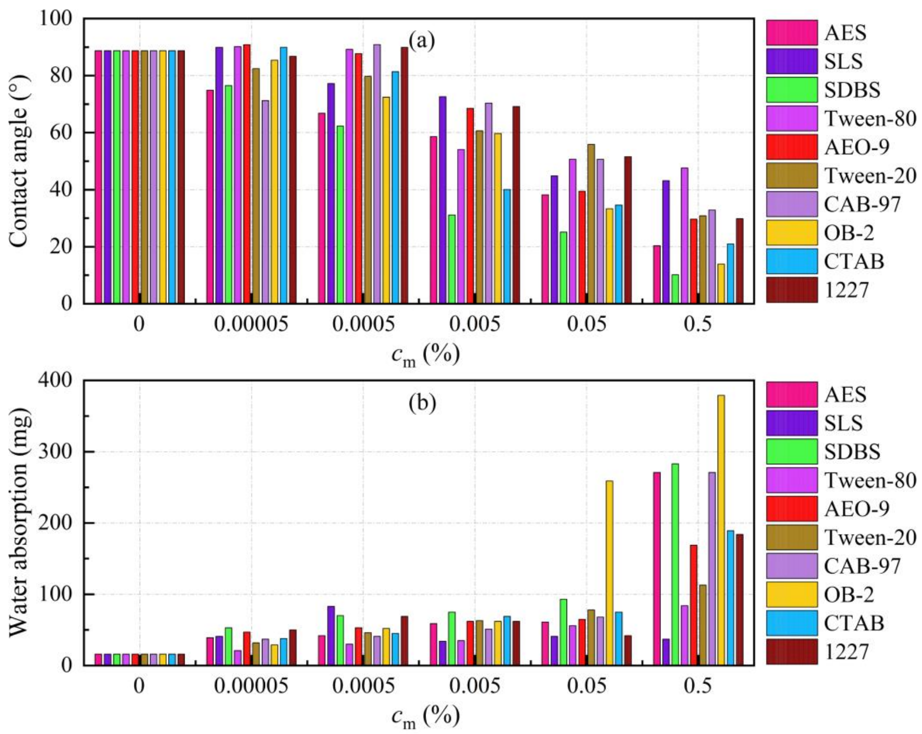

Fig. 4. Contact angle and moisture absorption of 10 surfactants: (a) contact angle; (b) moisture absorption.

It can be seen from Fig. 4(a) that as the mass concentration of the surfactant increases, the contact angle of the solution on the tablet surface continuously decreases. According to Young's equation, the relationship between the contact angle of a liquid on a solid surface and the interfacial tension is as follows:

$$\cos\theta = \frac{\gamma_{sg} - \gamma_{sl}}{\gamma_{lg}} \tag{2}$$

where θ is the contact angle (°), γ_{sg}, γ_{sl}, γ_{lg} are the solid-gas, solid-liquid, and liquid-gas interfacial tension (mN/m), respectively. When a surfactant is present in the solution, the adsorption of the surfactant at the solid-liquid and liquid-gas interfaces causes γsl and γlg to decrease greatly, thereby making the contact angle θ smaller, as shown in Figure 5.

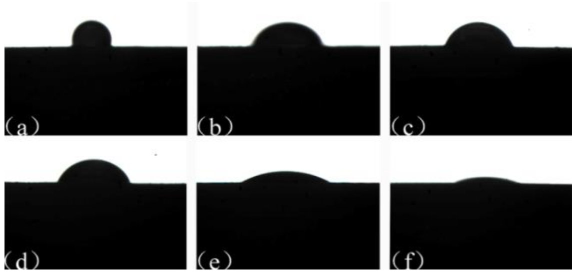

Fig. 5. Contact angle projection of coking coal in different SDBS mass fractions: (a) c_m=0; (b) c_m=0.00005%; (c) c_m=0.0005%; (d) c_m=0.005%; (e) c_m=0.05%; and (f) 0.5%.

The results of the reverse osmosis experiment in Fig. 4(b) show that the reverse osmosis moisture absorption of the ten surfactant solutions increases with the increase of the mass concentration. Comparing Figs. 4(a) and (b), it can be seen that the measurement results of the reverse osmosis hygroscopicity experiment and the contact angle measurement results basically have the same trend. By combining the results of contact angle experiment and reverse osmosis experiment, six surfactants wereselected based on the wetting performance: anionic AES and SDBS, nonionic AEO-9 and Tween-20, zwitterionic OB-2, and cationic CTAB.

The data of reverse osmosis moisture absorption and contact angle for the above-selected six types of surfactant monomers were curve-fitted using Origin 9.0 software. The fitting results are shown in Figure 6. Figure 6 shows that the amount of moisture absorption decreases with the increase of contact angle. In addition, the moisture absorption and the contact angle are negatively correlated with a correlation coefficient close to 0.85. This indicates that it is feasible to evaluate the wetting performance of a surfactant solution using both contact angle and reverse osmosis moisture absorption. The relatively high error in the contact angle experiment and the difficulties to produce the coke coal test piece caused high inconvenience to the experiment (Huang et al., 2010). Therefore, in the subsequent compounding experiments, only the reverse osmosis absorption was used to evaluate the wetting performance of the solution.

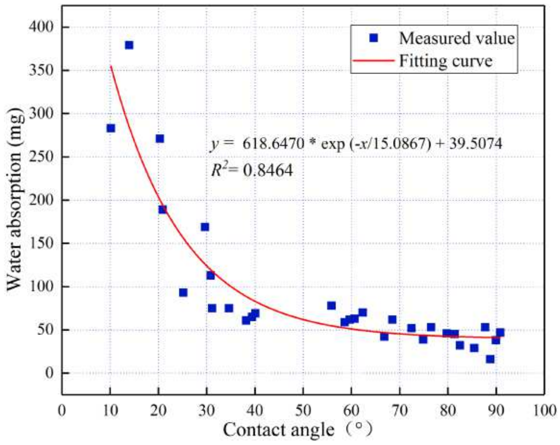

Fig. 6. Relationship between contact angle and moisture absorption.

4. Compounding experiment

4.1 Binary compounding of surfactants

A binary compound reverse osmosis experiment was conducted using the six monomer surfactants that were selected. The experimental results are shown in Table 4.

Table 4. Moisture absorption of surfactant binary compound solution.

NO.	0.05%	Types	Moisture absorption（mg）			Growth rate（%）
			The former	The latter	Compound	
1	AES+SDBS	A.+A.	61	93	116	24.73
2	AES+AEO-9	A.+N.	61	65	94	44.62
3	AES+20	A.+N.	61	78	84	7.69
4	SDBS+AEO-9	A.+N.	93	65	102	9.68
5	SDBS+20	A.+N.	93	78	90	-3.23
6	AES+OB-2	A.+Z.	61	95	98	3.16
7	SDBS+OB-2	A.+Z.	93	95	97	2.11
8	AES+CTAB	A.+C.	61	75	75	0.00
9	SDBS+CTAB	A.+C.	93	75	51	-45.16
10	AEO-9+20	N.+N.	65	78	108	38.46
11	AEO-9+OB-2	N.+Z.	65	95	98	3.16
12	20+OB-2	N.+Z.	78	95	90	-5.26
13	AEO-9+CTAB	N.+C.	65	75	95	26.67

14	20+CTAB	N.+C.	78	75	88	12.82
15	OB-2+CTAB	N.+C.	95	75	92	-3.16

Note: A. is Anionic surfactant; N. is Non-ionic surfactant; Z. is Zwitterionic surfactantt; C. is Cationic surfactant.

From Table 4, most of the compound solutions have stronger wetting effect and higher moisture absorption than the monomer solution (Zhang et al., 2019; Xu et al., 2019b). Considering the growth rate of moisture absorption, the four compounding schemes, i.e., Scheme 1 (AES + SDBS), Scheme 2 (AES + AEO-9), Scheme 10 (AEO-9 + 20), and Scheme 13 (AEO-9 + CTAB), were more effective. The wetting performance of the mixed solution was improved by more than 20% compared with the monomer. Based on further comparison, it can be found that the final moisture absorption of Scheme 1 was higher than the other three schemes. In view of the properties of each surfactant and the usage habits in coal mines, the two surfactant monomers in Scheme 1 were selected as the main components of the dust suppressant.

4.2 Inorganic salt additives experiment

Through the binary compounding experiments of surfactants, we selected AES and SDBS as two basic components of dust suppressant. Figure 7 shows the reverse osmosis experimentresults with two surfactant monomers (AES and SDBS) and inorganic salt additives. From Figure 7, after the surfactant AES was compounded with the four inorganic salts, the moisture absorption of coal dust was improved to varying degrees. This is because the surface of coal dust was composed of hydrophiliccrystal lattices and hydrophobic crystal lattices. The addition of a suitable surfactant can cause an adsorption effect on the hydrophobic lattice of the coal dust surface, thus improving the wettability of the coal dust (Zhao et al., 2011; Hu, 2014; Hapgood and Khanmohammadi, 2009). However, during the adsorption process, there was an electrostatic force between the surfactant and the charged ion layer on the surface of the coal dust, thereby limiting the adsorption of the surfactant on the surface of the coal dust. The ions ionized by the inorganic salt additives in the solution can reduce the action distance of the electrostatic force in the double-layer arrangement, increase the density of the adsorbed surfactant ions, and further improve the wetting ability of the surfactant to coal dust. Therefore, the coal dust reverse osmosis moisture absorption capacity was enhanced by the addition of the salt additives (Wang et al., 2020b; Zhan and Guo, 2013).

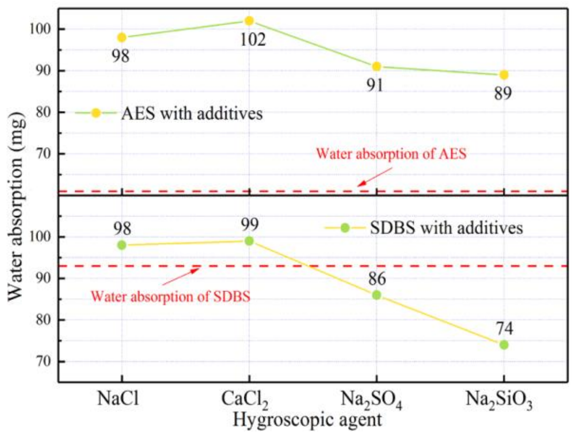

Fig. 7. The moisture absorption capacity of the solution of surfactant and inorganic salt.

From Figure 7, it can also be found that for anionic SDBS, compounding with salts does not lead to significant improvement in the wetting performance of solutions. Theincreasein the reverse osmosis moisture absorption caused by the addition of $CaCl_2$ and NaCl relative to the monomer solution rate did not exceed 10%. To make things worse, the two inorganic salts, Na_2SiO_3 and Na_2SO_4, even had an antagonistic effect with SDBS, and caused the moisture absorption of the compound solution to be lower than the monomer, which proved that these two inorganic salts were not suitable as additives. Therefore, in order to improve the wetting performance of the solution, the inorganic salts of $CaCl_2$ and NaCl were more suitable to be used as the additive of the dust suppressant.

Figure 8 shows the water retention experimentresults of four inorganic salt solutions. It can be seen from the figure that the coal dust without any inorganic salt has the fastestmoisture evaporation rate.After 132 hours, the moisture content was less than 5%. At the same time, the moisture content of coal dust with inorganic salts was higher than 15%. This is because after the coal dusts meet water, a large amount of water molecules are adsorbed on the surface of the coal dusts. The ions ionized from the inorganic salt in the solution enter the crystal layers of the coal dust through infiltration. The charge on the surface of coal dust and the ions adsorbed on the surface of the crystal will adsorb polar water molecules through exchange, and then form a water film on the coal dust surface. The formed water film can absorb and store a certain amount of water, thus improving the ability to resist evaporation (Wang et al., 2020b; Yao et al., 2017).

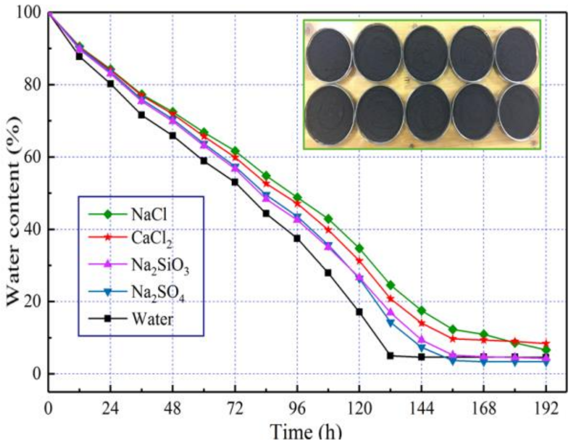

Fig. 8. Trend of moisture content of coal dust over time.

Before 168 hours, the moisture content of coal dust containing NaCl was higher than the other three inorganic salts. However, between 168 hours and 192 hours, the moisture content of NaCl coal dust was still decreasing, while the evaporation of theother three types of coal dustsbasically reached equilibrium between 156 hours and 168 hours. At 192 hours, the moisture content of $CaCl_2$ coal dust was the highest (8.40%), and the moisture content of the three coal dusts added with NaCl, Na_2SiO_3, and Na_2SO_4 were 4.88%, 4.55%, and 3.38%, respectively. From water retention experimentresults, it was found that $CaCl_2$ had the best water retention performance. The addition of $CaCl_2$ can slow the evaporation of water in coking coal dusts. Therefore, it is reasonable to choose $CaCl_2$ as an additive for the surfactant solution, which can further improve the wetting performance of the surfactant solution and also has good water retention. It is recommended to use this inorganic salt as the additive for the dust suppressant in engineering applications.

4.3 Orthogonal test

Through the previous compounding experiments, we identified AES, SDBS and $CaCl_2$ as the components of the dust suppressant. However, the optimal concentration of each component has not been determined. Orthogonal experiments were used to further determine the optimal compound concentration of the three components. The orthogonal table $L_9(3^3)$ was used in the three-factor, three-level orthogonal test. Table 5 shows the experimental results of the orthogonal test.

Table 5. Experimental results of Orthogonal test.

NO.	Factor			Experiment Index
	AES（%）	SDBS（%）	$CaCl_2$（%）	Moisture absorption（mg）

1	0.03	0.03	0.4	120
2	0.03	0.05	0.6	118
3	0.03	0.07	0.8	109
4	0.05	0.03	0.5	105
5	0.05	0.05	0.8	106
6	0.05	0.07	0.4	109
7	0.07	0.03	0.8	89
8	0.07	0.05	0.4	104
9	0.07	0.07	0.6	83

It can be seen from Table 5 that Scheme 1 is the best out of the 9 tested schemes. Using Scheme 1, the reverse osmosis hygroscopic mass was 120 mg. In order to further determine the influencing weights and optimal concentration levels of the three components, Table 6 lists the comprehensive average and range of reverse osmosis moisture absorption at each level.

Table 6. Comprehensive average and range of reverse osmosis quality.

Project		AES	SDBS	$CaCl_2$
Level	K1	115.7	106.7	92
	K2	106.7	109.3	102
	K3	92	100.3	101.3
R		23.7	9	10
Factor rank			SDBS> $CaCl_2$> AES	

Range is a key indicator to evaluate the importance of influencing factors. A larger range indicates that the factor has a greater influencing weight on the result (Sun et al., 2019; Li et al., 2019). On the contrary, a smaller range indicates a smaller influencing weight of the factor. From the results of the range analysis in Table 6, it can be seen that the three factors can be ordered based on the influencing weight on the reverse osmosis moisture absorption as follows: AES> $CaCl_2$> SDBS. From the comprehensive average calculation results in Table 6, it can be seen that K2 is the largest in the factor of AES, K1 is the largest in the factor of SDBS, and K2 is the largest inthe factor of $CaCl_2$. Therefore, in the recommended formulation, the concentrations of AES, SDBS and $CaCl_2$ are 0.05%, 0.03% and 0.6%, respectively. Using this formulation, the obtained solution had a reverse osmosis of 127 mg, which indicated that the solution had better wetting performance.

5. Conclusions

In this study, we first selected 6 surfactants from 10 types of surfactant monomers as the dust suppressant for coking coal dusts through surface tension, contact angle, and reverse osmosis experiments. Then the six selected surfactant monomers were binary compounded, and the wettability of the solution was investigated using the reverse osmosis moisture absorption capacity. Based on the results, SDBS and AES were determined as theoptimal components of dust suppressant. Then, SDBS and AES were compounded with four inorganic salts, and their wetting properties were investigated. By combing the wetting properties and the water retention properties of the four inorganic salt solutions, $CaCl_2$ was finally selected as the inorganic salt additive for the dust suppressant. Finally, three-factor three-level orthogonal experiments were used to obtain the optimal concentration combinations of the three components, i.e., AES (0.05%), SBS (0.03%), and $CaCl_2$ (0.6%). The dust suppressant solutionpreparedwith the above scheme has moisture absorption of up to 127 mg and good wetting performance.

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Figures

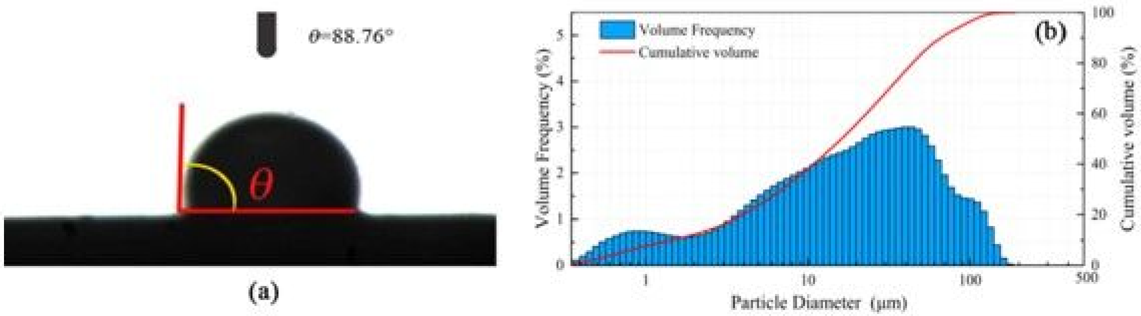

Figure 1

Contact angle and particle size distribution of coal dust samples: (a) contact angle; and (b) particle size distribution.

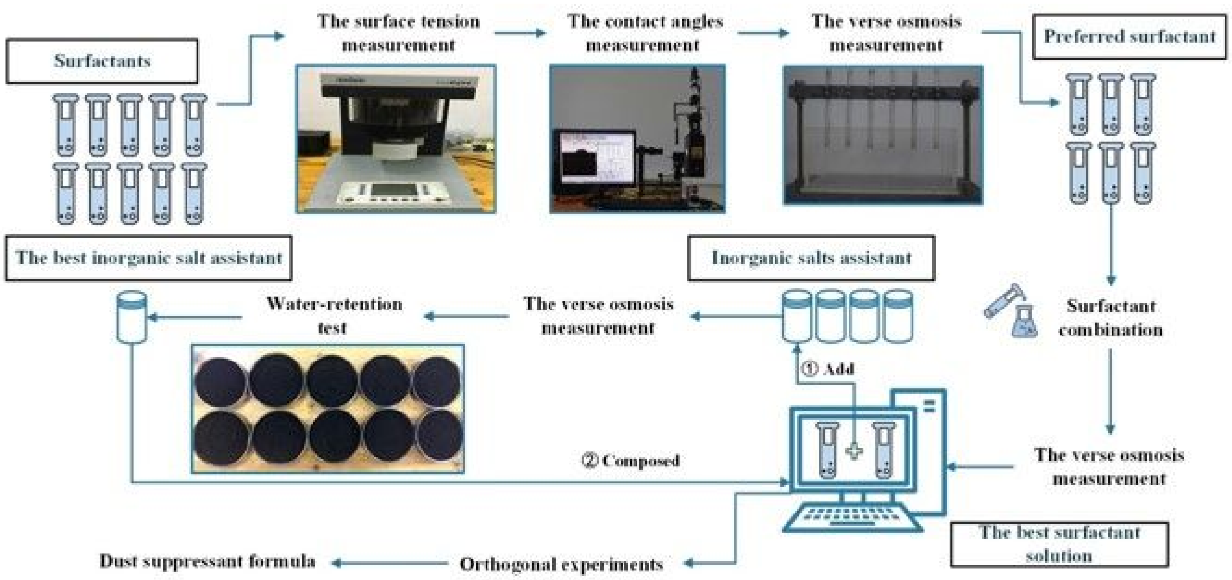

Figure 2

Flow chart of the dust suppressant.

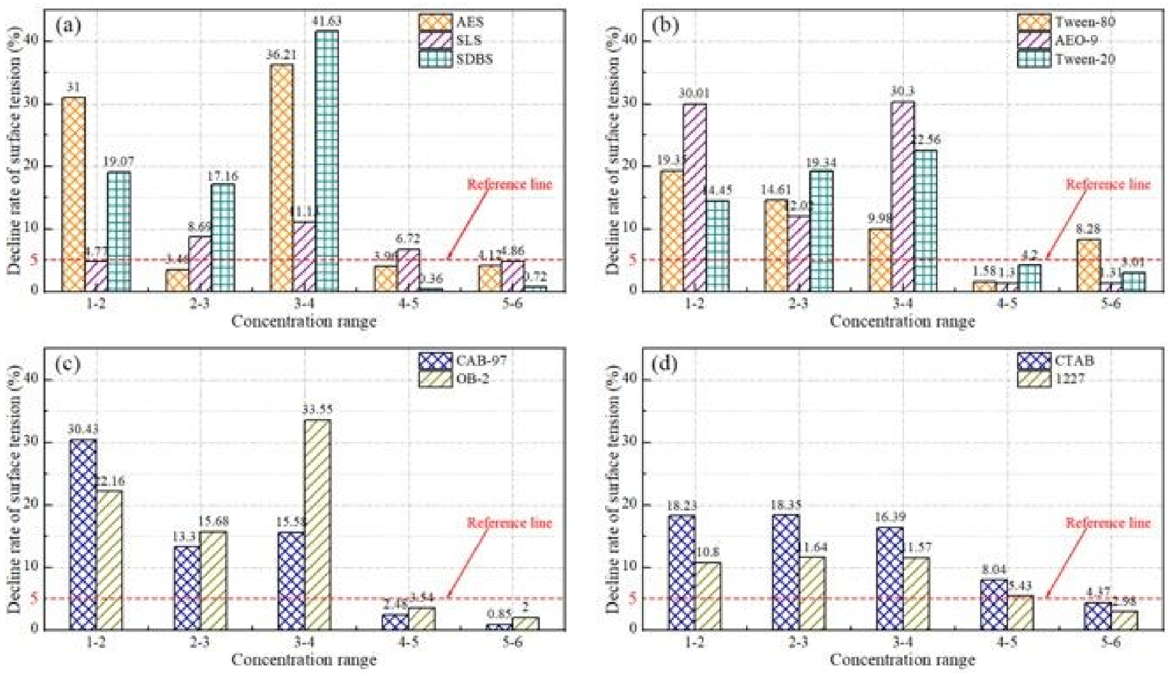

Figure 3

Changing rates of the surface tensions of 10 surfactants in different concentration ranges: (a)a-SAA; (b)n-SAA; (c)z-SAA; (d)c-SAA.

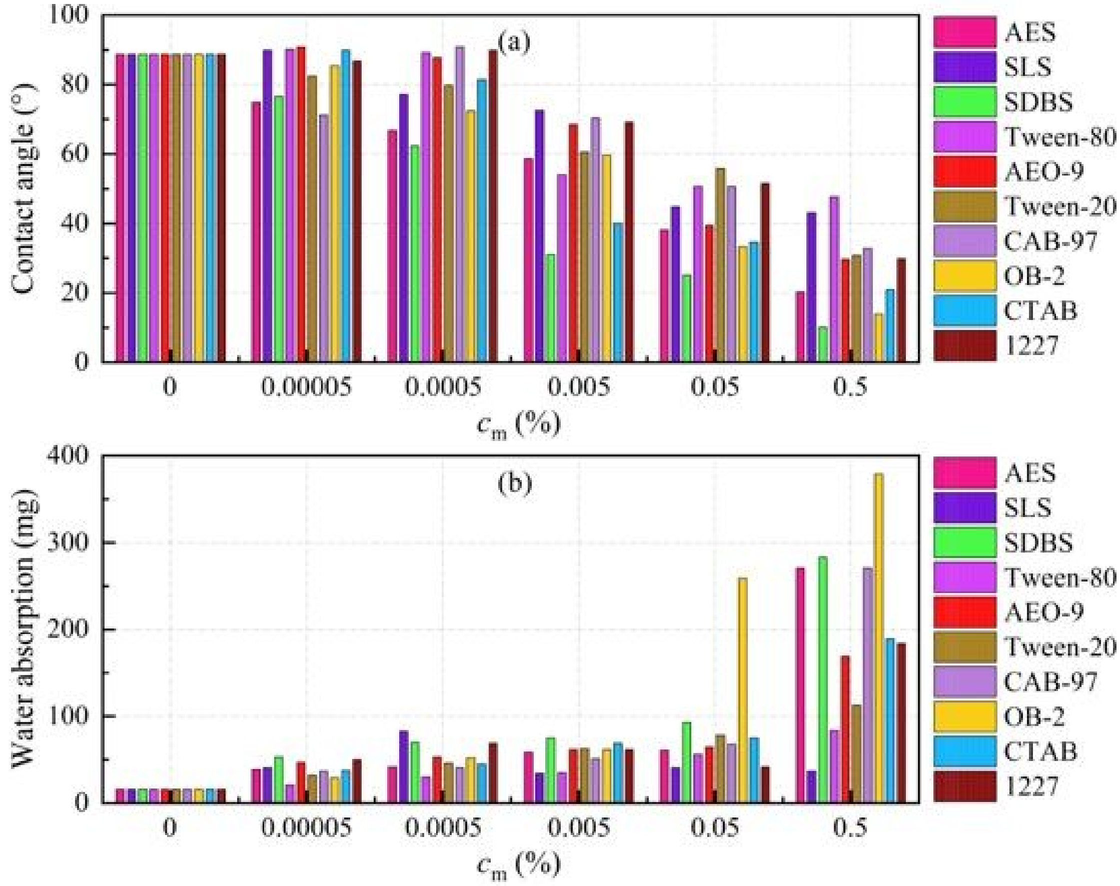

Figure 4

Contact angle and moisture absorption of 10 surfactants: (a) contact angle; (b) moisture absorption.

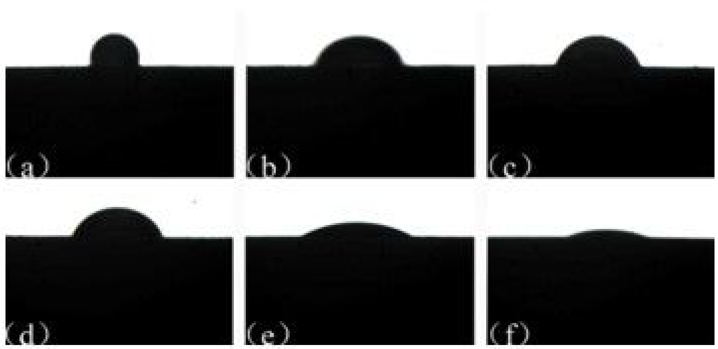

Figure 5

Contact angle projection of coking coal in different SDBS mass fractions: (a) cm=0; (b) cm=0.00005%; (c) cm=0.0005%; (d) cm=0.005%; (e) cm=0.05%; and (f) 0.5%.

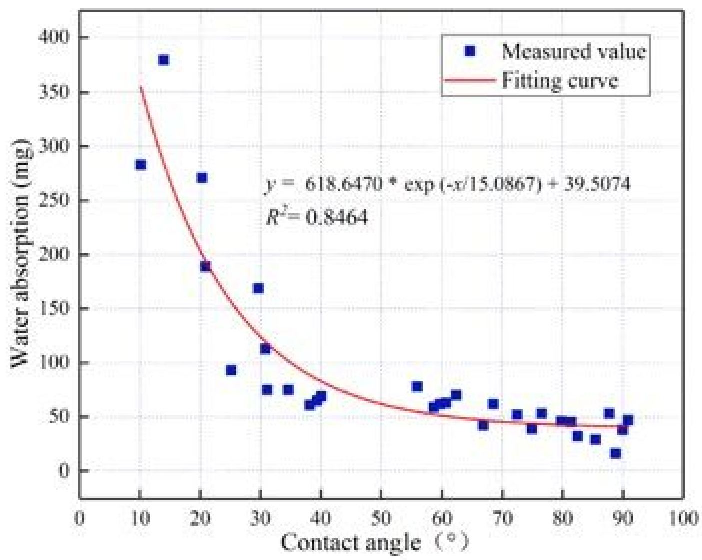

Figure 6

Relationship between contact angle and moisture absorption.

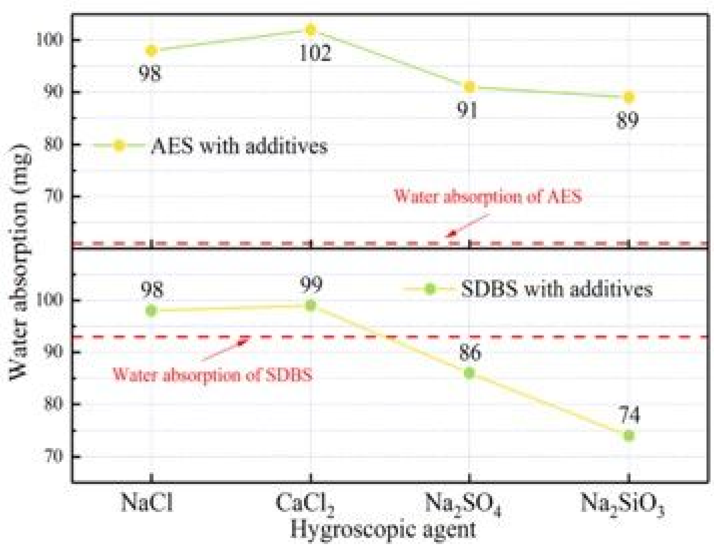

Figure 7

The moisture absorption capacity of the solution of surfactant and inorganic salt.

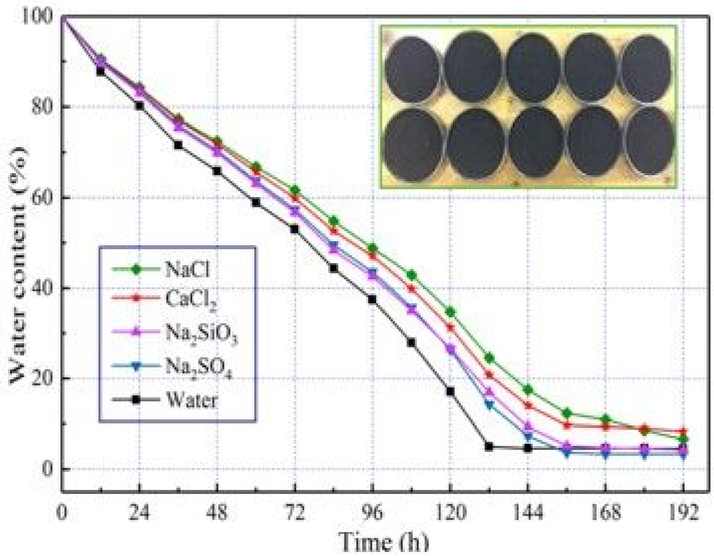

Figure 8

Trend of moisture content of coal dust over time.