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Physical and Chemical Characteristics of Explosive Dust at Large Open-Pit Coal Mines in Inner Mongolia, China and Dust Control Research

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Abstract: To further promote dust control efforts in Chinese open-pit coal mines, this study focuses on the research of coal dust and rock dust produced by different explosions in the Haerwusu open-pit coal mine in China. By investigating the relationship between the physical and chemical characteristics of dust particles from explosions in open-pit mines and the wetting properties of dust, the main factors influencing the wetting properties of explosive dust are identified. This provides a theoretical basis for subsequent dust control work in open-pit coal mines. Simultaneously, to formulate more effective dust suppressants and reduce explosive dust pollution, this study conducts experiments on the surface tension, contact angles, and complex solution compatibility to select suitable surfactants. Ultimately, the effectiveness of the dust suppressants is evaluated through permeability experiments and indoor dust suppression experiments. The research findings are as follows: (1) The significant factors affecting the wetting properties of coal dust are the fixed carbon content and *D50*, while the significant factor affecting the wetting properties of rock dust is *D50*. (2) The formulated dust suppressants can increase the permeation height of coal dust by at least 10 times, increase moisture absorption by at least 4 times, and reduce the TSP concentration by at least 81.4%.

Keywords: open-pit coal mine; blast pile dust; wettability studies; dust management; dust suppressant research

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1. Introduction

While coal plays a crucial role in driving economic and social development, it also brings a series of environmental pollution issues, and dust from open-pit mining is one of the most severe forms of pollution. During production operations, the accumulation of broken ore and rock fragments, resulting from blasting, is referred to as "explosive dust piles". These piles are susceptible to disturbances from factors such as wind and mining operations, leading to the suspension of substantial dust particles. As a consequence, this can cause damage to various parts of the human body, including the eyes and respiratory system, for the workers involved in these operations [1–3]. Currently, for the dust-producing scenarios in open-pit coal mining due to explosive piles, dust control measures involve the application of either water or dust suppressants to the dust-emitting points. When dealing with rock dust, the use of water alone is sufficient to achieve effective dust settlement [4]. However, when it comes to coal dust, its hydrophobic nature limits the effectiveness of using water alone for dust control [5]. Therefore, it is necessary to use dust suppressants as an auxiliary measure for coal dust control. Currently, many open-pit mining enterprises in China commonly purchase dust suppressants directly from the materials market. These types of dust suppressants are suitable for common dust-producing scenarios found in everyday life, such as dust on urban roads. However, when faced with dust-producing scenarios in open-pit mining, their specificity and effectiveness are limited. Therefore, there is a need for enhanced research on dust suppressants tailored to the requirements of open-pit mining scenarios. Presently, research on dust suppressants in open-pit coal mining predominantly focuses on road dust, with relatively fewer studies on dust suppressants for dust-producing scenarios like explosive piles. In contrast to road dust, dust from explosive piles is one of the primary sources of dust in open-pit coal mining. It is characterized by high dust production, extended durations of dust emissions, and sensitivity to mining and excavation activities, making it more challenging to control. Therefore, to reduce coal dust pollution from explosive piles, a comprehensive understanding of the physical and chemical properties of the original dust particles and the key factors affecting their wetting properties is essential. This will enable the development of a more targeted dust suppressant that is suitable for the dust-producing scenarios in Inner Mongolia's open-pit mines.

At present, numerous researchers have investigated the factors influencing the wetting properties of dust, with the aim of advancing new dust control technologies in coal mining. Wang [6] conducted a focused study on the wetting characteristics of respirable coal dust and the impacts of functional groups on its wetting properties. They found that respirable coal dust from different types of coal exhibited varying wetting properties. Jin [7] used the water flotation method to collect primary explosive dust from an open-pit copper mine and discovered that the particle size and pore structure were the main factors influencing its wetting properties.

In addition to the physical and chemical properties of dust particles themselves affecting their wetting properties, the type and nature of dust suppressants also play crucial roles in the wetting properties of dust and, consequently, the efficiency of dust control. Tessum [8] conducted a study on the capturing capacity of different types of surfactants for charged coal dust and found that the strength of the particle charge was closely related to the coal dust settling efficiency, with nonionic surfactants providing the best capture results in coal dust. Copeland [9] used glycol as a surfactant to enhance the wetting kinetics of fine particles by almost 99%, while the use of hygroscopic materials and high-oil asphalt reduced airborne dust by 58%. Over the past four decades, with ongoing research on dust suppressants, these suppressants have been classified into four major types based on their mechanisms, wetting-type, binding-type, agglomeration-type, and composite-type suppressants, each with their respective applications, advantages, and disadvantages, as shown in Table 1 [10]. Considering the characteristics of these four types of dust suppressants, this study ultimately chose to introduce wetting-type chemical dust suppressants into a water spray as the dust control method for open-pit coal mining explosive dust.

Table 1. Comparison of the performances of different types of dust suppressants.

Types of Dust Suppressants	Application Scenarios	Advantages of Dust Suppressants	Disadvantages of Dust Suppressants
Wetting Dust Suppressant [11]	It is often added to misting systems or fresh water to spray or sprinkle dust.	The wetting ability of water on dust can be improved by reducing the surface tension of water.	There is a lack of research on the mechanism of action of surfactant molecules at the microscopic level.
Bonded Dust Suppressant [12]	It is commonly used for dust control in open areas such as construction sites, open-pit mining roads, and stockyards.	Good dust fixing effect, low cost, relatively mature preparation technology.	Difficult to degrade, easily leaves residue, easily pollutes the environment.

Table 1. *Cont.*

Types of Dust Suppressants	Application Scenarios	Advantages of Dust Suppressants	Disadvantages of Dust Suppressants
Cohesive Dust Suppressant [10]	It is commonly used for dust control on roads, in material handling, and in warehouses.	Good moisture-absorbing and humidity-retaining powers, strong adhesion, prevents dust from lifting, and is anti-freezing in extreme weather.	Corrosive to work equipment, effect is greatly affected by the weather, high production and application costs, easily causes pollution.
Composite Dust Suppressant [13]	It is used in a wide range of scenarios, including the management of dust from construction sites, road surfaces, stockyards, living areas, etc.	Comprehensive functions, environmentally friendly, and economically beneficial.	Complex application scenarios make it difficult to achieve the desired results.

In order to further advance the dust control efforts in Chinese open-pit coal mines, this study focuses on the dust from explosive piles originating from different blasting steps in the Haerwusu open-pit coal mine in China. Through conducting physical and chemical tests on dust particles, this study aims to qualitatively and quantitatively analyze the influences of dust's physical and chemical characteristics on its wetting properties. Ultimately, the main factors affecting the wetting properties of explosive dust piles will be determined, providing a theoretical basis for subsequent dust control efforts in open-pit coal mining. To reduce dust pollution from explosive pile dust, this study employed an instrument called the "TeClis Tracker" for the surface tension and contact angle experiments. Using the measured surface tension and contact angle values as a basis, we provided guidance for the experiments with complex solutions. This approach enabled the selection of optimal wetting dust suppressant ingredients to formulate a dust suppressant that works best for explosive pile dust. Subsequently, we evaluated the dust suppression effects of the formulated suppressants based on permeability experiments and indoor spray dust reduction experiments. This work aims to improve the working environment on-site and reduce the harm of explosive pile dust to workers.

2. Materials and Methods

2.1. Selection of Materials

(1) Selection of dust sample materials

In this paper, we conducted sample collection by selecting blast piles from various blast stages at the Haerwusu open-pit coal mine in China. Six groups of dust samples, labeled as 1#, 2#, 3#, 4#, 5#, and 6#, are illustrated in Figure 1 below. Specifically, the first three groups (1#, 2#, and 3#) represent coal dust samples obtained from the 965th, 955th, and 935th blasting stages, respectively, at the Haerwusu open-pit coal mine. The remaining three groups (4#, 5#, and 6#) comprise rock dust samples collected from the 1055th and 1010th blasting stages and the 980th coal roof, also at the Haerwusu open-pit coal mine.

(2) Selection of surfactant materials and water-retaining materials

Surfactants and water-retaining materials should meet specific criteria, including cost-effectiveness, non-corrosiveness, easy solubility, and stable physicochemical properties during storage. Referring to the relevant papers [10,14–24], we identified nine types of wetting surfactants and three varieties of water-retaining inorganic salts that fulfill these requirements as raw materials, as outlined in Table 2. Additionally, the surfactants were prepared as solutions at mass fractions of 0.05 wt%, 0.1 wt%, 0.2 wt%, and 0.5 wt%, while the water-retaining inorganic salts were prepared as solutions at mass fractions of 0.5 wt% and 1 wt%, respectively.

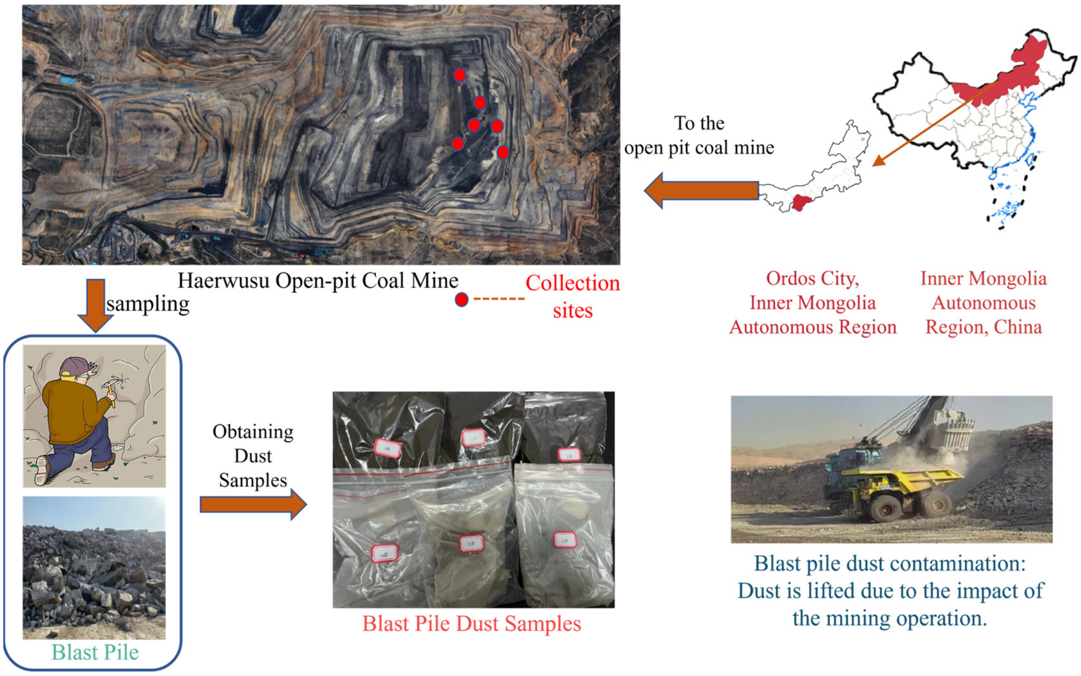


Figure 1. Location of sampling and samples.

Table 2. Materials with screening: surfactants and inorganic salts used for water retention.

No.	Names of Surfactants	Abbreviation for Surfactant	Properties of Surfactants
1	Alkyl polyglucoside	APG	nonionic
2	Cocoamidopropyl betaine	CAB-35	amphoteric ion
3	Isooctyl alcohol polyoxyethylene ether	JFC	nonionic
4	Cocamidopropylamine oxide	LAO-30	amphoteric ion
5	Dodecyl methyl oxazolidinium chloride	OB-20	amphoteric ion
6	Sodium dodecyl benzene sulfonate	SDBS	anion
7	Sodium dodecyl sulfate	SDS	anion
8	Polyethylene glycol sorbitan monostearate	Tween 80	nonionic
9	Sodium diethylhexyl sulfosuccinate	AOT	anion
10	Magnesium chloride	$MgCl_2$	inorganic salt
11	Sodium chloride	NaCl	inorganic salt
12	Sodium metasilicate	Na_2SiO_3	inorganic salt

2.2. A Study on the Testing Program of Physical and Chemical Characteristics of Dust from Open-Pit Mine Bursting Piles

(1) Particle size distribution test method

In this paper, we employed the Mastersizer 2000 laser particle sizer to conduct multiple tests on six sample groups, from which we derived average values for parameters linked to particle size distribution. Specifically, *D10*, *D50*, and *D90* represent the particle sizes at 10%, 50%, and 90% of the differential volume fractions of dust, respectively. The median particle size, denoted as *D50*, serves as a robust indicator of the dust particle size [5].

(2) Mineral Component Test Method

In this paper, six sets of dust samples were analyzed for mineral fractions (hereafter referred to as XRD) using an Ultima IV (Rigaku, Japan).

(3) Industrial Composition Test Methods

The industrial composition of coal is divided into four components: moisture, ash, volatile matter, and fixed carbon. The measurements were conducted according to the

Chinese standard, "GB/T 3521". For the determination of moisture, this paper adopted the loss on drying method; for the determination of ash, this paper adopted the 815 (±10) °C burning method for measurement; for the determination of volatile matter, this paper adopted the high temperature heating of 900 (±10) °C; and the corresponding measurements were made through the collection of volatile gases. For fixed carbon determination, its content was calculated using the following Equation (1):

$$FCad(FC) = 100 - (Mad + Aad + Vad) \tag{1}$$

In Equation (1), Mad, Aad, Vad, and $FCad$ are the air-drying base moisture, air-drying base ash, air-drying base volatile matter, and fixed carbon content measured in the experiment, respectively.

(4) Wettability Measurement Method

Wettability refers to the degree to which a liquid wets the surface of dust when they come into contact. Wettability can be assessed through surface tension tests and contact angle measurements, where smaller values of surface tensions and contact angles indicate better wetting of the liquid on the dust surface. This study conducted wetting experiments using an instrument called the "TeClis Tracker" to measure surface tension and contact angle values.

2.3. A Program of Studies on the Key Influences on the Wettability of Blast Pile Dusts

In order to investigate the key physical and chemical characteristics of the dust wettability factors, this paper firstly obtained the dust and water contact angle data and the physical and chemical characteristics of the first second after the contact data were obtained; this was carried out to conduct the correlation analysis so as to obtain the Pearson's correlation coefficient (r) of the contact angle of dust regarding the influence of the physical and chemical characteristics of the dust wettability factors. Subsequently, a multiple regression analysis was carried out to establish a multiple correlation regression model between the physical and chemical characteristics of the blast pile dust and the contact angle. Finally, a mathematical analysis was used to derive the key physicochemical characteristic factors affecting dust wettability.

2.4. Experimental Study of Inorganic Salt Compounding

2.4.1. Experiments on Water Retention of Compounded Solutions

To minimize the frequency of spraying and prolong the effectiveness of the dust suppressant, it is essential to introduce inorganic salts with water retention properties in addition to selecting appropriate surfactants. This combination forms a compound solution, thereby enhancing the dust suppressant's moisturizing capabilities.

Ten milliliters of three water-retaining inorganic salt solutions, each with mass fractions of 0.5 wt% and 1 wt%, were mixed with 10 g of dried 1#, 2#, and 3# coal dust to create test specimens. The mass of the Petri dish was measured at air-drying intervals of 3, 9, 21, 36, and 48 h, allowing for the calculation of the water loss rate for the three types of coal dust. This process was employed to identify the inorganic salts with the most effective water retention performance, using plain water as the experimental control group.

The calculation of water loss rate is shown in Equation (2):

$$X = \frac{M_1 - M_2}{M_2} \times 100\% \tag{2}$$

In Equation (2), X (%) is the water loss rate, and the lower the value, the better the water retention of the material; M_1 (g) is the initial mass of the wetted coal sample; and M_2 (g) is the mass of the coal sample at T moment.

2.4.2. Wetting Test of Compound Solution

The introduction of water-retaining inorganic salts, while notably enhancing the moisture-retaining qualities of the mixed solutions, may also impact the wettability of the surfactants. To assess whether the inclusion of water-retaining inorganic salts affects the wettability of the surfactants, the inorganic salts with the most effective water-retaining properties were once again used as the foundation for the mixture with the nine surfactants detailed in Table 2. Subsequently, the surface tension and contact angle values of the resultant mixtures were separately measured to determine whether the addition of the best water-retaining materials had any influence on the wettability of the surfactants.

2.5. Study on the Evaluation Method of Dust Suppression Effect

2.5.1. Chemical Dust Suppressant Permeability Test

The capillary reverse osmosis experiment aims to validate the penetrating effect of the optimally proportioned solution for each stage on the respective coal dust. After a 10 h experiment, measurements were taken for the dust wetting height and hygroscopic mass. Three experiments were conducted for each sample, and the average value was considered as the measurement result. Wetting height and moisture-absorbing mass serve as indicators of the reagents' penetration performance on the samples, with higher values indicating better penetration of the reagents on the samples [25–27]. Furthermore, plain water was used as the control group for coal dust.

2.5.2. Spraying Dust Reduction in Indoor Experiment

To assess the effectiveness of the developed dust suppressant on the corresponding coal dust, indoor experiments involving dust reduction through spraying were conducted to visually demonstrate the reduction effect. The process involved three key steps:

1. Pile Simulation: To mimic on-site explosion piles, coal and rock fragments were collected from the dust sample collection site and piled separately, and they were identified as a#, b#, and c# coal piles, and A#, B#, and C# rock piles.
2. Sample Application: A total of 200 g of each of the six dust samples were evenly spread over their respective piles. The optimal chemical dust suppressant for each coal pile was applied to the coal surfaces, while water was sprayed on the rock dust surfaces to simulate on-site dust suppressant spraying.
3. Wind Simulation: Wind speed was set to 3–5 m/s to replicate natural on-site conditions. Wind blew for 1 min, and a dust concentration meter was used to measure changes in $PM_{2.5}$, PM_{10}, and TSPs (Total Suspended Particles) concentrations of the dust before and after dust suppressant application. The dust reduction efficiency was calculated using Equation (3).

$$\eta = \frac{c_1 - c_2}{c_1} \times 100\% \quad (3)$$

In Equation (3), η (%) represents the dust reduction efficiency; c_1 (μg/m^3) represents the dust concentration before spraying; and c_2 (μg/m^3) represents the dust concentration after spraying.

3. Experimental Results and Discussions

3.1. Characterization of the Physicochemical Characteristics of Blast Pile Dust from Open-Pit Mines

3.1.1. Particle Size Distribution Analysis of Blast Pile Dust

The dust particle size correlation results for the six sets of dust samples are presented in Figure 2 and Table 3 below. As indicated in Table 3, based on the median particle sizes, *D50* and *D90*, it can be deduced that the overall particle size distribution of the three coal dusts is greater than that of the three rock dusts. Furthermore, Figure 2 illustrates that the proportion of respiratory dust particles smaller than 5 μm in the six dust sample groups falls within the range of a value that is higher than 10% and lower than 50%. This finding further suggests that the dust from explosive piles primarily consists of coarse particles, and the fraction of respiratory dust is relatively low. This respiratory dust tends to deposit quickly in the nasal cavity and has a relatively minor impact on the lungs [3].

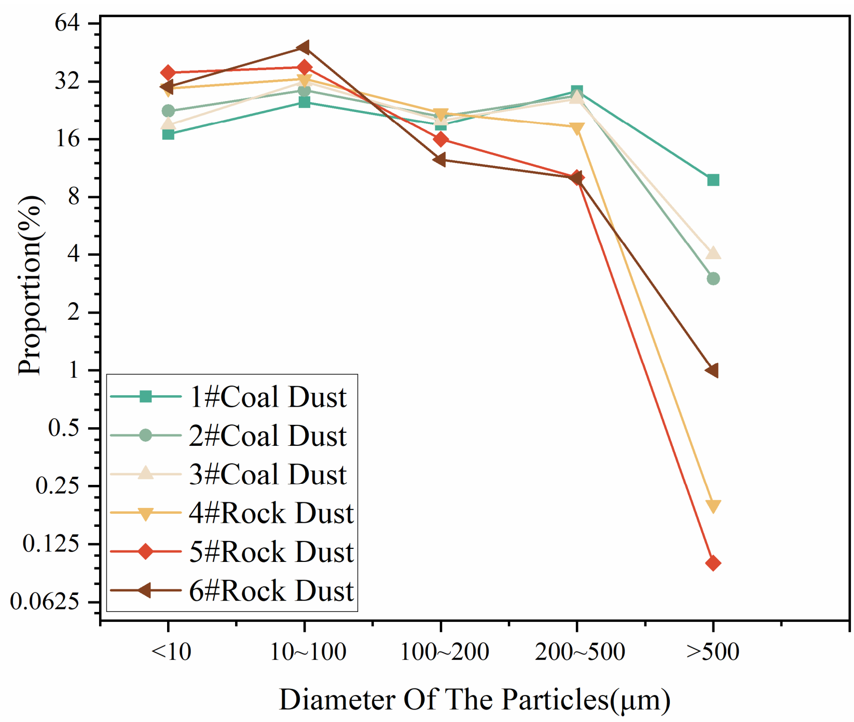


Figure 2. Particle size distribution of blast pile dust.

Table 3. Particle size composition of blast pile dust.

Dust Samples	*D10* (μm)	*D50* (μm)	*D90* (μm)	Specific Surface Area (m^2/g)
1# Coal dust	3.7	120.9	442.0	0.52
2# Coal dust	2.1	114.4	429.9	0.51
3# Coal dust	2.7	110.2	417.9	0.50
4# Rock dust	3.4	77.9	370.8	0.76
5# Rock dust	3.3	73.9	350.5	0.72
6# Rock dust	2.06	71.9	330.3	0.70

3.1.2. Industrial Analyses of Blast Pile Dust

The industrial analysis results for three groups of coal dust are displayed in Table 4. Based on the data in Table 4, there appears to be a correlation between the *Mad*, *Aad*, and *FCad* contents of the coal dust. Specifically, as the *Fcad* content increases, both the Aad and Mad contents tend to decrease. Furthermore, given that the *Fcad* content falls within the range of 40% to 51%, it can be inferred that the coal quality of the three coal dust groups corresponds to lignite. Lignite typically possesses characteristics such as a relatively short coal formation time, a low degree of coalification, and limited hydrophilicity [2].

Table 4. Results of industrial analyses of coal dust.

Types of Coal	Coal Sample No.	*Mad* (%)	*Aad* (%)	*Vad* (%)	*FCad* (%)
brown coal	1# Coal Dust	5.95	18.27	32.60	43.18
	2# Coal Dust	5.45	17.12	30.70	46.73
	3# Coal Dust	5.18	16.86	27.74	50.22

Finally, when combining Tables 3 and 4, it becomes evident that as the *Fcad* content in the coal dust increases, the specific surface area decreases. Generally, a smaller specific surface area value in the dust particles indicates a less developed internal pore structure. This underdeveloped pore structure reduces the ability of dust particles to retain water molecules. Consequently, we can infer that the hydrophilicity is the poorest in the case of the 3# coal dust, while the 1# coal dust exhibits the best hydrophilicity.

3.1.3. XRD Analysis of Explosive Pile Dust

The XRD results are provided in weight percentage, and the outcomes are illustrated in Figure 3 below. As evident from Figure 3, all three sets of coal dust contain calcite ($CaCO_3$), kaolinite ($Al_2Si_2O_5(OH)_4$), and boehmite ($AlO(OH)$), and in addition, the 1# coal dust also contains a small quantity of quartz (SiO_2).

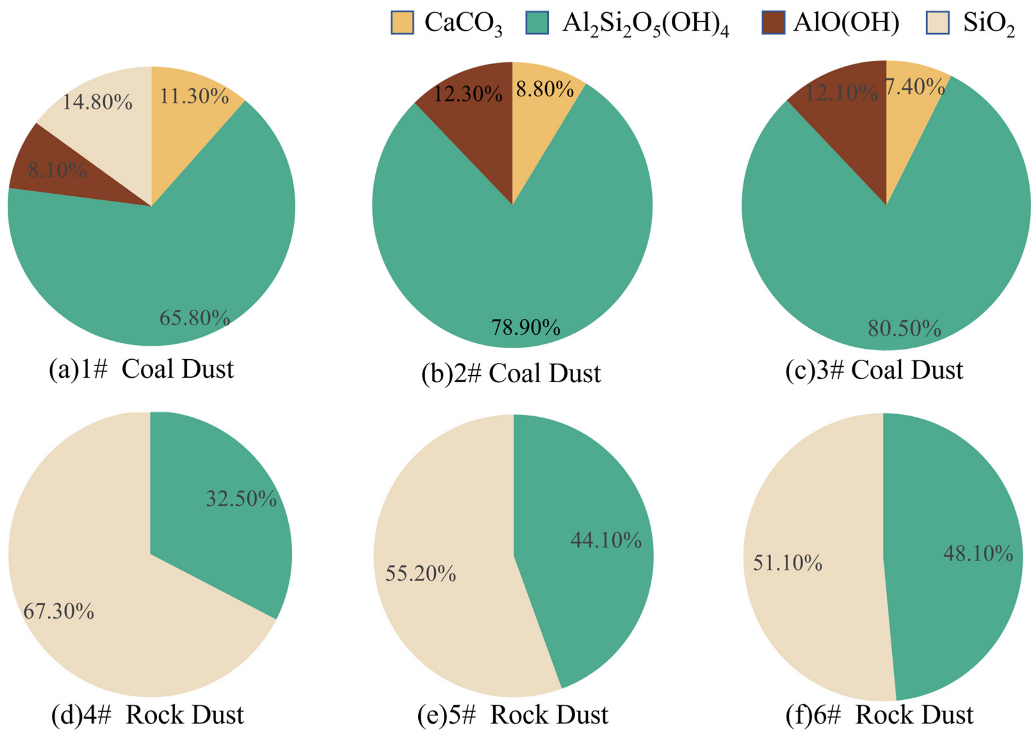


Figure 3. XRD analysis results of dust. (Subplots a–c show the XRD results of the three coal dust samples, and subplots d–f show the XRD results of the three rock dust samples).

In all three types of rock dust, quartz and kaolinite are the predominant constituents. It is well documented [28] that quartz is a hydrophilic substance, meaning it can be readily wetted with water and possesses good wettability. On the other hand, kaolinite is a hydrophobic substance and exhibits inferior wettability. Given that the quartz content in rock dust exceeds that in coal dust, it can be deduced that rock dust has better wettability than coal dust. This implies that the dust reduction effect can be achieved by using water alone for rock dust, as it readily wets the surfaces due to the higher proportion of hydrophilic quartz.

3.2. Physicochemical Characteristics of Blast Pile Dust in Relation to Wettability

A Pearson correlation analysis was conducted 100 times for the various physicochemical characteristics of the dust and contact angle data. The Pearson correlation coefficients and significance values are presented in Table 5. All of the significance values (p) are less than 0.05, indicating that the experimental results are statistically significant.

(1) Effect of particle size distribution on wettability

Table 5. Results of Pearson's correlation coefficients and significant values of dust contact angle with respect to various physical and chemical properties of dusts.

Physicochemical Characteristics of Dust		Pearson Correlation Coefficient (r)		*p*
		Contact Angles of Coal Dust	**Contact Angles of Rock Dust**	
Particle Sizes (μm)	*D10*	0.68	−0.85	<0.05
	D50	−0.93	−0.98	<0.01
	D90	−0.95	−0.97	<0.01
Specific Surface Area (m^2/g)		−0.91368	−0.91	<0.01
Content Of Industrial Components (%)	*Mad*	−0.94	/	<0.01
	Aad	−0.91	/	<0.01
	Vad	−0.98	/	<0.01
	FCad	0.98	/	<0.01
Mineral Composition Content (%)	Kaolinite	0.96	0.96	<0.01
	Quartz	−0.97	−0.97	<0.01
	Calcite	−0.52	/	<0.05
	Boehmite	0.47	/	<0.05

From Table 5 and the correlation coefficient (r), it is evident that the contact angle is strongly negatively correlated with *D50* and *D90* for both coal dust and rock dust. This suggests that as the dust particle size increases (*D50* and *D90* values increase), the contact angle decreases, indicating improved hydrophilicity. There is no significant correlation between the contact angle and *D10* for both coal dust and rock dust. This lack of correlation is attributed to the fact that *D10* only represents 10% of the volume of all particles, which does not effectively depict the overall particle size distribution of the dust. Additionally, its randomness makes it unrepresentative in this context.

(2) Effect of specific surface area on wettability

As can be seen from Table 5, the contact angle and the mass specific surface area of coal dust and rock dust both showed a significant negative correlation, in which the correlation coefficients (r) were −0.91368 and −0.96336, respectively, indicating that the larger the specific surface area of the coal dust and rock dust, the smaller the contact angle, and the better the hydrophilicity.

(3) Effect of industrial composition of coal dust on wettability

As indicated in Table 5, the contact angle exhibits a negative correlation with the moisture, ash, and volatile matter. This suggests that higher contents in these three components result in a smaller contact angle, signifying improved wettability. Conversely, the contact angle displays a significantly positive correlation with the fixed carbon content, meaning that a higher fixed carbon content leads to a larger contact angle and decreased wettability. This relationship highlights the significant influence of the coalification level on the wettability. This effect is attributed to an increase in the number of condensed aromatic rings and a decrease in the weakly stabilized side chains and bridging chains in coal molecules during the coalification process, ultimately resulting in poorer wettability of the coal [28,29].

(4) Influence of mineral fractions on wettability

As all three coal dusts and rock dusts contain kaolinite ($Al_2Si_2O_5(OH)_4$), the 1# coal dust and all three rock dusts contain quartz (SiO_2), and all three coal dusts contain calcite ($CaCO_3$) and boehmite ($AlO(OH)$), we performed an extended correlation analysis of the contact angle and mineral components, creating four combinations:

(a) Contact angle data of three types of coal dust with three types of rock dust—kaolinite content;
(b) Contact angle data of 1# coal dust and three types of rock dust—quartz content;
(c) Contact angle data for three types of coal dust—calcite content;
(d) Contact angle data for three types of coal dust—boehmite content.

The results of the Pearson's correlation coefficient (r) are provided in Table 5, leading to the following analyses:

The two substances in combination (a) show a significant positive correlation, indicating that the larger the proportion of kaolinite in the dust mineral fraction, the poorer the wettability of the dust, which is consistent with the hydrophobic mineral property of kaolinite [27].

The significant negative correlation between the two substances in combination (b) indicates that the larger the proportion of quartz in the dust mineral fraction, the better the wettability of the dust, and this result is consistent with the hydrophilic mineral property of quartz [30].

In combination (c) and combination (d), the contact angle of coal dust is weakly correlated with the contents of calcite ($CaCO_3$) and boehmite (AlO(OH)), which suggests that calcite or boehmite has a weak effect on the overall wettability of coal dust, which may be due to the fact that the total contents of calcite or boehmite are too low (<15%).

In summary, the correlation between the kaolinite, quartz, and dust contact angles is much stronger than that of calcite and dolomite. From this, we can infer that kaolinite and quartz are the primary minerals affecting the wetting properties of coal dust in the open-pit coal mines of Haerwusu.

3.3. Analysis of Key Influencing Factors on the Wettability of Blast Pile Dusts

3.3.1. Analysis of the Key Factors Influencing the Wettability of Blast Pile Coal Dusts

Regression modeling was carried out on each physical and chemical characteristic parameter of the coal dust and the contact angle data, and the results of the model correlation test are shown in Table 6 below.

Table 6. Coal dust modeling related test results.

Model Parameter	Unstandardized Coefficient		Standardized Coefficient	F-Test		T-Test		Coefficient of Determination (R^2)
	B	Standard Error	Beta	F	p	T	p	
Constant	45.461	18.163	/	276.79	<0.01	2.503	0.046	0.989
FCad	1.348	0.119	0.837			11.32	<0.01	
D50	−0.078	0.031	−0.185			−2.503	0.046	

During the stepwise regression modeling process, we observed that among the particle size distribution parameters (*D10*, *D50*, *D90*, and specific surface area), the *D50* content had the most significant impact on the wettability of the coal dust. Among the other physicochemical characteristics, the FCad content had the most substantial influence on the wettability of the coal dust.

Based on the above analysis, the regression equation between the independent and dependent variables was derived as follows:

$$\theta_c = 45.461 + 1.348 \times FCad - 0.078 \times D50 \tag{4}$$

In Equation (4), θ_c (°) is the coal dust contact angle; $FCad$ (%) is the fixed carbon content; and $D50$ (μm) is the median particle size.

The F-test of the constructed model shows that $p < 0.05$, which indicates that the linear relationship of the model is significant; the T-test of the model shows that the p. of each parameter in the model is less than 0.05, which indicates that each parameter is significant; and the coefficient of determination (R^2) of the model is 0.989, which indicates that the constructed model is extremely well fitted.

In summary, the median particle size (*D50*) of the coal dust and the fixed carbon content in the coal dust composition are significant factors affecting the wettability of coal dust.

3.3.2. Analysis of the Key Factors Influencing the Wettability of Blast Pile Rock Dusts

Regression modeling was performed on the contact angle data of the rock dust with respect to the various physicochemical parameters. The modeling results are presented in Table 7.

Table 7. Rock dust modeling-related test results.

Model Parameter	Unstandardized Coefficient		Standardized Coefficient	F-Test		T-Test		Coefficient of Determination (R^2)
	B	Standard Error	Beta	F	p	T	p	
Constant	69.636	2.394	/	195.257	<0.01	29.09	0.000	0.965
D50	−0.451	0.032	−0.983			−13.97	0.000	

The F-test of the constructed model shows that $p < 0.05$, which indicates that the linear relationship of the model is significant; the T-test of the model shows that the p of each parameter in the model is 0.000, which is less than 0.01, which indicates that the median particle size of the rock dust, *D50*, plays a significant role in the contact angle; and the coefficient of determination (R^2) of the model is 0.965, which indicates that the constructed model is extremely well fitted.

Based on the above analysis, the regression equation between the independent and dependent variables was derived as follows:

$$\theta_r = 69.636 - 0.451 \times D50 \quad (5)$$

In Equation (5), θ_r (°) is the rock-dust contact angle, and *D50* (μm) is the median particle size.

As shown in Equation (5), the median particle size *D50* of the rock dust is the most significant factor affecting the wettability of the rock dust.

3.4. Analysis of Surfactant Screening Results

To initially assess the surfactants, experiments involving the surface tension and contact angle measurements were conducted on the prepared surfactants. These experiments aimed to evaluate the extent to which the various surfactants wet the three types of coal dust. The results helped to determine the effectiveness of each surfactant in terms of its wetting performance on the coal dust samples, thus allowing for an assessment of the surfactants' performances.

(1) Analysis of the results of surface tension experiments

The experimental results for the surface tensions of various surfactants at different mass fractions are presented in Table 8 below. It is important to note that coal surfaces are characterized as low-energy surfaces, and the critical surface tension (γc) required for effective wetting is approximately 45 mN/m. Therefore, for the improved wetting of coal dust, the surface tension of the surfactant should be lower than γc [31].

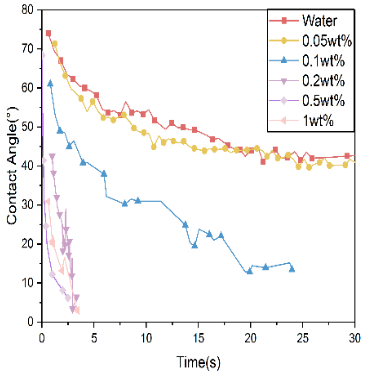
Table 8. Surface tensions of surfactant solutions with different mass fractions.

Surfactant Mass Fraction	Surface Tension ($mN\cdot m^{-1}$)								
	APG	CAB-35	JFC	LAO-30	OB-20	SDBS	SDS	Tween 80	AOT
0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0	73.0
0.05	36.7	40.6	58.8	36.0	39.7	66.7	32.9	54.9	25.9
0.1	35.5	40.2	38.4	31.4	33.9	60.8	30.5	51.7	25.0
0.2	30.4	39.0	32.3	30.0	29.5	45.9	30.3	50.2	21.7
0.5	29.5	36.8	29.6	28.7	29.5	31.7	32.8	50.0	23.4
1	29.2	36.6	28.6	29.8	28.9	29.1	32.4	46.9	24.0

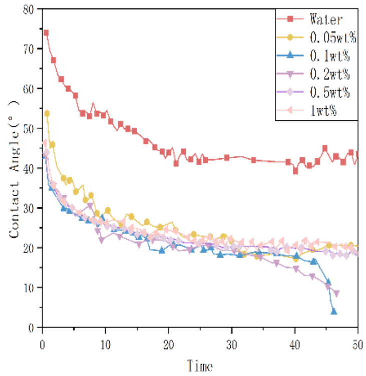
Among the tested surfactants and their mass fractions, the findings regarding their ability to achieve a surface tension below the critical surface tension (γc) of 45 mN/m are as follows: (a) APG, CAB-35, LAO-30, OB-20, SDS, and AOT were able to reach surface tension values below γc at a mass fraction of 0.05 wt%; (b) JFC could attain surface tension values below γc at mass fractions exceeding 0.1 wt%; (c) SDBS demonstrated surface tension values below γc at mass fractions exceeding 0.2 wt%; and (d) Tween, however, did not achieve surface tension values lower than γc at any of the five mass fractions tested.

(2) Analysis of the results of contact angle experiments

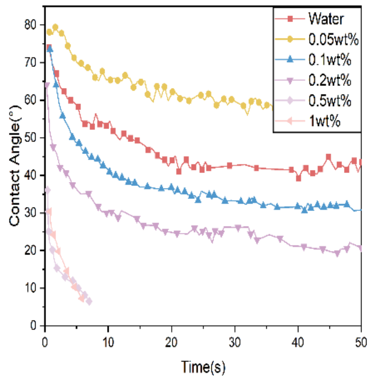
The results of the contact angle measurements for the 1#, 2#, and 3# coal dusts with different surfactant solutions at five mass fractions are displayed in Figures 4–6, respectively.



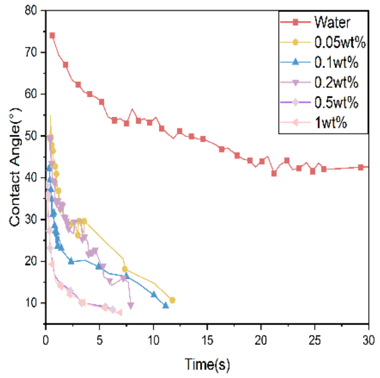
(**a**) APG



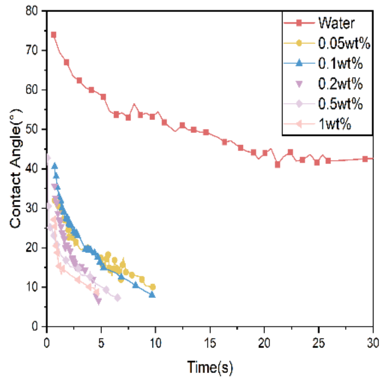
(**b**) CAB-35



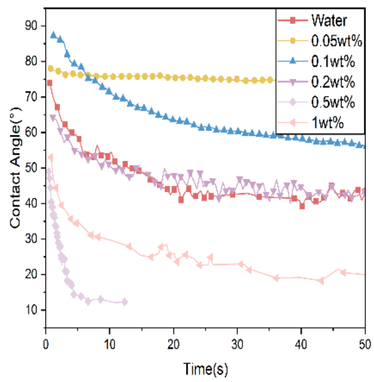
(**c**) JFC



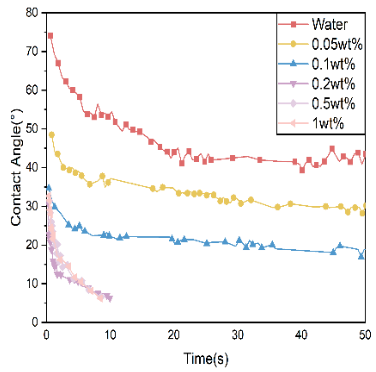
(**d**) LAO-30



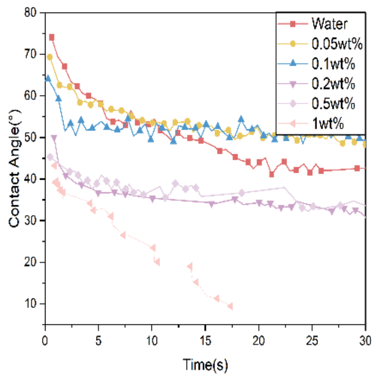
(**e**) OB-20



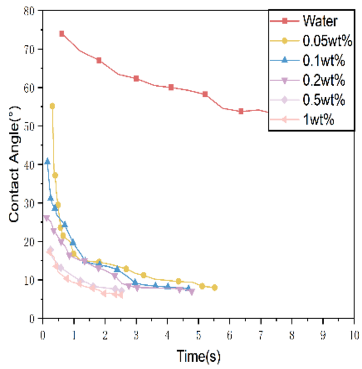
(**f**) SDBS



(**g**) SDS

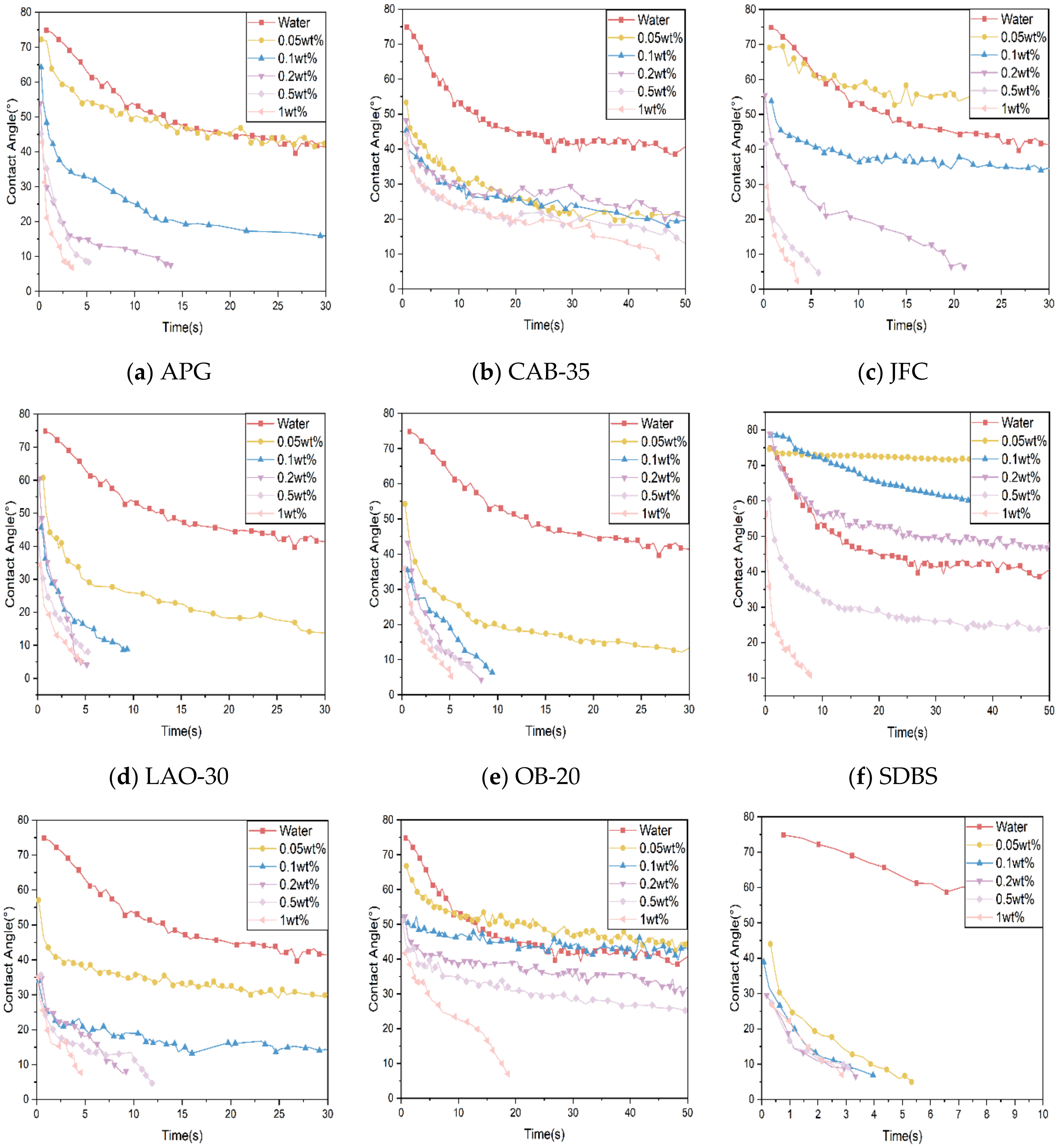


(**h**) Tween 80



(**i**) AOT

Figure 4. Contact angle of 1# coal dust with different surfactants at different mass fractions.

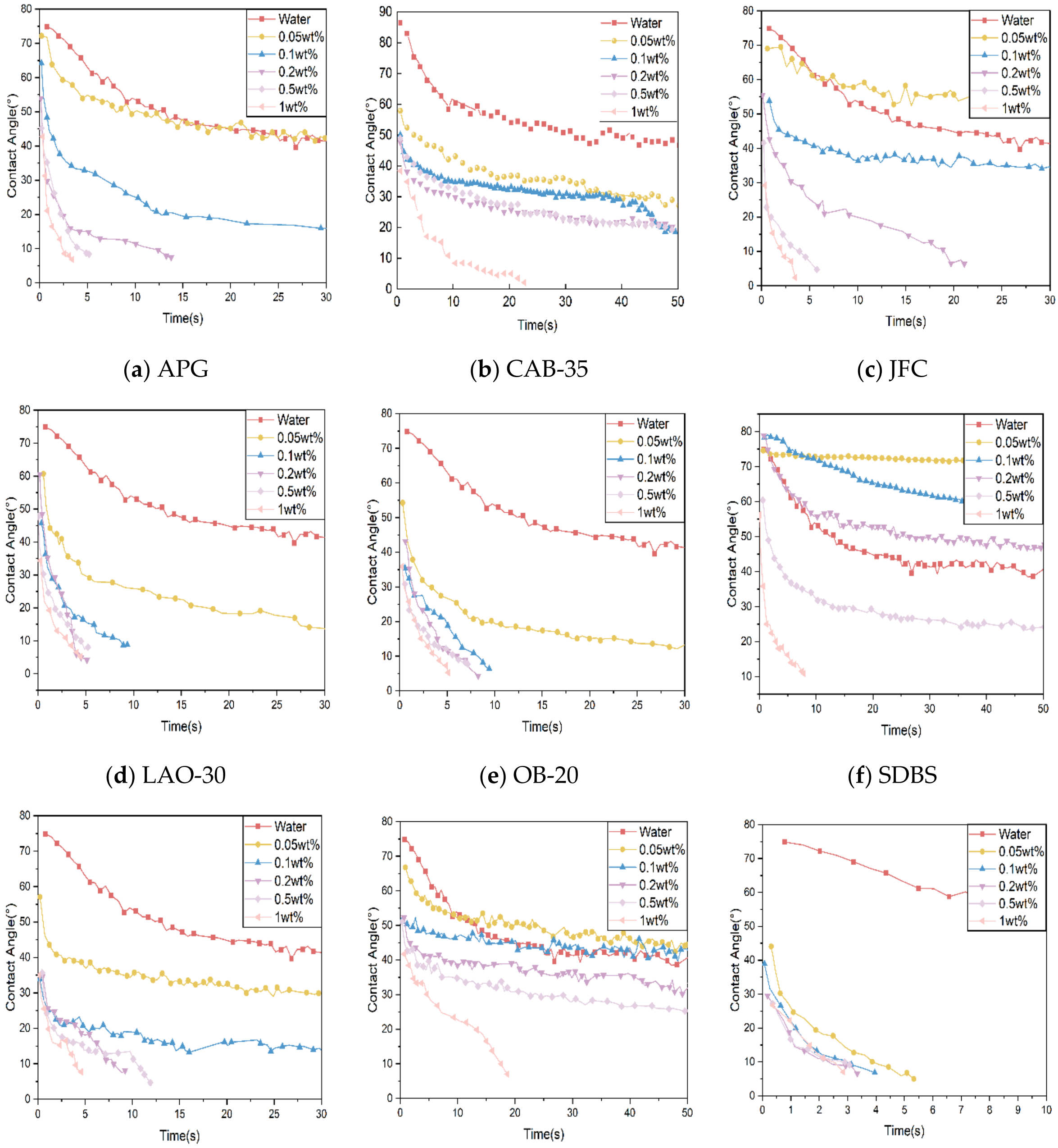


(**a**) APG (**b**) CAB-35 (**c**) JFC

(**d**) LAO-30 (**e**) OB-20 (**f**) SDBS

(**g**) SDS (**h**) Tween 80 (**i**) AOT

Figure 5. Contact angle of 2# coal dust with different surfactants at different mass fractions.



(**a**) APG (**b**) CAB-35 (**c**) JFC

(**d**) LAO-30 (**e**) OB-20 (**f**) SDBS

(**g**) SDS (**h**) Tween 80 (**i**) AOT

Figure 6. Contact angle of 3# coal dust with different surfactants at different mass fractions.

The results indicate varying wetting performances of the different surfactants at different concentrations for the three types of coal dust. Below is a summary of the findings:

(a) APG: To achieve complete wetting within 5 s, the solution concentration needs to be above 0.2 wt% for the 1# and 3# coal dusts, and above 0.5 wt% for the 2# coal dust.

(b) CAB-35: CAB-35 showed a poor overall performance for all three coal dust types. Even at a 1 wt% concentration, it took at least 10 s to wet the samples. For the 2# coal dust, none of the tested concentrations achieved rapid wetting.

(c) JFC: Concentrations of 0.5 wt% and 1 wt% displayed excellent wetting performances for all three coal dust types.

(d) LAO-30: Concentrations above 0.1 wt% rapidly reduced the contact angle for all three coal dust types within 5 s.

(e) OB-20: For the 1# coal dust, all concentrations displayed similar wetting performances. For the 2# and 3# coal dusts, concentrations of 0.2 wt% or higher led to rapid wetting within 5 s.
(f) SDBS: A 0.5 wt% solution was the most effective for the 1# and 3# coal dusts, achieving complete wetting within 10 s and 5 s, respectively. For the 2# coal dust, a 1 wt% solution was needed to achieve complete wetting within 10 s.
(g) SDS: For the 1# coal dust, the best wetting performance was seen with a 0.2 wt% concentration. For the 2# and 3# coal dusts, concentrations of 0.5 wt% or higher rapidly achieved wetting.
(h) Tween 80: The wetting performance of all concentration solutions was poor. Even with a 1 wt% solution, which exhibited the best performance for the three coal dust types, it took 10 s for the coal dust to reach rapid wetting.
(i) AOT: All three coal dust types were completely wetted within 6 s at all five mass fractions when using AOT.

These results provide valuable insights into the choice of surfactants and their optimal concentrations for achieving the rapid wetting of different coal dust types.

(3) Preliminary surfactant screening results

Considering the wetting effect and the consumption of dust reduction, the optimum concentration of each type of surfactant for different coal dusts is shown in Table 9 below.

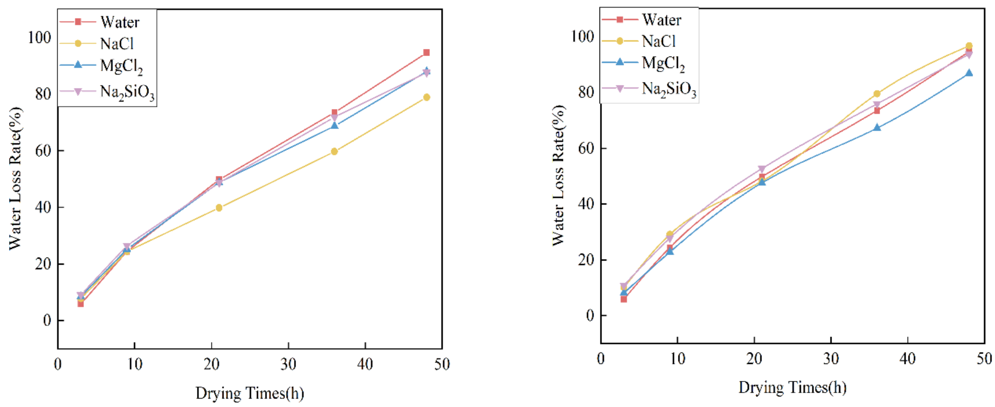
Table 9. Optimum concentration of monomer surfactant.

Coal Dust No.	Optimum Concentration of Each Type of Surfactant (wt%)								
	APG	**CAB-35**	**JFC**	**LAO-30**	**OB-20**	**SDBS**	**SDS**	**Tween 80**	**AOT**
1#	0.2	0.2	0.5	0.1	0.05	0.5	0.2	1	0.05
2#	0.5	1	0.5	0.1	0.2	1	0.5	1	0.05
3#	0.2	1	0.5	0.1	0.2	0.5	0.5	1	0.05

3.5. Analysis of Experimental Results of Inorganic Salt Compounding

3.5.1. Analysis of Experimental Results on Water Retention of Inorganic Salts

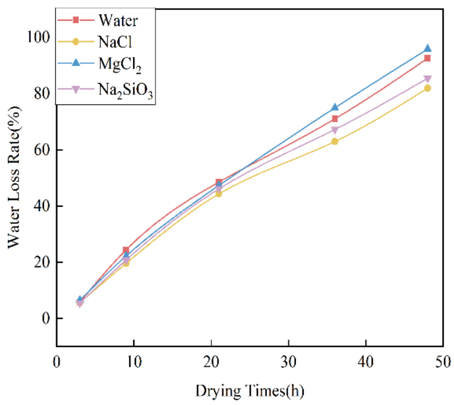
The results of the experiment conducted to determine the inorganic salts' water retention capacities are shown in Figure 7. For the sample 1# coal dust, as seen in Figure 7a,b, it is evident that when the drying time reaches 48 h, the moisture loss of the coal dust sample with 0.5 wt% of NaCl solution added is significantly lower than 80% and lower than the moisture loss in the other inorganic salt solutions. Compared to using plain water, the moisture loss is reduced by 15.8%.



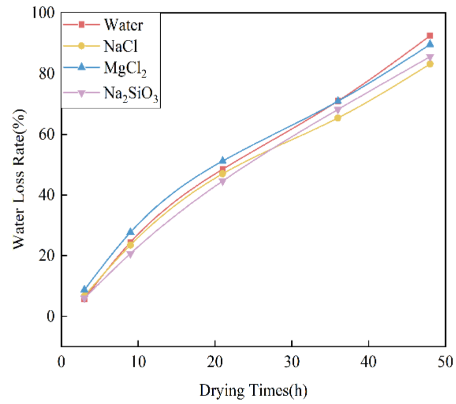
(**a**) 1# Coal dust added to 0.5 wt% inorganic salt solution

(**b**) 1# Coal dust added to 1 wt% inorganic salt solution

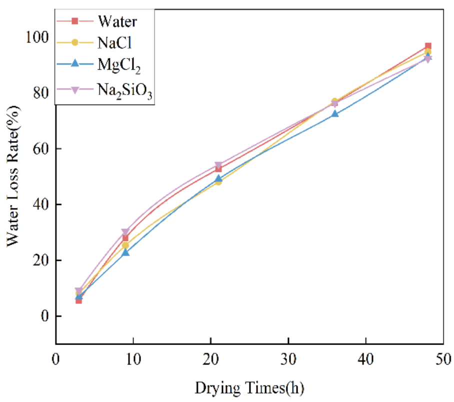
Figure 7. *Cont.*



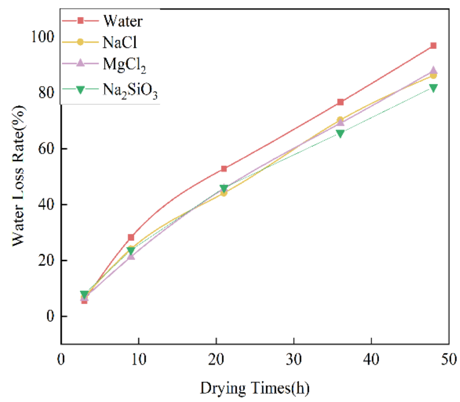
(**c**) 2# Coal dust added to 0.5 wt% inorganic salt solution



(**d**) 2# Coal dust added to 1 wt% inorganic salt solution



(**e**) 3# Coal dust added to 0.5 wt% inorganic salt solution



(**f**) 3 # Coal dust added to 1 wt% inorganic salt solution

Figure 7. Variation in water loss rate of coal dust with time after adding inorganic salt solution.

For the 2# coal dust, it can be seen from Figure 7c,d that when the drying time is increased to 48 h, the water loss rate of the NaCl solution with mass fractions of 0.5 wt% and 1 wt% NaCl solution are both the lowest, and compared with the water, the water loss rate is reduced by 10.6% and 9.3%, respectively, which shows that the water retention of the 0.5 wt% NaCl solution is stronger than that of the 1 wt% NaCl solution.

For the 3# coal dust, it can be seen from Figure 7e that the overall water retention performance of the $MgCl_2$ solution with a concentration of 0.5 wt% is optimal when the drying duration reaches 36 h. Compared with clear water, the 0.5 wt% $MgCl_2$ solution reduces the water loss rate by 5.5%, 3.6%, 4%, and 3.9%, respectively, when the drying duration reaches 9 h, 21 h, 36 h, and 48 h. As can be seen from Figure 8, the overall water retention of 1 wt% Na_2SiO_3 is optimal, but due to the crystal precipitation of the Na_2SiO_3 solution (Figure 8), the addition of Na_2SiO_3 to the dust suppressant may result in the absorption of moisture in the air, thus reducing the humidity in the air and, in turn, making it more difficult for the dust in the air to precipitate. At the same time, inorganic salt solutions that precipitate crystals are usually not recommended as additive formulations in order to protect the environment [32]. Therefore, a 1 wt% NaCl solution, which is ranked second overall in water retention performance, should be selected as the water retention formulation, and compared to water, the 1 wt% NaCl solution reduced water loss by 4.1%, 8.7%, 16.4%, and 10.6% at drying durations of up to 9 h, 21 h, 36 h, and 48 h, respectively. From the analysis, it can be seen that for the 3# coal dust, the 1 wt% NaCl solution retains water better than the 0.5 wt% $MgCl_2$ solution.

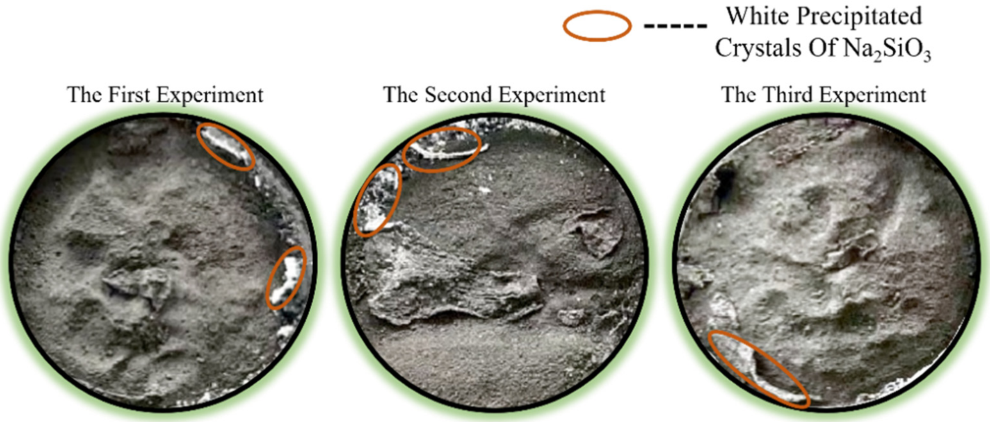


Figure 8. The water retention test for inorganic salt for 3# coal dust was repeated for three times at a concentration of 1 wt%, which was the best performing Na_2SiO_3 solution for all precipitated white crystals.

In summary, based on the experimental results and considering the industrial prices of inorganic salts, 0.5 wt% NaCl, 0.5 wt% NaCl, and 1 wt% NaCl solutions were selected as the best water retention materials to be added into the dust suppressant for the 1#, 2#, and 3# coal dusts, respectively.

3.5.2. Analysis of the Results of Compound Solution Wetting Experiments

The optimal water retention material specific to coal dust was combined with the surfactant solution detailed in Table 9. The formulation of the resulting compound solution, along with the corresponding contact angle test results, is presented in Table 10 below. Additionally, the outcomes of the surface tension experiments conducted on the compound solution are illustrated in Figure 9.

Table 10. Formulation of compounded solutions and associated contact angle test results.

Solution Combination No.	Coal Dust	Compound Solution	Contact Angle Values for the 5th Second (°)	
			Monomer Surfactant Solution——Coal Dust	Compound Solution ——Coal Dust
1	1#	0.5 wt% NaCl + 0.2 wt% APG	0	0
2		0.5 wt% NaCl + 0.2 wt% CAB-35	24.1	23.2
3		0.5 wt% NaCl + 0.5 wt% JFC	11.65	6.18
4		0.5 wt% NaCl + 0.1 wt% LAO-30	16.5	17.64
5		0.5 wt% NaCl + 0.05 wt% OB-20	15.53	35.18
6		0.5 wt% NaCl + 0.5 wt% SDBS	14.59	19.21
7		0.5 wt% NaCl + 0.2 wt% SDS	11.97	10.6
8		0.5 wt% NaCl + 1 wt% Tween 80	23.46	20.35
9		0.5 wt% NaCl + 0.05 wt% AOT	8.01	0
10	2#	0.5 wt% NaCl + 0.5 wt% APG	8.72	9.94
11		0.5 wt% NaCl + 1 wt% CAB-35	27.8	22.8
12		0.5 wt% NaCl + 0.5 wt% JFC	8.38	5.75
13		0.5 wt% NaCl + 0.1 wt% LAO-30	15.1	17.01
14		0.5 wt% NaCl + 0.2 wt% OB-20	18.98	35.06
15		0.5 wt% NaCl + 1 wt% SDBS	13.14	17.18
16		0.5 wt% NaCl + 0.5 wt% SDS	14.84	15.88
17		0.5 wt% NaCl + 1 wt% Tween 80	30.1	29.48
18		0.5 wt% NaCl + 0.05 wt% AOT	6.72	0

Table 10. *Cont.*

Solution Combination No.	Coal Dust	Compound Solution	Contact Angle Values for the 5th Second (°)	
			Monomer Surfactant Solution——Coal Dust	Compound Solution——Coal Dust
19		1 wt% NaCl + 0.2 wt% APG	8.7	8.31
20		1 wt% NaCl + 1 wt% CAB-35	22.7	20.1
21		1 wt% NaCl + 0.5 wt% JFC	5.13	4.3
22		1 wt% NaCl + 0.1 wt% LAO-30	6.48	23.56
23	3#	1 wt% NaCl + 0.2 wt% OB-20	23.65	30.12
24		1 wt% NaCl + 0.5 wt% SDBS	0	20.8
25		1 wt% NaCl + 0.5 wt% SDS	13.33	0
26		1 wt% NaCl + 1 wt% Tween 80	29.28	18.92
27		1 wt% NaCl + 0.05 wt% AOT	5.84	5.44

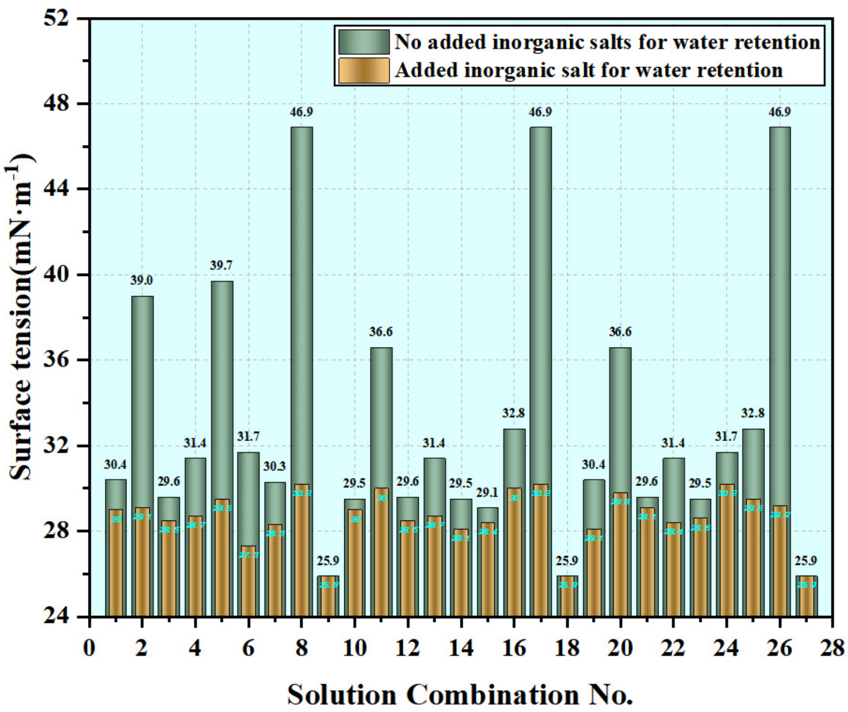


Figure 9. Changes in surface tension before and after addition of inorganic salts to surfactants.

An analysis of the surface tension experiment results indicates that with the addition of 0.5 wt% and 1 wt% NaCl, except for the two groups (9th group and 27th group) containing AOT Fast Penetrating T complex solutions, the surface tensions of the remaining 25 complex solutions decreased. This suggests that NaCl does not have a negative impact on the surface active agents and is suitable as a hygroscopicity additive.

In the contact angle experiment, a solution is considered to meet the requirements of good wettability when it can reduce the contact angle data to below 10° within 6 s. Therefore, a comparison was made between the contact angle data of the monomer surfactant solution with coal dust and the compounded solution with coal dust at the fifth second. The results showed that all of the compounded solutions listed in Table 11, which included the surfactants combined with NaCl, achieved the necessary wetting performance.

Table 11. Compound solution combinations that synergized and met the wettability requirements.

Coal Dust	Compound Solution
1#	0.5 wt% NaCl + 0.2 wt% APG 0.5 wt% NaCl + 0.5 wt% JFC 0.5 wt% NaCl + 0.05 wt% AOT
2#	0.5 wt% NaCl + 0.5 wt% JFC 0.5 wt% NaCl + 0.05 wt% AOT
3#	1 wt% NaCl + 0.2 wt% APG 1 wt% NaCl + 0.5 wt% JFC 1 wt% NaCl + 0.5 wt% SDS 1 wt% NaCl + 0.05 wt% AOT

Furthermore, in some complex solutions, a wetting gain effect was observed in the surface tension experiment. However, during the contact angle experiment, certain combinations exhibited an antagonistic effect, where some surface active agents and the hygroscopic inorganic salt NaCl increased the contact angle, which was particularly noticeable in cases like the 5th combination in the 1# coal dust, the 14th combination in the 2# coal dust, and the 22nd combination in the 3# coal dust. This might be because the surface tension reflects the relationship between the solution and the atmosphere, while the contact angle reflects the relationship between the solution and the solid dust pellet.

3.6. Analysis of the Results of the Selection of Dust Suppressants for Blast Pile Dusts

Taking into account consumption and environmental considerations, the optimal dust suppression solution was chosen from the combinations of compounded solutions listed in Table 11. This chosen solution is indicated in Table 12, and it appears to be the combination with lower concentrations.

Table 12. Optimal dust suppression program proportion for coal dust.

Coal Dust	Optimal Dust Suppression Program Ratio
1#	0.5 wt% NaCl + 0.05 wt% AOT
2#	0.5 wt% NaCl + 0.05 wt% AOT
3#	1 wt% NaCl + 0.05 wt% AOT

3.7. Analysis of Dust Suppression Effect

3.7.1. Analysis of the Results of Chemical Dust Suppressant Permeability Experiments

The capillary rise infiltration experiment results, as shown in Table 13, indicate that compared to pure water, the formulated dust suppressants significantly increased the infiltration height of the coal dust from 0.2~0.3 cm to 3.1~3.3 cm, representing at least a ten-fold improvement. The hygroscopic mass increased from 0.69~0.78 g to 3.76~4.06 g, showing at least a four-fold increase. This demonstrates that the formulated dust suppressants have strong penetration capabilities and exhibit excellent infiltration effects. The significant increase in the penetration height allows for the dust suppressant to penetrate deeper into the soil, promoting overall soil compaction, and thus enhancing its cohesion and ultimately improving the coal dust's resistance to wind disturbance. The substantial increase in moisture absorption indirectly strengthens the dust suppressant's moisture retention capability, reducing the frequency and quantity of suppressant application in a given time, leading to cost savings.

Table 13. Dust sample counter seepage height.

Dust Samples	Solutions	Height of Reverse Osmosis (cm)	Moisture Absorption Weight (g)
1# Coal Dust	water 0.05 wt% AOT + 0.5 wt% NaCl	0.3 3.2	0.78 3.91
2# Coal Dust	water 0.05 wt% AOT + 0.5 wt% NaCl	0.2 3.1	0.76 3.76
3# Coal Dust	water 0.05 wt% AOT + 1 wt% NaCl	0.2 3.3	0.69 4.06
4# Rock Dust	water	2.8	2.97
5# Rock Dust	water	2.8	2.85
6# Rock Dust	water	2.6	2.84

Furthermore, in Section 3.1.3, we inferred that the 1# coal dust exhibited the best hydrophilicity and the 3# coal dust showed the poorest hydrophilicity based on the relationship between the specific surface area values. In this regard, the dust capillary counter-infiltration experiment confirmed our inference. According to the experimental results, after adding water to the three types of coal dust, the 1# coal dust indeed absorbed the highest amount of moisture, while the 3# coal dust had the lowest moisture absorption.

In contrast, when it came to the three types of rock dust, they exhibited a counter-permeability height ranging from 2.6 cm to 2.8 cm, and the moisture absorption amount varied from 2.84 g to 2.97 g when treated with water alone. These results confirm that rock dust can achieve good permeation effects with water alone, as demonstrated by the moisture absorption and penetration capabilities [33].

3.7.2. Analysis of the Results of Indoor Experiments on Spray Dust Reduction

The results of the indoor experiments on the spray dust reduction ability of blast pile dust are shown in Tables 14 and 15 below. For coal piles, after spraying the corresponding optimal dust suppressant for different coal dusts, the TSP dust reduction efficiency of the a#, b#, and c# coal piles were 82.5%, 83%, and 81.4%, respectively. Compared with clear water, the dust reduction rate increased by 37.2%, 38.4%, and 27.5%, respectively, and the dust removal efficiency was significantly improved.

Table 14. Coal dust blast pile dust reduction efficiency after spraying.

Coal Pile No.	Original Concentration (μg/m^3)			Concentration of Indicators after Spraying with Water (μg/m^3)			Concentration of Indicators after Dust Suppressant Spraying (μg/m^3)			Dust Reduction Efficiency (TSP) (%)	Percentage of Increase (%)
	PM2.5	PM_{10}	TSP	PM2.5	PM_{10}	TSP	PM2.5	PM_{10}	TSP		
a#	199	411	503	108	211	275	37	48	88	82.5	37.2
b#	240	483	596	120	215	330	40	55	101	83	38.4
c#	196	402	495	99	175	228	38	48	92	81.4	27.5

Table 15. Rock dust blast pile dust reduction efficiency after spraying.

Rock Pile No.	Original Concentration (μg/m^3)			Concentration of Indicators after Spraying with Water (mg/m^3)			Dust Reduction Efficiency (TSP) (%)
	$PM_{2.5}$	PM_{10}	TSP	$PM_{2.5}$	PM_{10}	TSP	
A#	224	411	521	32	52	66	87.3
B#	214	390	482	39	58	71	85.3
C#	233	428	549	35	57	81	85.2

For the rock piles, after spraying clean water, the TSP dust reduction efficiencies of rock piles A#, B#, and C# were 87.3%, 85.3%, and 85.2%, respectively. This can once again confirm that for rock dust, there is no need to add auxiliary dust suppressants, and the dust suppression effect can be good with only a single spray of clear water.

4. Conclusions

In order to mitigate the blast pile dust pollution generated during various blasting steps in the Haerwusu open-pit coal mine, this study focused on collected coal dust and rock dust from different blasting steps at the mine. This research aimed to understand the physicochemical characteristics of the dust and identify the primary factors influencing the dust's wettability. Furthermore, surfactant selection experiments and inorganic salt compounding experiments were conducted to formulate a dust inhibitor specifically designed for burst pile coal dust. The performance of this dust inhibitor was evaluated through permeability experiments and indoor dust reduction experiments. The key conclusions drawn from this study are as follows:

(1) Blast pile dusts consist of coarse particles with a low proportion of fine respiratory dust. These coarse particles tend to settle rapidly, primarily in the nasal cavity, and have a relatively limited impact on the lungs.
(2) The significant factors affecting coal dust wetting are *FCad* and *D50*; the significant factor affecting the wetting of rock dust is *D50*.
(3) The best chemical dust suppressant ratio for the different coal dusts is as follows: 1# coal dust: 0.05 wt% AOT + 0.5 wt% NaCl; 2# coal dust: 0.05 wt% AOT + 0.5 wt% NaCl; and 3# coal dust: 0.05 wt% AOT + 1 wt% NaCl.
(4) The addition of 0.5 wt% NaCl and 1 wt% NaCl hygroscopic inorganic salts in the dust suppressant, with a drying time of 48 h, can reduce the moisture loss of the dust suppressant by at least 10.6% compared to when using plain water.
(5) According to the reverse osmosis experiment, the configured dust suppressant can increase the penetration height of the coal dust from 0.2~0.3 cm to 3.1~3.3 cm and increase the moisture absorption from 0.69~0.78 g to 3.76~4.06 g.
(6) Based on the indoor spray dust reduction experiments, the TSP concentrations for the three groups of coal dust were reduced by 82.5%, 83%, and 81.4% after spraying the appropriate chemical dust suppressants. These reductions represented improvements of 37.2%, 38.4%, and 27.5%, respectively, when compared to the use of clear water alone.

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References

1. Bui, X.-N.; Lee, C.W.; Nguyen, H.; Bui, H.-B.; Long, N.Q.; Le, Q.-T.; Nguyen, V.-D.; Nguyen, N.-B.; Moayedi, H. Estimating PM10 concentration from drilling operations in open-pit mines using an assembly of SVR and PSO. *Appl. Sci.* **2019**, *9*, 2806. [CrossRef]
2. Entwistle, J.A.; Hursthouse, A.S.; Marinho Reis, P.A.; Stewart, A.G. Metalliferous mine dust: Human health impacts and the potential determinants of disease in mining communities. *Curr. Pollut. Rep.* **2019**, *5*, 67–83. [CrossRef]
3. Saedpanah, S.; Amanollahi, J. Environmental pollution and geo-ecological risk assessment of the Qhorveh mining area in western Iran. *Environ. Pollut.* **2019**, *253*, 811–820. [CrossRef]
4. Prostański, D. Development of research work in the air-water spraying area for reduction of methane and coal dust explosion hazard as well as for dust control in the Polish mining industry. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *427*, 012026. [CrossRef]
5. Jin, H.; Zhang, Y.; Chen, K.; Niu, K.; Wu, G.; Wei, X.; Wang, H. Preparation and characterization of a composite dust suppressant for coal mines. *Polymers* **2020**, *12*, 2942. [CrossRef]
6. Wang, H.; Zhang, L.; Wang, D.; He, X. Experimental investigation on the wettability of respirable coal dust based on infrared spectroscopy and contact angle analysis. *Adv. Powder Technol.* **2017**, *28*, 3130–3139. [CrossRef]
7. Jin, L.; Liu, J.; Guo, J.; Wang, J.; Wang, T. Physicochemical factors affecting the wettability of copper mine blasting dust. *Int. J. Coal Sci. Technol.* **2021**, *8*, 265–273. [CrossRef]
8. Tessum, M.W.; Raynor, P.C. Effects of spray surfactant and particle charge on respirable coal dust capture. *Saf. Health Work* **2017**, *8*, 296–305. [CrossRef]
9. Copeland, C.R.; Kawatra, S. Dust suppression in iron ore processing plants. *Min. Metall. Explor.* **2005**, *22*, 177–191. [CrossRef]
10. Dong, H.; Yu, H.; Xu, R.; Cheng, W.; Ye, Y.; Xie, S.; Zhao, J.; Cheng, Y. Review and prospects of mining chemical dust suppressant: Classification and mechanisms. *Environ. Sci. Pollut. Res.* **2023**, *30*, 18–35. [CrossRef]
11. Zhou, L.; Yang, S.; Hu, B.; Yuan, Z.; Wu, H.; Yang, L. Evaluating of the performance of a composite wetting dust suppressant on lignite dust. *Powder Technol.* **2018**, *339*, 882–893. [CrossRef]
12. Li, M.; Yin, W.; Tang, J.; Qiu, L.; Fei, X.; Yang, H.; Tang, Z.; Chen, F.; Qin, X.; Li, G. Experimental study on ratio optimization and application of improved bonded dust suppressant based on wetting effect. *J. Air Waste Manag. Assoc.* **2023**, *73*, 394–402. [CrossRef] [PubMed]
13. Sun, J.; Zhou, G.; Gao, D.; Wei, Z.; Wang, N. Preparation and performance characterization of a composite dust suppressant for preventing secondary dust in underground mine roadways. *Chem. Eng. Res. Des.* **2020**, *156*, 195–208. [CrossRef]
14. Zhang, X.-N.; Sun, H.; Jiang, P.; Cui, X.-Z.; Wang, J.-R. Development and performance characterization of a composite dust suppressant for Yellow River alluvial silt using response surface methodology. *J. Clean. Prod.* **2022**, *376*, 134293. [CrossRef]
15. Xu, L.; Pei, Z. Preparation and optimization of a novel dust suppressant for construction sites. *J. Mater. Civ. Eng.* **2017**, *29*, 04017051. [CrossRef]
16. Shen, Z.; Ao, Z.; Wang, Z.; Yang, Y. Study on Crust-Shaped Dust Suppressant in Non-Disturbance Area of Open-Pit Coal Mine—A Case Study. *Int. J. Environ. Res. Public Health* **2023**, *20*, 934. [CrossRef]
17. Yan, J.; Nie, W.; Zhang, H.; Xiu, Z.; Bao, Q.; Wang, H.; Jin, H.; Zhou, W. Synthesis and performance measurement of a modified polymer dust suppressant. *Adv. Powder Technol.* **2020**, *31*, 792–803. [CrossRef]
18. Jin, H.; Zhang, Y.; Wu, G.; Yang, J.; Li, N. Optimization via response surface methodology of the synthesis of a dust suppressant and its performance characterization for use in open cut coal mines. *J. Environ. Sci.* **2022**, *121*, 211–223. [CrossRef]
19. Zhang, H.; Nie, W.; Wang, H.; Bao, Q.; Jin, H.; Liu, Y. Preparation and experimental dust suppression performance characterization of a novel guar gum-modification-based environmentally-friendly degradable dust suppressant. *Powder Technol.* **2018**, *339*, 314–325. [CrossRef]
20. Liu, Y.; Nie, W.; Jin, H.; Ma, H.; Hua, Y.; Cai, P.; Wei, W. Solidifying dust suppressant based on modified chitosan and experimental study on its dust suppression performance. *Adsorpt. Sci. Technol.* **2018**, *36*, 640–654. [CrossRef]
21. Wu, M.; Hu, X.; Zhang, Q.; Zhao, Y.; Cheng, W.; Xue, D. Preparation and performance of a biological dust suppressant based on the synergistic effect of enzyme-induced carbonate precipitation and surfactant. *Environ. Sci. Pollut. Res.* **2022**, *29*, 8423–8437. [CrossRef]
22. Yu, X.; Zhao, Y.; Feng, Y.; Hu, X.; Liu, J.; Wang, X.; Wu, M.; Dong, H.; Liang, Y.; Wang, W. Synthesis and performance characterization of a road coal dust suppressant with excellent consolidation, adhesion, and weather resistance. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *639*, 128334. [CrossRef]
23. Ding, J.; Zhou, G.; Liu, D.; Jiang, W.; Wei, Z.; Dong, X. Synthesis and performance of a novel high-efficiency coal dust suppressant based on self-healing gel. *Environ. Sci. Technol.* **2020**, *54*, 7992–8000. [CrossRef]
24. Liao, Q.; Feng, G.; Fan, Y.; Hu, S.; Shao, H.; Huang, Y. Experimental investigations and field applications of chemical suppressants for dust control in coal mines. *Adv. Mater. Sci. Eng.* **2018**, *2018*, 6487459. [CrossRef]
25. Sun, J.; Zhou, G.; Wang, C.; Liu, R.; Miao, Y. Experimental synthesis and performance comparison analysis of high-efficiency wetting enhancers for coal seam water injection. *Process Saf. Environ. Prot.* **2021**, *147*, 320–333. [CrossRef]
26. Hüttinger, K.J.; Michenfelder, A.W. Molecular structure of a brown coal. *Fuel* **1987**, *66*, 1164–1165. [CrossRef]
27. Tabrizy, V.A.; Denoyel, R.; Hamouda, A. Characterization of wettability alteration of calcite, quartz and kaolinite: Surface energy analysis. *Colloids Surf. A Physicochem. Eng. Asp.* **2011**, *384*, 98–108. [CrossRef]
28. Jiang, J.; Yang, W.; Cheng, Y.; Liu, Z.; Zhang, Q.; Zhao, K. Molecular structure characterization of middle-high rank coal via XRD, Raman and FTIR spectroscopy: Implications for coalification. *Fuel* **2019**, *239*, 559–572. [CrossRef]

29. Zhang, R.; Xing, Y.; Xia, Y.; Luo, J.; Tan, J.; Rong, G.; Gui, X. New insight into surface wetting of coal with varying coalification degree: An experimental and molecular dynamics simulation study. *Appl. Surf. Sci.* **2020**, *511*, 145610. [CrossRef]
30. Huang, P.; Fuerstenau, D.W. The effect of the adsorption of lead and cadmium ions on the interfacial behavior of quartz and talc. *Colloids Surf. A Physicochem. Eng. Asp.* **2001**, *177*, 147–156. [CrossRef]
31. Zhou, G.; Qiu, H.; Zhang, Q.; Xu, M.; Wang, J.; Wang, G. Experimental investigation of coal dust wettability based on surface contact angle. *J. Chem.* **2016**, *2016*, 9452303. [CrossRef]
32. Antony, A.; Low, J.H.; Gray, S.; Childress, A.E.; Le-Clech, P.; Leslie, G. Scale formation and control in high pressure membrane water treatment systems: A review. *J. Membr. Sci.* **2011**, *383*, 1–16. [CrossRef]
33. Chen, L.; Li, P.; Liu, G.; Cheng, W.; Liu, Z. Development of cement dust suppression technology during shotcrete in mine of China-A review. *J. Loss Prev. Process Ind.* **2018**, *55*, 232–242. [CrossRef]

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