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Research Article

Preparation of Lignite Dust Suppressant by Compound Surfactants and Effect of Inorganic Salt on Dust Suppressant

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In order to improve the safety, operability, and cleanability of the dust suppressant, this paper uses the surfactant monomers selected in the previous experiment as the main material formula and adds the inorganic salt as the synergist to prepare the dust suppressant for the PM_X. The wetting property of the solution was characterized by the surface tension and contact angle of the pressed coal pieces. The sedimentation experiment was used to screen the compounding system of the surfactant. Finally, the dust suppressant was used to reduce the dust of the PM_X in the coal dust simulation system. The results show that (1) the surfactant compounding system can effectively improve the wetting property and the sedimentation time of coal dust. The fast penetration T (0.06%), SDBS (0.15%), and APG (0.20%) are the preferred main ingredients. (2) Adding inorganic salts on the basis of compounding, according to the effect of inorganic salts on the effect of dust suppressant, it is concluded that NaCl (1.00%) is the best synergist. (3) In order to save costs, reduce the amount of surfactant. According to the simulated dust reduction experiment, formula N: anionic surfactant SDBS (0.06%), anionic surfactant fast-permeability T (0.06%), and inorganic salt NaCl (1.00%) are the best for PM_X dust fall.

1. Introduction

Coal is still the main energy source in China in the short term. There will be a lot of dust in coal mining [1–3]. Although it is generally mechanized production, the high dust concentration still has security risks [4, 5]. The dust pollution of coal mines is mainly characterized by ultra-high PM_{10}, $PM_{2.5}$, and PM_1 [6]. Coal dust is a coal particle with diameter less than 1 mm. Its main hazards are that high concentration of dust aggravates wear and tear of electrical equipment, shows the hidden danger of coal mine safety, and endangers the health of workers [7–9]. Therefore, it is very important to control the coal dust pollution in the mining face area. It is of great significance to prevent and control coal dust pollution reasonably and minimize its harm to the safety production and control of mines [10, 11].

In order to prevent underground coal dust explosion accidents and to ensure the health of employees, effective dust reduction measures are required. Coal seam water injection, spraying, and water curtain purification are commonly used measures to prevent coal dust explosion, among which wet spraying dust reduction technology is commonly used in coal mines at present. But some coal dust particles are very fine, and it is impossible to reduce PM_X concentration through physical settlement. This is because the surface tension of water is relatively large, and coal dust is not easily wetted by water, which makes it difficult for water spray to wet it quickly to achieve effective dust reduction effect [12–14].

The effect of chemical dust suppression is more significant than that of watering dust and dust suppression nets [15–17]. Researchers at home and abroad have been studying dust suppressants for a long time and attach great importance to the study of chemical dust suppressants [18–20]. According to the dust suppression mechanism, the dust suppressant can be classified into three types: wet type, bonded type, and cohesive type [21]. Bonding dust suppressants are oil organic and salt inorganic. Oil-based organic dust suppressants generally include crude oil, paraffin, high molecular polymers, asphalt, lignin derivatives, resins, and bio-oil residues [18, 22]. However, since such materials are insoluble in water, it is necessary to emulsify these materials, and finally, they are formulated into emulsion of oil, water, and emulsifier. Emulsion is in contact with dust particles and binds the emulsion to dust through physical adsorption and chemical adsorption [23]. The salt inorganic dust suppressant mainly includes clay, halide, gypsum, fly ash, and kaolin. After spraying on the surface of the dust, the dust suppressant can form a hard shell on the surface, thereby suppressing dust flying. Condensed dust suppressants prevent dust from being formed by forming a water film on their own surface to capture dust. It consists of hygroscopic inorganic salt and high water absorption resin, including NaCl, $MgCl_2$, $AlCl_3$, $CaCl_2$, Na_2SiO_3, silica gel, and activated alumina. High-powered water-absorbent resin is a series of polyacrylic acid sodium polymer chemical products [24–26]. It can be divided into three series of starch, fiber, and synthetic polymers according to the source of raw materials. After the water-absorbing resin sol is sprayed on the dust surface, the water starts to evaporate, and the resin loses its viscosity. When it absorbs moisture again, the dust surface has a certain viscosity, thereby controlling the dust flying [27]. The wet type chemical dust suppressant is prepared by mixing a plurality of surface active and inorganic salts, the surfactant mainly serves as a wetting action, and the inorganic salt acts as a moisture absorption. Surfactants are mainly used as anionic, cationic, nonionic, and amphoteric surfactants. The results show that the addition of a small amount of surfactant will greatly improve the efficiency of water capture, so the dust suppressant is suitable for spray system application in fully mechanized mining [28].

Surfactants have a special amphiphilic molecular structure consisting of a hydrophobic group and a hydrophilic group. The strong hydrophobicity of coal dust is the main reason for the effect of water spray on its dust reduction. When the surfactant dissolves in water, the hydrophobic groups change the structure of the water [29]. The surface of the water is covered by a monolayer of surfactant, and the hydrophobic groups of the monolayer mainly face to the air. This arrangement reduces the difference between the two phases contacting each other on the surface. The hydrophobic groups on the surface of coal dust interact with the hydrophobic groups of surfactants [30]. The hydrophilic groups of surfactants extend to the solution, which enhances the hydrophilicity of coal dust and makes it easier for the coal dust to be wetted by the solution. The surface tension can be reduced by improving the effect of wetting dust. It can be used to prepare dust suppressant in a small amount, which can effectively improve the surface tension and contact angle of the solution, and increase the wettability of coal dust to improve the dust control effect [31].

Inorganic salts will ionize anions and cations in the solution. For nonionic surfactants, since they are neutral in water, inorganic salts have little effect on them [32]. But for ionic surfactants, the addition of inorganic salts has a significant impact on it, mainly because the electrostatic effect of the ionic bond enables the inorganic salts to compress the thickness of the electric double layer of the ion head, reduce the repulsive force between the electric double layers, and make the surfactant more easy in the solution [33, 34]. Surface aggregation increases the number of surfactant molecules in the monomolecular adsorption layer on the surface of the solution. Therefore, adding an appropriate amount of inorganic salt to the surfactant system can increase its activity, so that the ability and efficiency of the surfactant to reduce the surface tension of the solution are improved to a certain extent [35].

Therefore, this topic was to screen out different types of surfactant monomers in the research ideas of wetting dust suppressants, compounding according to their properties and performing characteristic analysis and sedimentation experiments on compound solution systems. The effect of inorganic salts on the wettability of the complex solution was studied by adding inorganic salts and verified by characteristic analysis and sedimentation experiments. On the basis of the research, in order to further reduce the cost, the concentration of the surfactant was reduced, and the effect was compared by simulated dust reduction. Finally, the best dust suppressant formula was obtained, which had a certain guiding effect on the treatment of coal dust in the fully mechanized mining face during the coal mining process.

2. Experimental

2.1. Experimental Materials and Reagents

2.1.1. Preparation of Simulated Dust. The simulated dust used in the experiment was lignite from Shaanxi Shenmu. The collected coal samples were pulverized and sieved to prepare 200-mesh dust for use.

2.1.2. Experimental Reagents. Experimental materials are shown in Table 1. Critical Micelle Concentration (CMC) is an important parameter for surfactants and is defined as the lowest concentration at which surfactant molecules associate in a solvent to form micelles. In general, the surface tension is used to measure the critical micelle concentration. When the concentration is greater than CMC, the surface tension does not change.

2.2. Experimental Instruments. Contact angle meter, CA-100, is from Shanghai Yingnuo Instrument Co., Ltd. Wetting is a physical phenomenon common in nature and usually refers to the ability of a liquid to spread on a solid surface. It is now believed that the force at the solid-liquid interface can be expressed by the interfacial tension at the solid-liquid interface. If the droplet is stationary on the solid surface, the sum force of the interfacial tension in the horizontal direction is assumed to be zero, which is called the Young

Table 1: Experimental materials.

Reagent name	Abbreviation	CMC (%)	Types
Sodium dodecyl benzene sulfonate	SDBS	0.15	Anionic
Quick penetrating agent T	T	0.06	Anionic
Cetyl trimethyl ammonium chloride	1631	0.08	Cationic
Dimethyl dodecyl amine oxide	OA-12	0.06	Amphoteric
Dodecyl dimethyl betaine	BS-12	0.10	Amphoteric
Alkyl glucoside	APG	0.20	Nonionic
Fatty alcohol polyoxyethylene ether	JFC	0.15	Nonionic

equation. The contact angle can be derived using the Young equation in combination with contact angle and thermodynamic conditions.

Surface tension meter, SFZL-S, is from Shanghai Yingnuo Instrument Co., Ltd. In this experiment, the surface tension of various surfactants was measured by a platinum plate method. The depth of the platinum plate was measured by an internal sensor of the surface tension meter, and the surface tension value of the liquid was calculated using computer software.

Dust measuring instrument, Model 8530, is from Shaanxi Furunke Electronic Technology Co., Ltd. It uses lignite coal dust with a particle size of less than 200 mesh to simulate particulate matter in the mining face. It adjusts the flow rate of the mixed gas so that the dust concentration meets the requirements of the simulation experiment.

2.3. Sedimentation Experiment. Analysis of the surface tension and contact angle of the monomer solution revealed that they did not directly reflect the relationship between coal dust and droplets. The contact angle is only for the wettability of the solution for the coal piece, and the surface tension is the tension of the liquid surface acting on the gas phase interface, both of which are mainly concerned with characterizing the solution itself. The coal dust sedimentation experiment is more suitable for the relationship between the solution and the coal dust, which can better reflect the dust sedimentation performance of the solution.

Steps of the sedimentation experiment: (1) Prepare a series of surfactant solutions for each concentration required for the experiment. (2) Weigh the drug, and weigh the coal sample 100 mg with an electronic balance. (3) Pour the coal dust into a beaker containing 50 mL of the surfactant solution while using a stopwatch to record the time required for the pulverized coal to start pouring into the solution until the coal dust completely sank into the solution.

This experiment assumes that the time for coal dust to completely sedimentation in the surfactant solution is t, when $t > 5$ h is not sinking, $3 < t \leq 5$ h is micro sinking, and $t \leq 3$ h is complete sinking. The specific settlement process is shown in Figure 1.

2.4. Simulated Dustfall Experiment. The wetting effect of the dust suppressant on the coal dust particles cannot fully characterize the dustfall effect. Therefore, this experiment shown in Figure 2 uses simulated device to study the application of dust suppressant to ultra-low emissions of coal dust and provides a theoretical guidance for the ultra-low emission of particulate matter.

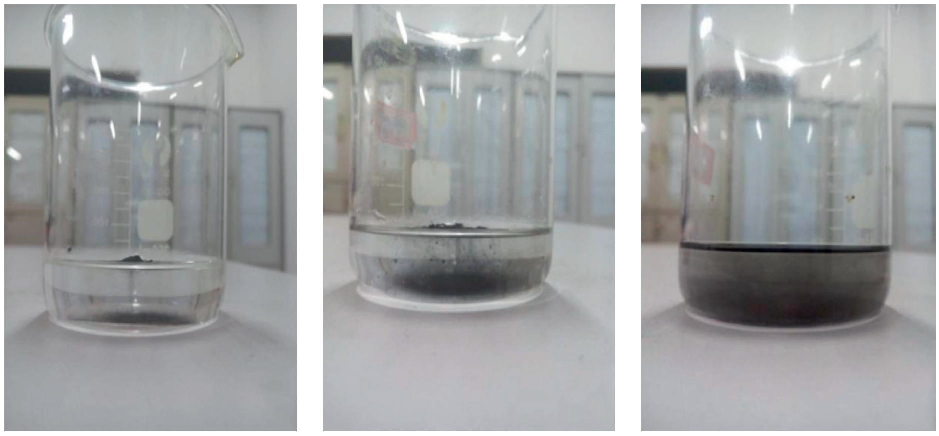
3. Results and Discussion

Various surfactants have their own advantages and disadvantages, and often the use of a single surfactant does not achieve the desired effect. Therefore, most of the industrial dust suppressant agents are in the form of plurality of surfactant monomers. The compounding of the surfactant means compounding between the surfactants or a mixture thereof with other compounds (inorganic salts, fatty alcohols, etc.). The compounding method is a combination of different types of surfactant monomers, and also that of the same of surfactant monomers. The purpose is to produce synergistic effects. Suitable compounding can not only exert the performance of a single surfactant, but also complement each other, so that the wetting effect is better than that of a single surfactant.

3.1. Preparation of Compound Coal Dust Suppressant. According to the previous experimental results, the optimum concentration of the monomer solution is selected by the surface tension, contact angle, and sedimentation experiments of seven different types of surfactant monomers. They are nonionic surfactants JFC (0.15%) and APG (0.20%), amphoteric surfactants BS-12 (0.10%) and OA-12 (0.06%), and anionic surfactants fast-permeability T (0.06%) and SDBS (0.15%), and cationic surfactant 1631 (0.08%).

3.1.1. Surface Tension of Compound Coal Dust Suppressant. These surfactant monomers are compounded in pairs to obtain different compound solutions. The results of the surface tension of the compound solutions are shown in Figure 3. As it can be seen from Figure 3, when the two surfactant monomers are mixed, the properties of the complex solution may be altered due to the intermolecular forces between them. Therefore, the surface tension of the compound solution may be higher, lower, or between the two monomers.

The surface tension of the two nonionic surfactants (JFC and APG) compound solution is smaller than that of the monomers, indicating that the two monomers have a good synergistic effect. The surface tension of the two anionic surfactants (T and SDBS) compound solution is less than that of the two monomers, resulting in synergistic effect. The surface tension of the amphoteric surfactants (BS-12 and



(a) (b) (c)

Figure 1: Different sedimentation effect. (a) Complete sinking, (b) micro sinking, and (c) not sinking.

Figure 2: Simulated PM_X and dustfall device.

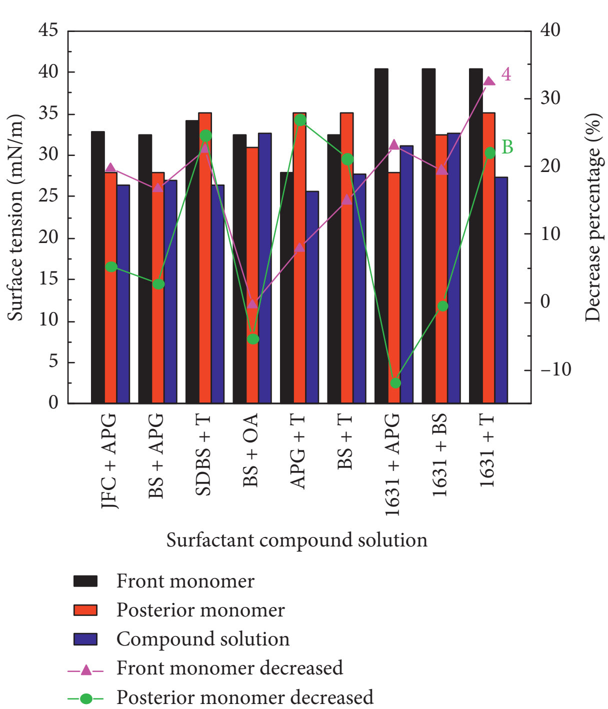


Figure 3: Surface tension of the surfactant compound solution.

OA-12) compound solution is greater than that of the two monomers because of antagonism. The surface tension of the anionic surfactant (*T*) and the nonionic surfactant (APG) is less than that of the two monomers caused by the synergistic effect. The surface tension of the cationic surfactant with any types of surfactant compound solution is greater than that of the two monomers, all of which produce antagonism.

Among them, the anionic surfactant (*T*) and the nonionic surfactant (APG) have the best compounding effect. The reason is that, after mixing the two monomer solutions, a new mixed micelle is formed in the solution, which reduces the homogenous electrical mutual repulsion between the polar groups of the original anionic surfactant. The combination of the anionic surfactant and the nonionic surfactant makes the nonionic surfactant more tight between the molecules, thereby lowering the surface tension of the compound solution. The anionic surfactant (*T* and SDBS) has a good compound effect because they belong to the sulfonate anionic surfactant, and the hydrophobic groups have similar structures, so synergistic effects are produced when compounded.

3.1.2. Contact Angle of Compound Coal Dust Suppressant. The measurement results of the contact angle of the compound solutions are shown in Figure 4. It can be seen from Figure 4 that the contact angles of most of the compound solutions are smaller than those of the monomers, indicating that the compound solutions have a good wetting effect on the coal pieces and completely penetrates the coal pieces in a short time. However, when the cationic surfactant (1631) is compounded with the amphoteric surfactant (BS-12) and the anionic surfactant (fast penetration *T*), the contact angles of the complex solution are between the two monomers. When the cationic surfactant 1631 is mixed with the fast-permeability *T* and BS-12, floccules and even precipitates are easily formed, so that antagonism occurs during compounding.

3.1.3. Sedimentation Performance of Compound Coal Dust Suppressant. It can be seen from Figure 5 that the compound solutions with nonionic surfactant have the better

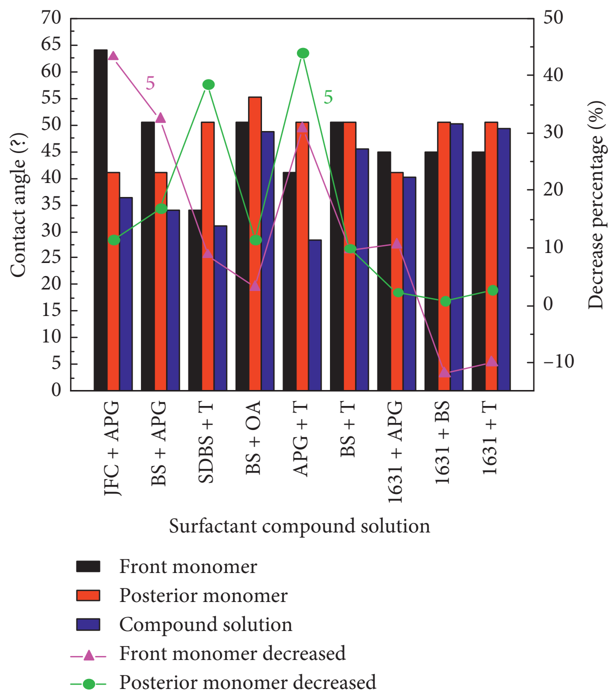


Figure 4: Contact angle of the surfactant compound solution.

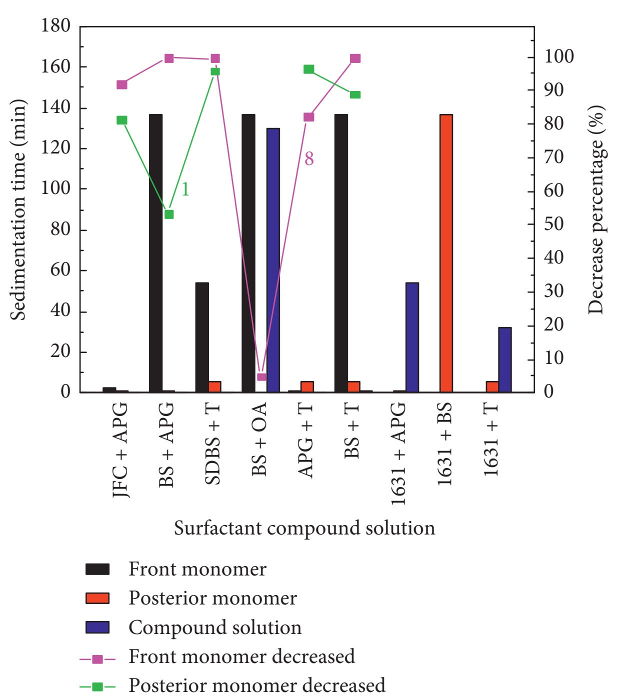


Figure 5: Sedimentation time of the surfactant compound solution.

sedimentation effect. Secondly, the combination with anionic surfactants can also achieve good wetting effect. However, the compound solution containing a cationic surfactant has a certain sedimentation effect, and the sedimentation time is still long compared to other types of compound solutions. Regarding the nonionic surfactant (APG) and nonionic surfactant (JFC), amphoteric surfactant (BS-12) and anionic surfactant (fast penetration *T*), and anionic surfactant (after the rapid infiltration of *T* and SDBS), the sedimentation time of the compound solution is less than that of the two monomers, and the sedimentation time is less than 1 min. Moreover, the sedimentation time is reduced over 95% in the APG + *T* and SDBS + *T* compared with that of the monomers, and the effect is remarkable. In summary, the fast penetration *T*, SDBS, and APG can be used as the main ingredients of the dust suppressant formulation.

In fact, the decrease percentage here is the ratio of the front and posterior monomers to the compound solution. The reason for the abrupt decrease here is that the front monomer is close to the compound solution, so there is basically no decrease, resulting an abrupt decrease in Figures 3 to 5 in the manuscript.

3.2. Influence of Inorganic Salts on Dust Suppressants

3.2.1. Effect of Inorganic Salts on the Surface Tension of Dust Suppressant. As is shown from Figure 6, in order to make the performance of dust suppressants better, the soluble inorganic salt is added as a synergist in the compound solution to improve its properties and achieve the best wettability. In this experiment, a synergist is added to the compound solution of APG and fast penetration *T*, fast penetration T, and SDBS. NaCl, $CaCl_2$, Na_2SO_4, and Na_2SiO_3 are selected as synergists to prepare a solution with a mass concentration of 1%. The surface tension, contact angle, and sedimentation performance of the dust suppressant are tested. And define NaCl, $CaCl_2$, Na_2SO_4, and Na_2SiO_3 as A, B, C, and D, respectively.

3.2.2. Effect of Inorganic Salts on the Contact Angle of Dust Suppressant. As it can be seen from Figure 7, the addition of an inorganic salt can reduce the contact angle of the dust suppressant. Among the four inorganic salts, NaCl can significantly reduce the contact angle of the dust suppressant and increase the wettability of the solution to the coal. Only Na_2SiO_3 has a negative correlation with the contact angle of SDBS + *T*, which produces an antagonistic effect.

3.2.3. Effect of Inorganic Salts on the Sedimentation Performance of Dust Suppressants. It can be seen from Figure 8 that the sedimentation time of the dust suppressants of APG + *T* after adding the synergist is smaller than that of SDBS + *T*. After the addition of the inorganic salt, the sedimentation time of the SDBS dust suppressant increases, while the sedimentation time of the dust suppressant of only APG + *T* of NaCl and Na_2SO_4 decreases. It is indicated that, for the anionic surfactant, the addition of the synergist is not conducive to the sedimentation of the coal dust in the dust suppressant solution.

The abrupt decrease in Figures 6 to 8 is due to an antagonistic effect of inorganic salt Na_2SO_4 on APG + *T*, and its surface tension, contact angle, and sedimentation

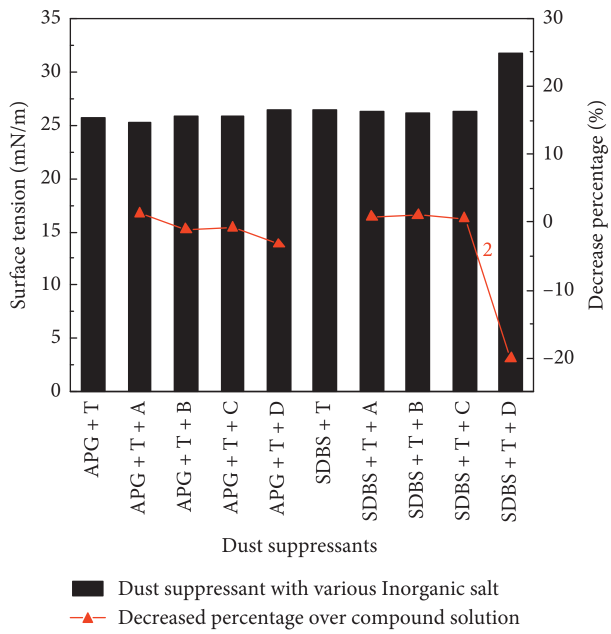


Figure 6: Effect of inorganic salts on the surface tension of dust suppressant.

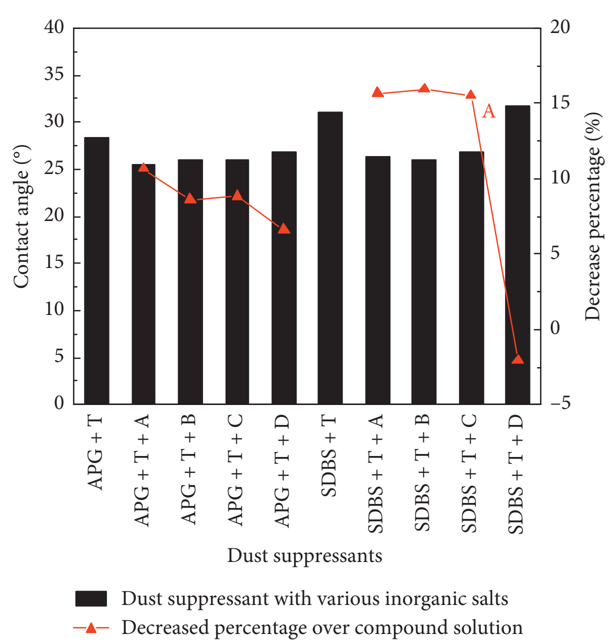


Figure 7: Effect of inorganic salts on the contact angle of dust suppressant.

performance are all lower than those of other inorganic salts (NaCl, $CaCl_2$, Na_2SO_4 and without inorganic salts).

3.3. Effect of Dust Suppressant on Coal Dust. On the basis of research and from the perspective of cost, the amount of surfactant of the dust suppressant described above is reduced. The dust suppressant was designated as Formula *M*: nonionic surfactant APG (0.10%), anionic surfactant fast

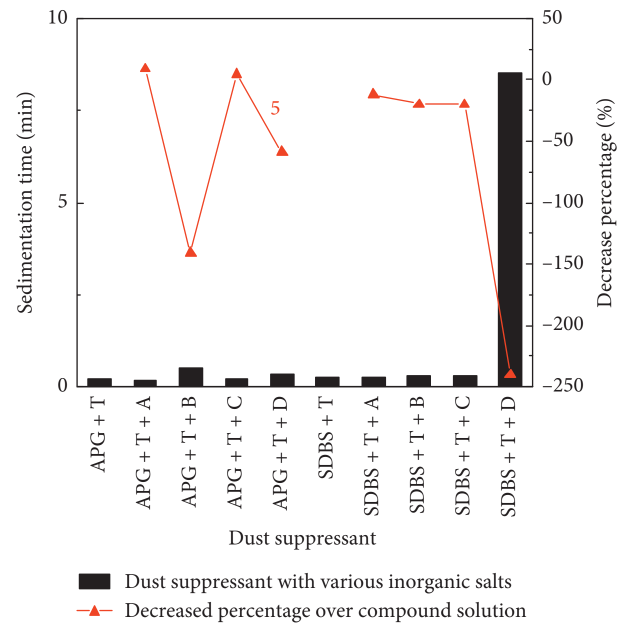


Figure 8: Effect of inorganic salts on the sedimentation time of dust suppressant.

osmosis *T* (0.06%) and inorganic salt NaCl (1%), and Formula *N*: anionic surfactant SDBS (0.06%), anionic surfactant fast osmosis *T* (0.06%) and inorganic salt NaCl (1%). It can be clearly seen from Figure 9 that spraying the dust suppressants *M* and *N* into the simulation device can effectively shorten the time required for the PM_X to be reduced from 80 to 30 mg/m^3. The time required to simulate the dust reduction effect of PM_X in the flue gas is reduced by about 60%, especially for PM_1.

After presenting the results and observations, these experimental results and phenomena have a good guiding significance for our work. We use coal dust as the research object, therefore, when we are in the coal mining face or where coal is deposited, due to the coal dust caused by fine particles, and we can use our surfactant solution to suppress dust, so as to achieve good environmental benefits. And the surfactant formula we prepared will not cause pollution to the environment, and it is a green and environmentally friendly dust suppressant.

And after being compounded with different types of surfactants, it shows different sedimentation properties for coal dust. Therefore, the activity of various surface is the main factor that affects the sedimentation of coal dust, because different surfactants show different properties in water. Nonionic surfactants are neutral in water and cannot ionize anions and cations. The ionic surface active agent can ionize the corresponding anions and cations to promote their directional arrangement in the aqueous solution and change the dust reduction effect of the aqueous solution on coal dust. However, how the specific surfactant compound system works with the surface of coal dust, and some related detection methods will be further developed in our follow-up research. As far as we know, the functional groups on the surface of coal dust will affect the effect of surfactants on it,

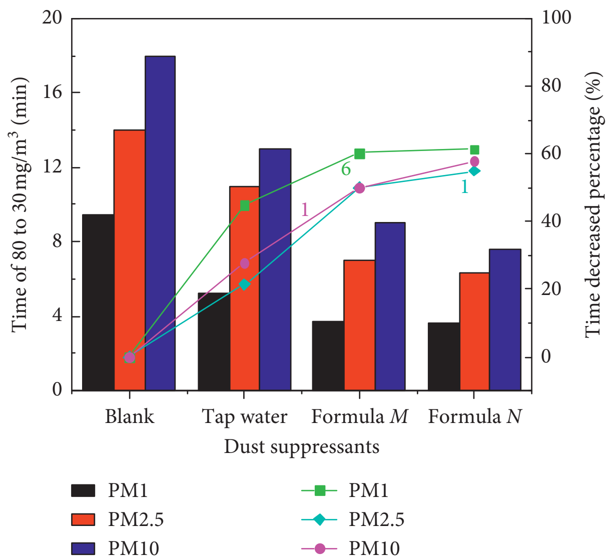


Figure 9: Dustfall effect of dust suppressant.

and the particle size distribution of coal dust is also one of the influencing factors. As for the surfactant, its functional group is also one of the research scopes, and the form and state in water are also the focus of research.

At present, the most effective and direct method for dust suppression is ground fugitive dust. The most effective and direct method for its suppression is the arrangement of dust suppression and dust nets by spraying water mist. Dust suppression agents prepared by surfactants are also one of the effective means. But for underground coal mining face and coal accumulation area, effective control of coal dust particles is the focus of environmental protection. However, because coal contains a large number of organic macromolecules, water has a poor dust suppression effect on coal dust particles, and the organic molecular structure and branch chains contained in surfactants make it have a good coal dust suppression effect. Moreover, the surfactant used in this experiment is a low-foaming or nonfoaming material, which will not cause foaming in a local area of the underground working face. Therefore, the development of this experiment has a good guide for the suppression of underground coal dust and environmental safety.

Regarding the coal dust suppression area, there is a great demand for water. The development of this experiment guides companies to add a small amount of surfactants to the water to achieve good dust suppression effects, and the surfactants are cheap and environmentally friendly. Therefore, most companies in the coal industry that need dust suppression can learn from the methods used in this experiment.

In the development of this experiment and the anticipation of subsequent work, the performance and structure of surfactants are more difficult to detect. Due to insufficient funding for scientific research, the structure of the material cannot be tested and explained in a cryo-electron microscope. In addition, there are relatively few characterization methods for surfactant liquid materials, which cannot describe the function and effect of the material itself in a more detailed and objective manner.

In future work, we hope that a substance similar to surfactant can be extracted from the roots, stems, and leaves of plants that are more environmentally friendly to meet the dust suppression effect. And related testing instruments can be used by us to illustrate the structure and function of liquid materials.

4. Conclusions

When compounding various types of surfactant monomers, the surface tension of the compound solution may be higher, lower, or between the two monomers. Among them, when two kinds of nonionic surfactants (JFC, APG) and two anionic surfactants (fast penetration *T*, SDBS) are compounded; synergism is produced. Antagonism occurs when an amphoteric surfactant (BS-12, OA-12) and a cationic surfactant (1631) are compounded with any type of surfactant. The combination of anionic surfactant and nonionic surfactant has the best effect, and the surface tension of the compound solution decreases the most.

Only the mixing of the cationic surfactant with the amphoteric surfactant and the anionic surfactant produces an antagonistic effect such that the contact angle of the compound solution is greater than the contact angle of the two monomer solutions. After compounding Nonionic surfactant (APG) and nonionic surfactant (JFC), amphoteric surfactant (BS-12) and anionic surfactant (fast penetration *T*), anionic surfactant (fast penetration *T*), and anionic surfactant (SDBS), the sedimentation time of the compound solution is less than that of the two monomer solutions. The sedimentation time is short, and all are less than 1 min.

After the addition of inorganic salts, the performance of the dust suppressant is improved to some extent. By measuring the surface tension, contact angle, and sedimentation test of the dust suppressant, it can be found that the inorganic salt with the best synergistic effect is NaCl.

On the basis of experiments, in order to reduce costs, the amount of surfactant is reduced. According to the dustfall experiment, the dust suppressant can effectively reduce the dustfall time. The best dust suppressant formula is nonionic surfactant (APG) (1.00%), anionic surfactant (fastening *T*) (0.06%), and synergist NaCl (1.00%).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Conceptualization is done by Zhang Lei (F) and Zhao Lu (M). Methodology is done by Shu Hao. Software is handled by Jia Yang. Validation is performed by He Jian and Wen Xin. Investigation is done by Zhang Lei (M). Data Curation is performed by Shu Hao. Writing-Original Draft Preparation is done by He Jian. Writing-Review & Editing are done by He Jian.

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