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Study on Multi-Factor Optimization and Application for Water Mist of a Wetting Dust Suppressant

Ming Li, Jiao Tang,* Xinzhu Song, Linling Qiu, Huaizhen Yang, and Zhi Li

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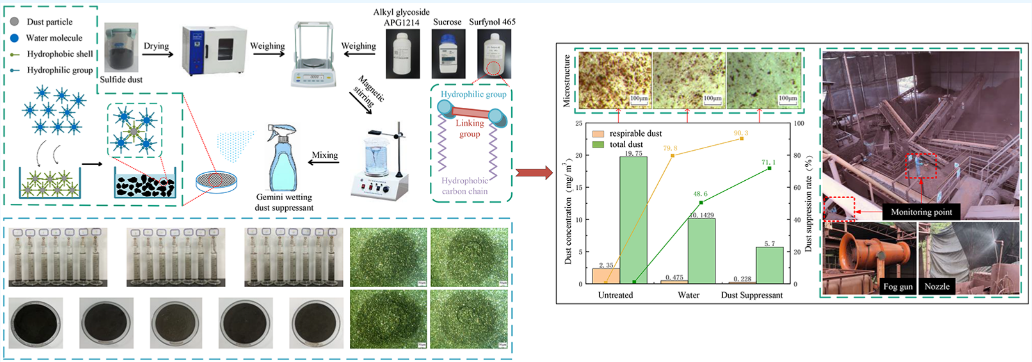

ABSTRACT: Aiming at the problem of low efficiency of capturing respirable and hydrophobic dust in water mist dust removal technology, a chemical dust suppression method is adopted. Based on the research idea of improving the wetting efficiency of water mist, prolonging the droplet retention time, and improving the contact opportunity with dust, the experiments of dust sedimentation time, solution spreading area, and water loss rate are selected to evaluate the wetting efficiency and anti-evaporation performance of dust suppression water mist. Considering the special double-chain structure of the Gemini surfactant and its high wettability, it is preferred as the main dust suppression component. Based on the indoor experimental data, the optimized formula of the composite wet water mist dust suppressant was obtained by CCD-RSM(central composite design-response surface methodology). The comparison of indoor experimental data shows that the sedimentation time of the dust sample in the water mist dust suppressant is 5.0 times faster than that of pure water, the spreading area of the dust suppressant solution is 1.8 times that of pure water, and the water loss rate of the dust sample treated by the dust suppressant is 70% that of pure water. The field investigation results show that compared with pure water mist, the dust removal rates of the Gemini wetting dust suppressant for respirable dust and total dust are 90.3 and 71.1%, respectively, which are 10.5 and 22.5% higher than that of pure water mist. It can be proved that improving the wetting efficiency and anti-evaporation performance of spray mist will increase the dust removal efficiency.

1. INTRODUCTION

Dust is often produced in the industrial production process; workers in occupational activities for long-term inhalation of dust are prone to respiratory diseases. Therefore, it is of great significance to study dust prevention and control technology to ensure national health.[1,2] To effectively solve the problem of low efficiency of spray dust removal, chemical dust suppression and spray dust removal are often combined.[3−5]

Zhu et al. prepared a surfactant−microbial dust suppressant. The molecular dynamics simulation and contact angle experiment confirmed that the surfactant could effectively improve the wettability of the microbial dust suppressant, and thus, dust suppression efficiency was improved.[6] Yan et al.[7] prepared an environmental dust suppressant by chemical modification of sodium alginate. The performance of the dust suppressant was evaluated by contact angle and spray experiments, and the results showed that it had good water retention and wettability.[7] Zou et al. used water-based SiO_2 nanofluids to change the wettability of the coal dust surface and evaluated its performance, revealing the potential application mechanism of water-based SiO_2 nanofluids in coal seam water injection technology.[8] Hehe et al., combining the experiment and molecular dynamics simulation, studied the effects of ionic liquid [Bmim][Cl] with different concentrations on the wetting of coal dust from macroscopic and microscopic perspectives.[9] Wang et al. used an orthogonal

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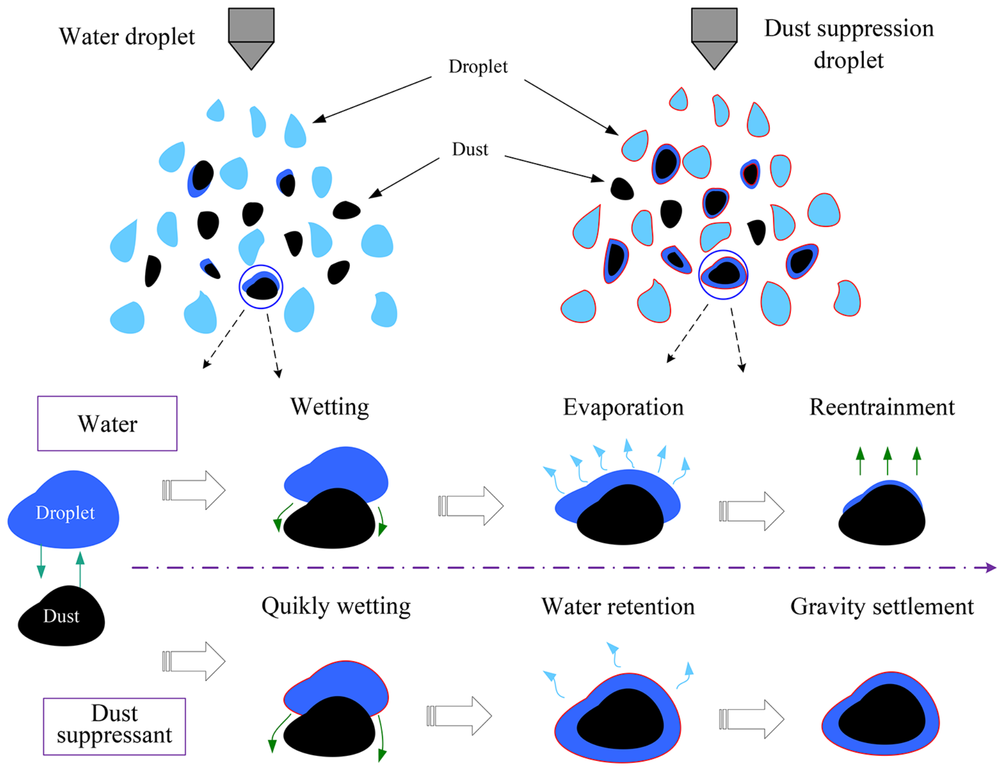

Figure 1. Diagram of dust capture for water mist.

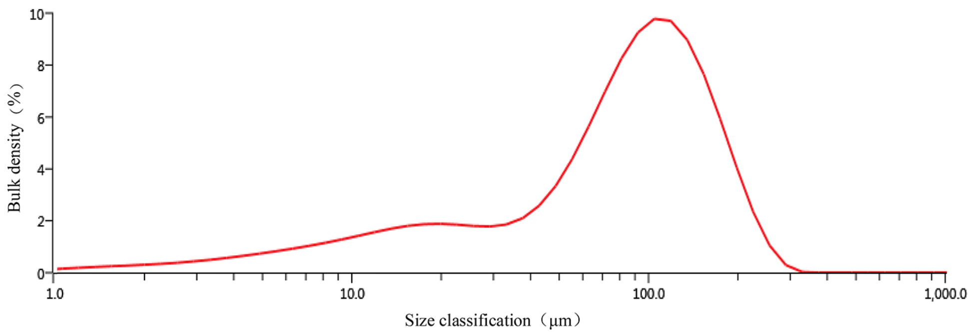

Figure 2. Results of particle size distribution of dust samples.

experimental design and response surface methodology to analyze the action mechanism of dust suppressants on coal dust from a microscopic view through the characterization experiment of dust suppressants.[10] The research of development and application of the chemical dust suppressant is more and more extensive.

However, the water mist dust suppression technology has some practical problems, such as low efficiency of capturing respirable and hydrophobic dust and short effective time of capturing dust. Based on the mechanism of water mist dust suppression and chemical dust suppression, a research idea of optimizing the wetting efficiency and anti-evaporation performance of dust suppression water mist is proposed.

2. ANALYSIS OF DUST CAPTURE FOR WATER MIST

In the process of water mist dust collection, the effective contact time between dust particles and droplets is short, and the residence time of the dust−droplet combination in dry air is relatively short, which easily leads to the failure of water mist dust collection. This requires that the dust suppression water mist must have faster wetting and wrapping dust performance and good anti-evaporation performance and then prevent dust re-entrainment. The main logical thinking is shown in Figure 1.

The droplets with low surface tension will engulf the dust particles more quickly in Figure 1. After the dust particles are completely wetted and wrapped, the volume of the droplets increases rapidly; when its gravity is greater than the buoyancy force, it will separate and settle from the air and play a role in dust reduction. However, some of the dust particles cannot be effectively settled due to the evaporation of the droplet itself during the sedimentation process. Therefore, it is necessary to select dust suppression materials with wetting and anti-evaporation effects to improve the wetting and anti-evaporation performance of droplets.

3. MATERIALS AND METHODS

3.1. Dust Suppression Components. The special dual-chain amphiphilic structure of the Gemini surfactant can significantly reduce the static and dynamic surface tension of aqueous solution, which is conducive to improving the wetting

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Table 1. Data of Element Content Analysis by Using X-ray Fluorescence

item	Fe	S	O	Si	Ca	F	Mg	Cu	Al
component ratio (%)	46.03	22.44	19	4.426	4.003	1.48	1.03	0.6134	0.546
item	Mn	K	Zn	Pb	Na	Mo	Bi	Cr	
component ratio (%)	0.193	0.111	0.0591	0.0431	0.024	0.0154	0.008	0.008	

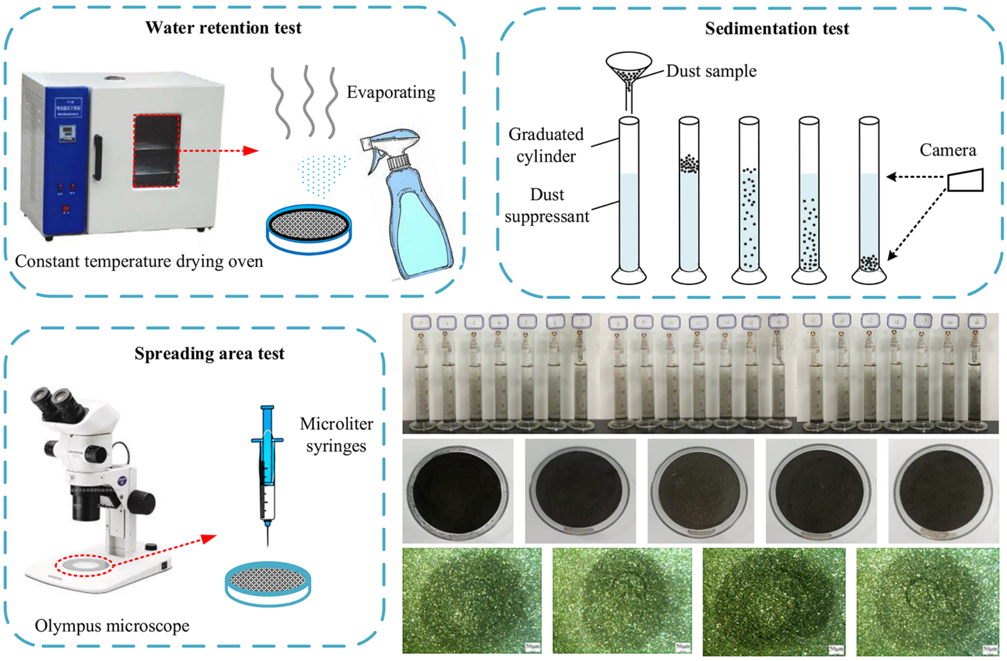

Figure 3. Experimental method and application diagram.

rate of water mist. Due to the existence of connecting groups, Gemini surfactants are more likely to produce strong interactions between hydrocarbon chains and have high surface activities.[11,12] In addition, the Gemini surfactant also has the characteristics of high efficiency, greenness, and environmental protection.[13]

When the Gemini surfactant is dissolved in water, hydrophilic groups are arranged toward water molecules, and the hydrophobic shell is repelled toward air. A tightly arranged interfacial adsorption layer is formed on the surface of water molecules, which effectively reduces the surface tension of water. When contacted with dust, the hydrophobic shell of Gemini surfactant molecules immediately adsorbs dust particles to form parcels, thus fully wetting them. Based on this, the Gemini surfactant Surfynol 465 with low foaming property and high hydrophilicity was used as the main raw material.[14] To make the moist dust particles continue to absorb water in the air and prevent the occurrence of dust re-entrainment, the alkyl glycoside APG1214 with good surface activity and compound performance and sucrose with strong hygroscopicity were selected as auxiliary materials.[15,16]

3.2. Dust Samples. The dust sample (120−200 mesh metal dust) was screened by vibrating screen machine and placed in a constant temperature drying oven at 80 °C. The main components of dust samples were Fe and S, and the particle size distribution D_{90} = 163 μm was measured by a Malvern Mastersizer 3000; the result is shown in Figure 2.

The qualitative analysis result of the dust sample by the X-ray fluorescence (semiquantitative) is shown in Table 1.

3.3. Performance Test Methods. To evaluate the dust suppression performance of the water mist of the wetting dust suppressant, the experimental test schemes were selected from the perspectives of wettability and water retention, respectively. The sedimentation test and spreading area test focused on the relationship between the dust particle and the dust suppression solution; the length of the time sedimentation test and the dispersion area of the spreading area test can directly reflect the wetting efficiency.[17,18] The water retention test is used to evaluate the water loss rate of the dust suppression solution, when the droplet collides with the dust particle and coagulates, the water loss rate determines the speed of water loss attached to the dust particles, and the dust suppressant solution with good water retention performance can effectively avoid dust re-entrainment, as shown in Figure 1.

3.3.1. Sedimentation Test. The sedimentation time is often used to measure the wetting effect of the dust suppressant on dust particles.[19,20] The experimental scheme is shown in Figure 3. The dried 0.3 g dust sample was evenly spread on the surface of 20 mL of the dust suppressant, and the whole process of dust settlement was recorded by a high-speed camera. The time required for the dust sample from the moment it contacted the liquid surface to complete settlement was obtained by analyzing the video.[21]

3.3.2. Spreading Area Test. The process of droplets impacting the dust pile surface and dynamic wetting is affected by many factors like liquid viscosity, surface tension, impact velocity, and surface porosity.[22,23] Analyzing the spreading behavior of droplets on the dust surface can effectively reflect the wetting rate of droplets on dust particles.[24,25] Taking the spreading area after droplet contacting with the dust surface and fully penetrating as a measure parameter, the larger spreading area indicates the better wetting rate. The

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experimental scheme is shown in Figure 3; the dust suppressant solution is placed in a micro-injector (10 μL) at the same height as the dust sample so that the dust suppressant droplets drop vertically to the dust sample surface at the same height. The droplet gradually penetrates on the dust surface after contacting with the dust pile surface, and the scope of action after complete penetration is used as the droplet spreading area.[18]

3.3.3. Water Retention Test. Huang et al.[26] analyzed the changes of dust samples after spraying a dust suppressant by simulating a high-temperature environment. In this way, the water retention performance of the dust suppressant can be measured.[26,27] The experimental photos are shown in Figure 3; place 20 g of the dust sample on the surface of a 90 mm culture dish and spray 5 g of the dust suppressant evenly. After the dust sample is completely wetted, put it into a 60 °C constant temperature drying oven drying to constant weight.[21] Each group of the samples was measured three times and averaged, and the water loss rate was calculated according to eq 1 as follows:

$$\varepsilon = (M_0 - M)/M_0 \times 100\% \quad (1)$$

In eq 1, ε (%) is the water loss rate, M_0(%) is the wet sample weight, and M (%) is the sample weight after dehydration.

4. INDOOR EXPERIMENTS AND RATIO OPTIMIZATION

4.1. Dust Component Ratio Optimization. The CCD-RSM (central composite design-response surface methodology) is selected as the method to get the optimal proportion of dust suppressant components, the Gemini surfactant Surfynol 465 concentration (A), alkyl glycoside APG1214 concentration, (B) and sucrose concentration (C) were selected as the variable factors, and the sedimentation time (Y1), water loss rate (Y2), and spreading area (Y3) were the response values. Through the previous single-factor experiment, the effective concentration range of each variable factor was determined as (A) 0.05−0.60%, (B) 0.10−0.25%, and (C) 0.50−3.00%. The experimental range and levels of the variables in the CCD are listed in Table 2.

Table 2. Experimental Range and Levels of the Variables in the CCD

	variable levels				
variable factors	−1.682	−1	0	+1	+1.682
A (%)	0.05	0.16	0.325	0.49	0.60
B (%)	0.10	0.13	0.175	0.22	0.25
C (%)	0.50	1.00	1.75	2.49	3.00

The dust suppressant was prepared by mixing it with the base material and water according to different mass percentages. The preparation process and mechanism of the dust suppressant are shown in Figure 4.

The arrangement and experimental results of various factors and levels in CCD-RSM are shown in Table 3.

Through Design-Expert analysis, the interaction term BC has the most significant effect on the dust sedimentation time and water loss rate, and the interaction term AB has the most significant effect on the spreading area. The three-dimensional response surface is drawn, as shown in Figure 5; a and b are the effect of the interaction between the alkyl glycoside APG1214 and sucrose on the sedimentation time and water loss rate when the Surfynol 465 concentration was 0.325%. c is the effect of the interaction between Surfynol 465 and the alkyl glycoside APG1214 on the spreading area when the sucrose concentration was 1.75%.

It can be seen from Figure 5 that when the concentration of component B is constant, the dust sedimentation time (Y1) increases first and then decreases with the increase of C concentration. When the C concentration is about 1.75%, the dust sedimentation time is the longest. The water loss rate (Y2) changed linearly with the increase of C concentration, and the water loss rate (Y2) decreased gradually with the increase of C concentration. When the concentration of B was low, the spreading area (Y3) gradually increased with the increase of A concentration. When the B concentration increased to about 0.22%, the spreading area (Y3) decreased with the increase of A concentration.

Through analysis, when the sedimentation time is the shortest, the water loss rate is the smallest, and the spreading area is the largest, the best formulation is the Gemini surfactant Surfynol 465 (0.26%), the alkyl glycoside APG1214 (0.11%), and sucrose (2.90%). It is predicted that the sedimentation time is 9.037 s, the water loss rate is 4.520%, and the spreading area is 0.993 mm^2.

4.2. Verification Experiment. The verification experiment was conducted to verify the accuracy of the regression model according to the optimal ratio of dust suppressant components. The dust sedimentation time, water loss rate, and spreading area were used as the evaluation criteria. The comparison between the experimental value and the predicted value of the optimal ratio experimental group is shown in Figure 6.

According to Figure 6, for the same dust sample, the sedimentation time in the dust suppressant is 5.0 times faster than that in water, and the water loss rate and spreading area of dust samples after spraying the dust suppressant are 0.7 and 1.8 times, respectively, after spraying water, indicating that the dust suppressant has a good wetting and moisturizing effect on dust. The deviation of each index was within 4.5%, indicating that the model had high accuracy and the formulation optimization scheme was credible.

It is generally believed that the smaller the surface tension and contact angle of the liquid, the better the wetting ability of the solution. The surface tension and contact angle of the prepared optimal ratio dust suppressant were tested, and the results are shown in Figure 7.

The average surface tension and contact angle of the dust suppressant were 29.38 mN/m and 34.27°, respectively, which are 42.8 mN/m and 25.30° smaller than that of water, indicating that the dust suppressant solution has a good wetting effect and is conducive to improving the dust suppression performance for water mist.

4.3. Field Investigation. The field application test was carried out in the crushing station of an open-pit iron mine in China. The test was divided into three stages. The crushing station generally works continuously for 5 min to enter a stable working state. The first stage is mainly to obtain the concentration value after the dust pollution is stable. The second and third stages are to evaluate the dust removal efficiency of the dust suppressant, and measure the dust concentration value after the system works continuously and stably for 10 min.

The respirable dust concentration is measured by a microcomputer laser dust sampler, and the total dust

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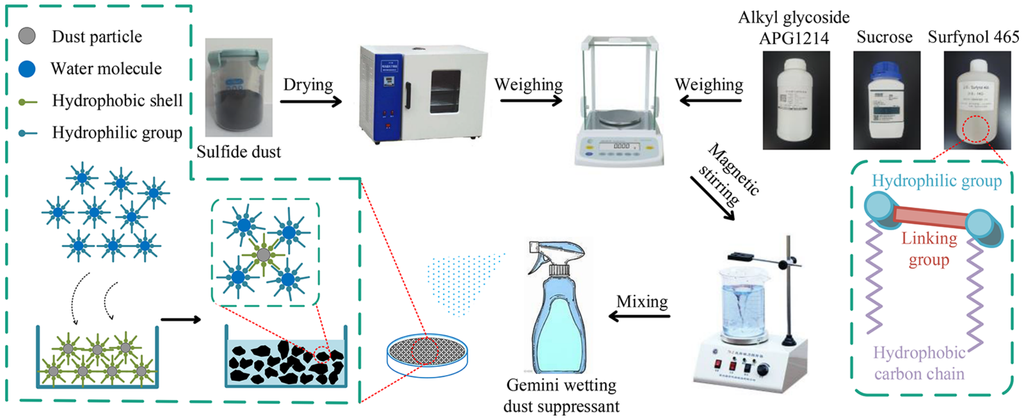


Figure 4. Preparation process and mechanism of the dust suppressant.

Table 3. Arrangement and Experimental Results of Various Factors and Levels in CCD-RSM

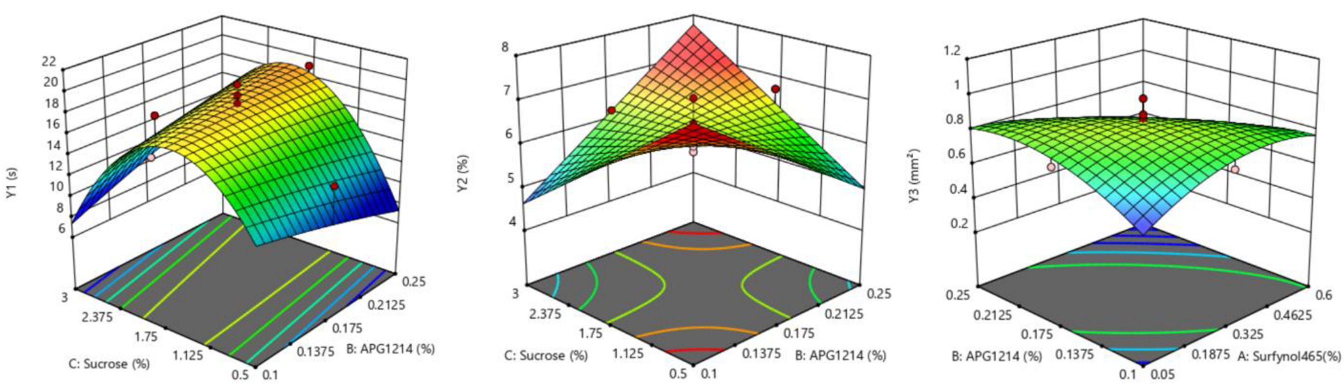
no.	A	B	C	Y1 (s)	Y2 (%)	Y3 (mm^2)
1	−1	−1	−1	12.11	6.584	0.947
2	1	−1	−1	9.21	6.279	0.833
3	−1	1	−1	11.04	6.407	0.991
4	1	1	−1	9.23	4.547	0.839
5	−1	−1	1	10.40	4.874	0.814
6	1	−1	1	11.48	6.372	0.988
7	−1	1	1	16.08	7.032	0.872
8	1	1	1	12.43	6.446	0.608
9	−1.682	0	0	13.17	6.587	0.755
10	1.682	0	0	11.54	6.159	0.630
11	0	−1.682	0	20.35	6.409	0.742
12	0	1.682	0	19.11	6.713	0.663
13	0	0	−1.682	13.39	7.095	0.978
14	0	0	1.682	10.42	6.201	0.990
15	0	0	0	16.02	6.478	0.865
16	0	0	0	19.14	7.061	0.764
17	0	0	0	17.09	5.841	0.783
18	0	0	0	18.27	5.967	0.857
19	0	0	0	18.39	6.117	0.980
20	0	0	0	20.14	6.286	0.889

concentration sampling by a dust sampler. The dust concentration is the average value of the two measuring points; the dust suppression efficiency was calculated according to eq 2 as follows:

$$\eta = (C_0 - C)/C_0 \times 100\% \tag{2}$$

In eq 2, η (%) is the dust suppression efficiency, C_0 (%) is the dust concentration before spraying the dust suppressant, and C (%) is the dust concentration after spraying the dust suppressant.

Figure 8 shows that when the spray dust removal system works continuously for 10 min, the inhibition rates of water mist on respirable dust and total dust are 79.8 and 48.6%, respectively, the inhibition rates of the dust suppressant solution are 90.3 and 71.1%, which are 10.5 and 22.5% higher compared to pure water, respectively, and the inhibition rate of the dust suppressant solution on respirable dust is generally higher than that on total dust; it shows that improving the wettability of water mist can remarkably increase the removal efficiency of the respirable dust. The value of the dust mass concentration of pure water mist is about two times the value of the dust suppressant solution, it is similar to the change value of the spreading area test, and the spreading area of the dust suppressant solution is about 1.8 times to the value of pure water mist. It can be proved that improving the wetting efficiency and anti-evaporation performance of spray mist will increase the dust removal efficiency.



(a) Sedimentation time **(b) Water loss rate** **(c) Spreading area**

Figure 5. Three-dimensional response surface diagram.

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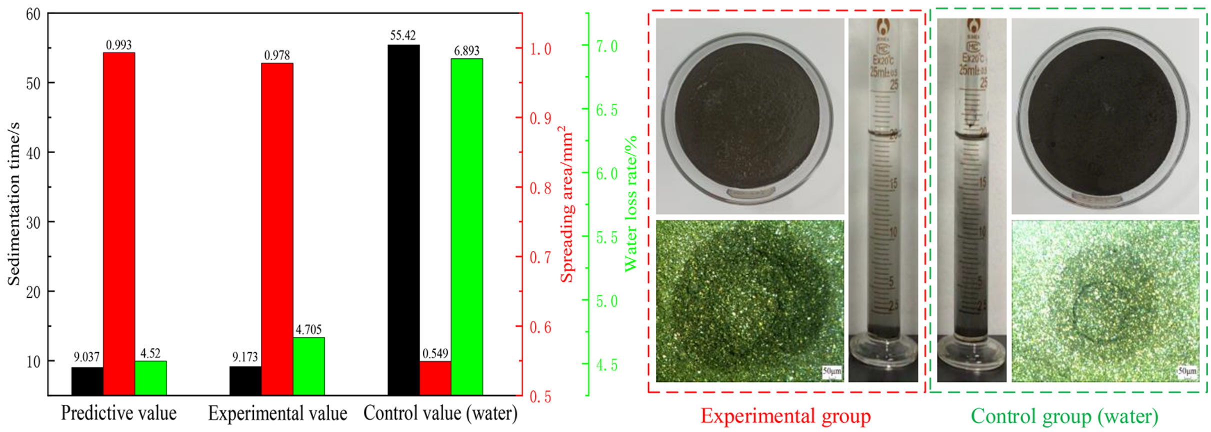

Figure 6. Comparison of experimental and predicted values under optimal conditions for final formulation.

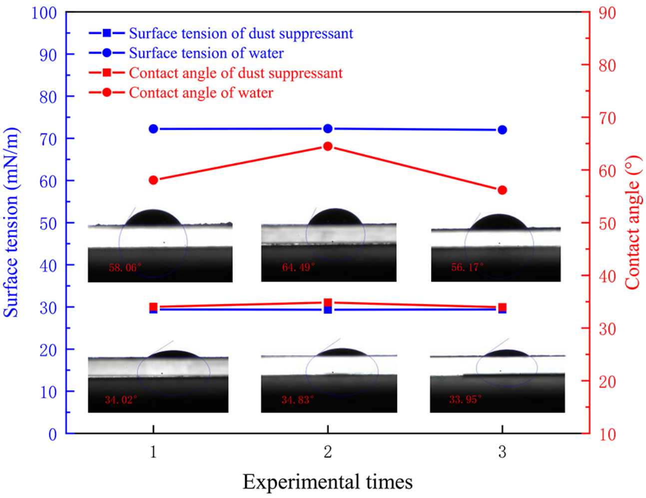

Figure 7. Characterization diagram of the dust suppressant and water.

5. CONCLUSIONS

(1) Aiming at the problems of low wetting efficiency of water mist on respirable and hydrophobic dust, short retention time of water mist and few opportunities for contact with dust, and dust re-entrainment because of the evaporation of the dust—droplet combination, it is proposed to improve the wetting performance and anti-evaporation of water mist to increase the dust removal efficiency of water mist according to the action law of water mist dust capture and chemical dust suppression.

(2) The sedimentation test, spreading area test, and water retention test were carried out to compare and optimize the concentration of dust suppressant components. The results showed that the sedimentation time of the dust sample in the dust suppressant solution was 5.0 times faster than that in water, the spreading area of the dust suppressant solution was 1.8 times that of water, and the water loss rate of the dust sample using the dust suppressant solution was reduced to 70% of that of water.

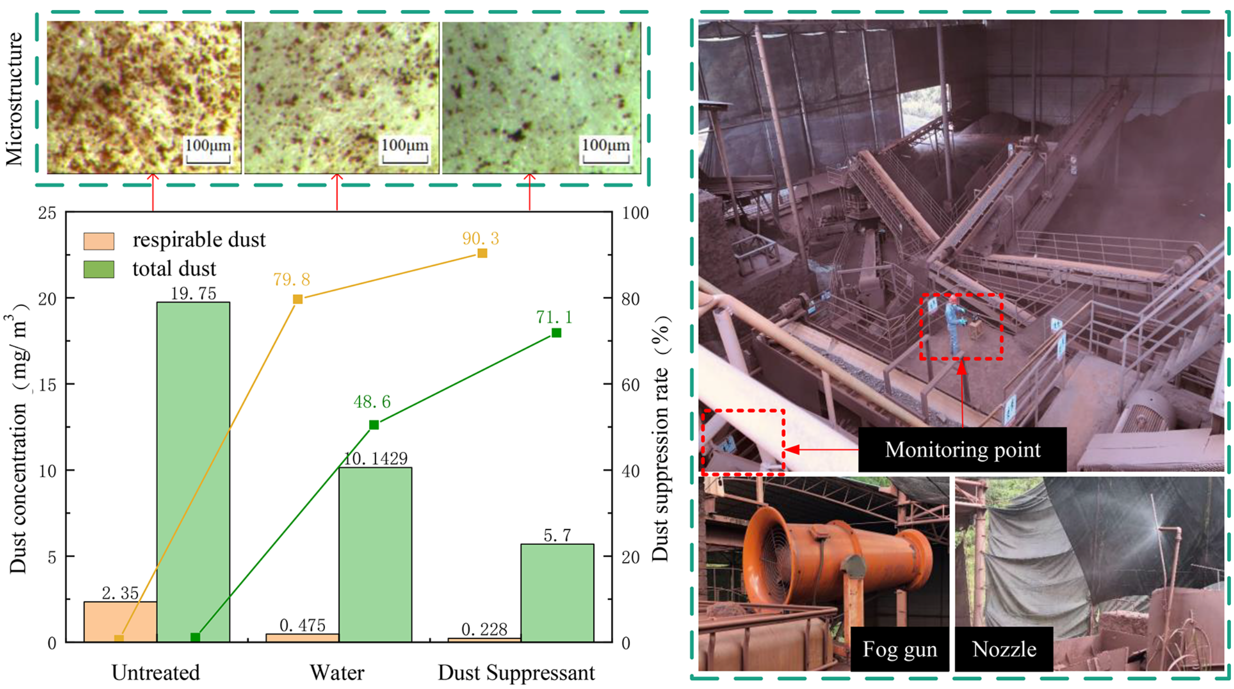

Figure 8. Experimental data and field application diagram.

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(3) The field investigation showed that the inhibition rates of respirable dust and total dust were 90.3 and 71.1%, which were 1.1 and 1.5 times that of water, respectively. It can be proved that improving the wetting efficiency and anti-evaporation performance of spray mist will increase the dust removal efficiency.

AUTHOR INFORMATION

Corresponding Author

Jiao Tang − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China;* orcid.org/0000-0003-1493-4800; Email: tang_jiao2022@163.com

Authors

Ming Li − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China*

Xinzhu Song − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China*

Linling Qiu − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China*

Huaizhen Yang − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China*

Zhi Li − *School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, China;* orcid.org/0000-0003-4062-5358

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c05691

Notes

The authors declare no competing financial interest.

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