ABSTRACT: With an aim at the dust problem of open dust sources in construction sites, open stockyards, mines, docks, and other areas, a polymer chemical dust inhibitor was developed in this study that is suitable for stockyards through theoretical analysis and laboratory tests. Through a single-factor experiment and an orthogonal experiment, the viscosity value of dust suppressant and the hardness value of the crust taken as evaluation indexes, the optimal formula of dust suppressant for a pile was finally obtained after an analysis of range and variance: the optimum formulation of the dust suppressant for stockpiles was finally obtained by: 0.6%A + 0.2%B + 0.28%C + 0.7%D. The performance of the dust suppressant was characterized. The results showed that the longer the suppression time of suppressants, the better the weather resistance and environmental friendliness. Polymeric dust suppressants for stockpiles can effectively suppress the open dust, improve the air quality, protect the climate environment, and maintain people’s health and have a certain industrial application prospect.

1. INTRODUCTION

The open dust sources of construction fields, open stockpile fields, mines, and wharves are an important increasing urban dust source. In the process of open stockpile transportation and long-term stacking, due to the lack of adhesion, looseness, dryness, friability, and protective layer, the stockpile is exposed to natural weathering, and it is easy to produce a great deal of dust by wind action. Such an open dust source is difficult to supervise without systematic control methods, and the dust pollution produced has seriously affected urban air quality, further endangering people’s health and affecting production safety. Therefore, it is urgent to implement the dust suppression of the stockpile and develop a dust suppressant.

Dust suppression by sprinkling water, dust containment structure suppression, dust-proof covering with a net, chemical dust suppression, and other dust-prevention methods are commonly used. At present, due to the lack of water resources, the cost of sprinkling water to suppress dust has increased. Moreover, due to the drought and little rain in northern China, rapid evaporation, a short time of sprinkling water to suppress dust, and freezing in winter, the effect of this practical application method is limited. The method of covering with canvas also has the disadvantages of a small coverage, such as small coverage area, poor use effect, and no solution for secondary dust. The method of using chemical dust suppressants to suppress dust has been widely adopted by countries all over the world since its birth and has achieved good results and broad application prospects. From the perspective of performance and economy of dust suppression products developed by various scholars, there are still common problems such as high cost, inconvenient use, relatively single performance, poor durability, and a certain degree of environmental pollution. Therefore, the large-scale promotion and use of dust suppressants in dust suppression and sand fixation are limited. Polymer dust suppression devices that are cheap, multifunctional, durable, convenient, and ecologically benign are on the horizon.
and application but also provides the theoretical data and technical basis for further research of new dust suppressants.

2. MATERIALS AND METHODS

2.1. Single-Factor Experiment. The best compounding agent and the most suitable concentration of each compounding agent were determined using a single-condition experiment of hygroscopic, film-forming, filler, and surfactant agents. The specific condition of the hygroscopic agent was determined among PAA-Na, CMS, glycerol, TEA, and TMPTA. Solution A was determined as the monomer of the moisture-absorbing agent by determining the hygroscopicity. The content varies between 0.45% and 0.6%. The surfactant single factors used were NADDBS, SLS, and SDS. Solution B was chosen as the surfactant monomers to execute an orthogonal test, whose concentration varied from 0.15% to 0.3%, on the basis of an osmosis test with a friction coefficient value. The packing components used were guar, xanthan, SAA, and soluble starch. The filler monomer C for the orthogonal test, whose concentration ranged from 0.16% to 0.28%, was identified by tests on the value of the hardness of the crust of the solution and the resistance to water. As a single condition of film formation, CMC cellulose, 1788 PVOH, and PEGA were used. For the orthogonal experiment (the ratio of 1 and 2 is 1:2) the film formation was determined as the monomer of the film-forming agent, whose concentration ranged from 0.5% to 0.8%, on the basis of the film-forming characteristics, stickiness level, measurement, correlation, a test of water resistance to corrosion of the finished layer, and tests on the film’s physical qualities.

2.2. Experimental Design of Orthogonal Experiment. This experiment’s goal is choosing the dust suppressant’s initial formula concentration; therefore, factors must be chosen and the level determined. Different explanations or circumstances that directly affect the test signs are referred to as “factors”. The so-called level refers to the variation in the value of the experiment’s chosen component. The variables in this experiment are the different compounding agents, such as water absorption agents, film-forming agents, surface active agent, and filters, and for every blending agent, the dose is the specified concentration value. In this paper, four components were chosen, each with a concentration level of 4. The standard orthogonal table L16(45) was used to arrange the experiment on the basis of the values of components and doses chosen. The chart can include up to four tiers and five elements. This experiment just requires four of them. The stochastic error can be approximated by using a blank column in doing an analysis of variance (ANOVA) for the orthogonal experiment data.

2.3. Experimental Design of Characterization of Dust Suppressant. 2.3.1. Design of an Experiment to Characterize the Fundamental Physical and Chemical Features of a Dust Suppressor.

(1) Viscosity. The dust suppressant’s stickiness is connected to its stability and is a significant indication to evaluate the dust suppressant’s performance. When the temperature in the solution was held at 25 °C, a rotating viscometer (the instrument model is NDJ-5S) was applied to test the stickiness of the dust suppressant, as stated in the GB/T10247-2008 standard Viscosity Measurement.

(2) Surface tension. The surface tension was measured by a surface tension meter (the instrument manufacturer was BZY). Due to the high viscosity of the measured solutions, a platinum plate needed to be wetted a 5 mm height in the process of measurement and some of the surface solution was gently wiped with paper. A sample table was used to record the stable value with maintenance of the displayed value of 0–5 mN/m.

(3) pH value. The pH value of the dust suppressant was measured with a pH meter (the instrument manufacturer was Mettler Toledo) in the experiment. A dust suppressant that had too much acid or too much alkali could change the performance of the materials and may might have an influence on the surrounding soils. After the best ratio of dust suppressant solutions was determined, the pH value was obtained with a pH meter.

2.3.2. Experimental Design of Surface Curing Effect. An 80 g portion of experimental sand was evenly deposited on a conical surface plate. A 15 mL portion of dust suppressant was sprayed uniformly on the sand pile’s surface, and the sand pile was then dried naturally at room temperature. The properties and cross-section of the sand pile were observed by properly spraying 40 g of the experimental sand on a 475 mm watch glass with 10 mL of deionized water or the dust suppression solution. When the samples of sand were naturally dried, the surface layers were taken as samples for carbon spraying. Then the surface layers of both samples were analyzed through an environmental scanning electron microscope. With an amplification of the surfaces of samples, the bonding state between sand grains could be observed directly from the surface microscopic morphology and compared with the sand mold surface sample in a control group dried after spraying deionized water.

2.3.3. Experimental Design of Compression Strength. The compressive strength represents not only the strength of the dust suppressant–sand particle bonding but also the intensity of the dust suppressant–sand combination generated consolidation level. A nonstandard component of a sand column sample (produced by the dust suppressant made according to the ideal formula) were crushed by a WDW-200D universal material testing machine at 2 mm/min compression speed in a room set at the specific temperature of 25 °C. The maximum compressive strength was determined by the connection between the sand column’s compressive strength and displacement.

2.3.4. Experimental Design of Performance of Moisture Absorption and Moisture Release. After they were sprayed with dust suppressant, sand grains of the sand mold sample on the surface layer could form a rigid consolidated layer due to the cohesive effect of dust suppressants. The hygroscopic agent in the dust suppressant could play a role in retaining moisture and reducing evaporation, and the consolidated layer could play a certain covering role in protecting the inner sand grains from causing the raising of dust. The moisture absorption and moisture release performance of dust suppressants reflects the sand-fixing effect of dust suppressants. The performance of moisture absorption and moisture release of dust suppressants is represented by the moisture absorption rate $W$ which is shown as eq 1

$$W = \frac{m_i - m_f}{m_0} \times 100\%$$  

(1)
where $W_r$ is the dust sample moisture absorption rate after spraying for several hours (%), $m_1$ is the Petri dish and dust sample weight (g) after spraying for several hours, and $m_2$ is the Petri dish and dust sample initial weight (g). Six identical sand molds were prepared; five sand molds were evenly sprayed with 10 mL of the dust suppressant solution, and the other sand mold was evenly sprayed with 10 mL of deionized water. All six samples were dried to constant weight at 105 °C in a drying oven and cooled naturally in a drying oven with the lid closed. Their weight was measured and recorded as the initial weight. All of the molds produced were placed in a cool and ventilated environment. The weights of all the sand mold samples was measured at 9 am and 18 pm for 10 days, to calculate the moisture absorption of the sand mold sample $W_r$.

2.3.5. Experimental Design of Performance of Resistance to Wind Erosion. The integrity of the consolidation level generated with the dust suppressant is mostly responsible for the wind erosion resistance. If the consolidated layer can stay immobile, reducing the risk of poor weather and wind raising dust. Fifteen milliliter portions of the dust suppressant solution and of deionized water solution were evenly sprayed on the surface of the sand pile samples, and the samples were dried at a temperature of 80 °C and weighed. The surface of a sand mold sample was blown in parallel through an SF type axial flow blower for 10 and 30 min, respectively, with four and seven gusts. The state of the consolidation layer under different conditions was observed. The wind erosion rate can be calculated by eq 2.

$$W = \frac{(m_1 - m_2)}{m_1}$$

(2)

where $W$ is the wind erosion rate (%), $m_1$ is the weight of the sand mold sample before blowing (g), and $m_2$ is the weight of the sand mold sample after blowing (g).

2.3.6. Experimental Design of Rain Resistance. This experiment studied the ability of dust suppressants to resist rain erosion in a natural environment. Fifteen milliliter portions of the dust suppressant solution and deionized water were evenly sprayed on the surfaces of the sand pile samples, and the samples were dried in a high-temperature blast drying oven (at the temperature of 80 °C) and weighed. Simulated rainfall was carried out by spraying water at a flow rate 2 mL/s for 2 min, and the sample was weighed after it was dried, constituting a spraying cycle. After each spraying cycle, the mass residual rate $L$ can be calculated according to eq 3, and the spraying cycle was repeated a total of five times.

$$L = \frac{m_2}{m_1}$$

(3)

where $L$ is the weight residue rate (%), $m_1$ is the weight of the sand mold sample before spraying (g), and $m_2$ is weight of the sand mold sample after it was sprayed and dried (g). The weight residue rates for two sets of sand mold samples were recorded.

2.3.7. Experimental Design of Performance of Freezing and Thawing Resistance. Since the dust suppressant will be exposed to extreme temperature variations in its actual use, it should be able to withstand freezing and thawing. The compressive strength of a dust suppression sand column sample that experienced varying thawing cycles was assessed in this experiment and utilized as an indication to balance the consolidated performance of dust suppressant after numerous freezing–thawing cycles. Five sand columns were sprayed with a dust suppressant and held at temperatures below −20 °C for 12 h and then below 80 °C for another 12 h. The columns were taken through a freeze–thaw cycle five times. A pressure test was performed on the samples from each freeze–thaw cycle using the procedure described in section 2.3.3.

3. RESULTS AND DISCUSSION

3.1. Study of the Dust Suppressant's Formulation. As is illustrated in Table 1 in the orthogonal test, 16 dust suppressant solutions were formulated. The stickiness of each mixture and the hardness for the curing layer were evaluated, and the best dust suppression formulation was eventually established using a range analysis and variance analysis.

3.1.1. Range Analysis of Orthogonal Test. According to the results of a single-factor experiment, the orthogonal experiment’s four factors are A, B, C, and D. The formula table for 16 orthogonal tests was obtained using an L$_{16}(4^4)$ orthogonal table, as shown in Table 1. As an assessment index, the stickiness of the dust suppression mixture is used. The average values of the stickiness and hardness as indicators are assigned to the vertical axis in Figure 1, and the values of the four indicators are determined as the horizontal coordinate in Figure 1, in order to display more directly the effect patterns of factors A, B, C and D with regard to the the index of the viscosity level. Figure 1a depicts the average response against the viscosity index.

The effect of the four values A, B, C and D on the stickiness factor is shown as the mean value of the stickiness index. The greater the stickiness, the more prominent the dust suppressant’s influence on dust collection and consolidation. Figure 1a shows that the maximum values of A, B, C, and D are 4, 1, 4 and 3, respectively. The best combination of the viscosity orthogonal experiment is 4, 1, 4, and 43 for A, B, C, and D, respectively. The stickiness of the dust suppressant mixture incrustation is used for the ssment index. The hardness of the cured layer of surface dust samples was examined after drying of 16 different dust suppression solutions. Figure 1b depicts the average value of the hardness index as a response figure. The effect of four tiers of variables on the hardness index is reflected in the mean value of the hardness index. The greater the hardness of the solidified layer, the more prominent

Table 1. Orthogonal Experiment Formulation Grouping Chart

| experiment no. | A   | B   | C   | D   |
|----------------|-----|-----|-----|-----|
| 1              | 0.45| 0.15| 0.16| 0.5 |
| 2              | 0.45| 0.20| 0.20| 0.6 |
| 3              | 0.45| 0.25| 0.24| 0.7 |
| 4              | 0.45| 0.30| 0.28| 0.8 |
| 5              | 0.50| 0.15| 0.20| 0.7 |
| 6              | 0.50| 0.20| 0.16| 0.8 |
| 7              | 0.50| 0.25| 0.28| 0.5 |
| 8              | 0.50| 0.30| 0.24| 0.6 |
| 9              | 0.55| 0.15| 0.24| 0.8 |
| 10             | 0.55| 0.20| 0.28| 0.7 |
| 11             | 0.55| 0.25| 0.16| 0.6 |
| 12             | 0.55| 0.30| 0.20| 0.5 |
| 13             | 0.60| 0.15| 0.28| 0.6 |
| 14             | 0.60| 0.20| 0.24| 0.5 |
| 15             | 0.60| 0.25| 0.20| 0.8 |
| 16             | 0.60| 0.30| 0.16| 0.7 |
the compressive and antirheumatic performance of the dust suppressant incrustation. As is shown in Figure 1b, the maximum values of A, B, C, and D are 4, 2, 4, and 2, respectively. The optimal combination of hardness orthogonal tests is 4, 2, 4, and 2 for A, B, C, and D, respectively.

3.1.2. Analysis of Variance in Orthogonal Experiment. A variance analysis was used to better understand the effect of all experimental conditions on the overall performance of dust suppressants, using the viscosity and hardness as assessment markers. Table 2 displays the results.

Table 2 shows that, when the viscosity of the dust suppression solution is used as the performance assessment index, the factor A has a considerable effect on this index. When the stickiness of the dust suppression mixture is used as the performance assessment indicator, factors A and B both have a considerable effect on the hardness of the dust suppressant mixture. The other two factors have no influence on the performance assessment index, whether it be viscosity or hardness.

The degrees of freedom for each source are denoted by df. The degrees of freedom are 2 (n − 1) if the factor has three levels, adj ss is the sum of squares between groups (factor) and within groups (error), adj ms is the sum of squares divided by the degrees of freedom as the mean square, the F value is calculated by dividing the factor ms by the error ms (this ratio can be compared to the F critical found in Table 2). F critical is a specific value that can be obtained by consulting the F boundary table. Since the formula results obtained by the range and variance analysis were different, the comprehensive balance method was adopted to confirm the optimal formula. A factor has a positive and considerable influence on each assessment index as the major factor governing the alterations of numerous evaluation indices. Furthermore, when the concentration of the dust suppressant was increased, the viscosity and hardness of the dust suppressant increased, therefore 4 was chosen as the best amount for factor A. Because factor B has a greater effect on the hardness index than on the viscosity index, 2 is chosen as the best amount on the basis of the hardness assessment index. The influence of factors C and D on the viscosity index is more significant in comparison to that on the hardness index; thus, 4 and 3 are chosen as the optimal levels for factors C and D, respectively, for the viscosity index. To sum up, the optimum ratio of dust suppressant is 4:2:4:3: namely, 0.6% A + 0.2% B + 0.28% C + 0.7% D.

3.1.3. Validation Experiments. According to the optimum conditions obtained from the orthogonal experiment, the experiment was conducted. The dust suppressant solution was prepared according to the formula of 0.6% A + 0.2% B + 0.28% C + 0.7% D (consisted of 0.46% D2 + 0.24% D1). After three parallel tests, the average viscosity is 4179 mPa s, and the average hardness is 37.45 HD. It can be seen that the viscosity and hardness of the dust suppressant are higher than those in

![Figure 1](image_url). (a) Mean value response graph of the viscosity of the curing layer. (b) Mean value response graph of the hardness of the curing layer.

| experiment | df | adj ss | adj ms | F   | F critical(0.10) | significance |
|------------|----|--------|--------|-----|-----------------|--------------|
| viscosity  |    |        |        |     |                 |              |
| factor A   | 3  | 3232988| 1077663| 7.87| 5.36            | remarkable   |
| factor B   | 3  | 279374 | 93125  | 0.68| 5.36            | unremarkable |
| factor C   | 3  | 1407519| 469173 | 3.42| 5.36            | unremarkable |
| factor D   | 3  | 523067 | 174336 | 1.27| 5.36            | unremarkable |
| error      | 3  | 411014 | 137005 |     |                 |              |
| total      | 15 | 5853961|        |     |                 |              |
| hardness   |    |        |        |     |                 |              |
| factor A   | 3  | 80.25  | 26.75  | 14.13| 5.36            | remarkable   |
| factor B   | 3  | 36.93  | 12.31  | 6.5  | 5.36            | remarkable   |
| factor C   | 3  | 10.51  | 3.51   | 1.85 | 5.36            | unremarkable |
| factor D   | 3  | 0.9    | 0.3    | 0.16 | 5.36            | unremarkable |
| error      | 3  | 5.68   | 1.89   |     |                 |              |
| total      | 15 | 134.28 |        |     |                 |              |

*a The F test is used to assess the relevance of decomposing the variance of a variable into various parts according to different needs, comparing the magnitudes between them, and decomposing the variance of a variable into different parts according to different needs. It is a significant test for the difference between the means of two or more samples, often known as the “analysis of variance” or “F test”.

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the orthogonal test. To sum up, the optimized formulation has a better comprehensive performance.

3.2. Characterization of Dust Suppressant. In the actual application process, different types of weather conditions will be faced. It is necessary to explore the performance of dust suppressants under different conditions (such as rainfall, gale, frost, heat, and so on). Therefore, a characterization experiment was carried out on the dust suppressant.

3.2.1. Dust Suppressant’s Basic Physical and Chemical Properties. The ideal dust suppressor formula’s viscosity, surface tension, and pH value were all examined. The dust suppressant has a viscosity of 4131 mPa s. When the viscosity values of the orthogonal tests are compared to the viscosity values for the same rotor and rotating speed, the viscosity value was clearly increased. It can be shown that the dust suppressant may be adequately diluted in practical applications, lowering the cost of dust suppression. The dust suppressant’s surface tension is 37.13 mN/m. The interfacial pressure of the dust suppressant is lowered as a result of the addition of the surfactant, and it can effectively penetrate into the sand during the spraying process. The pH value of dust suppressant is 8.31, which makes it weakly alkaline.

3.2.2. Surface Curing Effect. A certain thickness of the consolidation layer came into being on the surface of a sand mold sample after spraying dust suppressant (Figure 2a,b).

Figure 2. (a) Sand mold consolidation layer. (b) Section of a sand mold sample consolidation layer. (c) Scanning electron micrograph of a sand mold sample surface after spraying deionized water. (d) Scanning electron micrograph of a sand mold sample surface after spraying the dust suppressant solution.

The consolidation layer can prevent the diffusion of sand and the dust source, slow down the evaporation of water, and reduce the risk of inducing a dust-raising disaster. Figure 2c,d shows micrographs of the microstructure on the mold sample surface sprinkled with deionized water and dust suppressant taken with a scanning electron microscope (Figure 2d). Parts c and d of Figure 2 are compared. The loose sand particles on the sample surface sprinkled with deionized water do not form a solid agglomeration structure, resulting in a poor compressive strength. It is easy to see binders created between sand grains on the sample surface sprinkled with the dust suppression mixture after the dust suppressants have dried. Sand particles clump together, forming a consolidated layer with increased compressive strength. This microstructure also serves as a basis for sand stabilization, antiwind and antewater erosion, and dust emission reduction through the use of a dust depressant.

3.2.3. Compression Strength. Figure 3 shows the variation in compression strength of the sand column sample (Figure 3a) after spraying the dust suppression solution (Figure 3b).

Figure 3. (a) Optical image of the sand column sample before it was pressed. (b) Variation of compressive strength $t$ of the sand column sample with displacement. (c) Optical image of the sand column sample after being pressed. (d) Caking of the sand column sample after being pressed.

Figure 3b shows that, following elastic strain and hysteretic elastic deformation, the sand column sample sprayed with the dust suppressor solution reaches the yield point with increasing displacement. The maximum compressive strength was 0.33 MPa when the displacement was 2.41 mm. After that the sand column was broken (as shown in Figure 3c,d). In a word, the compression experiment showed that the dust suppressants in this paper have good binding ability and a consolidation effect to sand and dust and also have some toughness and impact resistance, which meet the needs of the actual sand fastening and dust suppression.

3.2.4. Performance of Moisture Absorption and Moisture Release. After 10 days of continuous measurement, the changes in the sand mold sample moisture absorption rate of six samples with time are shown in Figure 4, including the moisture absorption rate measured at 9 am and 18 pm. It can be seen from Figure 4 the variation trend and range of solution moisture absorption rate for samples sprayed with dust suppressant are basically same in five samples. Samples placed under natural conditions do not contain water, but this rate rose to 0.16% 12 h later, and the maximum moisture absorption rate of dust samples reached 0.20% on the third day, but it declined on the fourth day and rose on the fifth day. Its moisture absorption rate was 0.18% at 9 am on the fifth day. Its moisture absorption rate has a gentle decrease on both the sixth and seventh days and decreased to 0.11% on the seventh day. The moisture absorption rate of the sand mold sample had a gentle increase on the eighth, ninth, and tenth days, but
the moisture absorption rates at daytime and night had large differences. On the tenth day, the moisture absorption rate was 0.19% at 9 pm, indicating that the dust suppressant effect of sand mold samples sprinkled with a dust suppressant mixture had not deteriorated when the observation period of 10 days ended. It may still have a hygroscopic function in response to alterations in air moisture and use hygroscopic agents to control the humidity of dust mixtures. When the hygroscopic rate of sand mold samples sprinkled with deionized water was compared to the curve line of the moisture absorption rate of sand piles sprinkled with the dust suppressant mixture, it is clear that the moisture absorption rate has improved. When the suppressant is deployed in the air, it absorbs water and retains the capacity to moisten dust particles.

The average values of the moisture absorption and release rate of five sand mold samples changed with time, and they could give a curve line of average value of this rate changing with time, as shown in Figure 5 by the combination of temperature and relative humidity changes over 10 days. Figure 5a is a line chart of the average moisture absorption rate and relative humidity changes with time of the sand models. It can be seen that the span of relative humidity range is great over 10 days, ranging from 35% to 70%. The relative humidity in first to fourth days was around 60% and dropped to 47% by the fifth evening. The relative humidity continued to fall steadily in the following 2 days and dropped to 39% by the seventh evening. The relative humidities in the eighth, ninth, and tenth days were generally increasing, but there were large differences in the daytime and at night. For example, the relative humidity between daytime and night was different in a range of 13% on the eighth day, while the moisture absorption rate of the sand mold sample in the first day had a large increase because samples was placed under natural room conditions after drying to constant weight; thus, its moisture absorption rate rose greatly after constantly absorbing the water in air. The relative humidity in the air dropped in the evening of the first day, and the sand mold sample began to release moisture, leading to a moisture absorption rate decrease to 0.14% from 0.16%. In the following days, as the relative humidity in the air became higher, the sand mold started to be hygroscopic, and its hygroscopic rate increased; as the relative air humidity decreased and the sand mold started to release water, its hygroscopic absorption rate decreased. This indicates that the moisture absorption and release is defined by a dynamic equilibrium with the air’s relative humidity. Figure 5b is a line chart of the average moisture absorption rate and temperature of the sand models with time. In Figure 5b, there is a range of environmental temperatures over the 10 days varied from 25 to 30 °C and there was a large difference in temperatures in the daytime and at night, which are in accordance with a great variation in sand mold moisture absorption rates in the daytime and at night. The environmental temperature by the second evening reached a maximum temperature at 29.4 °C, and then gradually decrease. The temperature dropped to 24.4 °C by the seventh morning, and the temperature by the ninth and tenth days rose on the whole and finally reached 28.5 °C by the tenth evening. Overall, the change trend of temperature was a process of increase, decrease, and finally increase, which was in line with the general basic change trend of the moisture absorption rate of the sand mold sample. However, the moisture absorption rate in the daytime and at night was in opposition to the specific temperature. The temperature in the morning was low but the moisture absorption was high, and the temperature was low but the moisture absorption was high at night. In general, the environmental temperature had some effect on the rate of the sample sprinkled with a dust suppressant mixture, but the relative humidity had a greater effect on its hygroscopic rate, with the relative humidity increasing and decreasing to cause moisture absorption and release.

3.2.5. Performance of Experiment That Is Not Affected by the Weather. W, which is determined as the rate of wind erosion to the sand mold, was computed; the results are shown in Figure 6. Figure 6 shows that the wind erosion speed of a deionized-water-sprayed sand mold increases with an increase in wind speed and also with the blowing duration for the sand mold sample. After 30 min of blowing at a wind speed of 14 m/s, the wind erosion rate was 6.07%. However, when a dust suppression solution was sprayed on the sand mold sample at various wind speeds and blowing times, the wind erosion rate was essentially zero. After 30 min of blowing in a 7 m/s wind, the the wind erosion speed of a sample sprinkled with a dust suppressant increased. The increased mass of the sand mold samples was due to the hygroscopic nature of the dust suppressant, which absorbed the moisture from the air. This

Figure 4. Line chart of changes in sand mold sample moisture absorption rates with time.

Figure 5. (a) Line chart of the average moisture absorption rate and relative humidity of sand models changing with time. (b) Line chart of the average moisture absorption rate and temperature of sand models changing with time.
fully shows that the dust suppressant solution has a strong ability to resist wind erosion, which satisfies the requirement for a practical application.

3.2.6. Rain Resistance. Figure 7 shows the initial states and cross sections of sand mold samples in the first to fifth rain resistance cycles. The weight residue rates of sand mold samples after different spraying cycles are shown in Figure 8a. From Figure 7, we can see that the consolidated sand layer thickness of the cross section has risen for a well effect to consolidate sand with an increasing amount of rain resistance. Figure 8a shows that the sand mold sample lost nearly 50% of its mass after five deionized water spraying cycles. However, the sand mold sample experienced almost no mass loss after five cycles of dust suppressant spraying. To sum up, the consolidated layer formed by the dust suppressant is characterized by a high performance of water erosion resistance, and this meets the requirements of actual sand consolidation and dust suppression.

3.2.7. Freezing and Thawing Resistance. Figure 8b shows the compressive strength variation of the sand column sample after freeze–thaw cycles. From Figure 8b, it can be seen that the compression strength of the sand column sample decreased from 0.33 to 0.179 MPa after the first freeze–thaw cycle. This showed that the structure of the dust suppressant was destroyed to some extent under the huge temperature change. The compressive strength of sand column sample increased by 0.182 MPa after a second freeze–thaw cycle and continuously increased by 0.203 MPa after three freeze–thaw cycles. The reason for the successive slight increases was that the freeze–thaw cycle allowed the dust suppressant solution to make the sand bond more tightly; thus, the compressive strength increased. In the fourth-round process, the compressive intensity of the sand sample remained unchanged. After the fifth-round process, the compression intensity decreased by 0.17 MPa, which was consistent with the general rule for a polymer adhesive material after multiple freeze–thaw cycles. After a drastic change in temperature, the compressive strength of the dust suppressants basically remained stable with good freezing and thawing resistance, which meets the needs of practical outdoor applications.

4. CONCLUSION

A theoretical analysis and laboratory experiments were used in this work. The best dust suppressant formula for stockpiles was investigated using single-condition and orthogonal trials. The ideal dust suppressant formula’s physicochemical features were determined, and the dust suppression performance was tested and investigated. The conclusions are as follows.

(1) Through a single-condition experiment, the most suitable single factors for the hygroscopic agent, selected surfactant, film-forming agent, and packing were determined. The range analysis and variance analysis to the orthogonal test were conducted with the viscosity value and the hardness value of the consolidation layer as evaluation indexes. Finally, the optimum formulation of the dust suppressant was obtained by a comprehensive balance method: 0.6% A + 0.2% B + 0.28% C + 0.7% D (0.23% D1 + 0.47% D2). In the orthogonal experiment, 16 solutions and the dust suppressant solution prepared in the optimum formulation were verified, which brought about a higher viscosity and stronger hardness of the solidified layer.

(2) The formula of the developed dust suppressant for stockpiles is weakly alkaline, which can neutralize the dust suppressant when it is sprayed with acid rain, and it is environmentally friendly. The curing effect on the surface is strong, which effectively prevents the material loss of the stockpile. The stockpile dust suppressant not
only has high compressive strength but also has a certain toughness and impact resistance, which can keep the sand mold sample from being damaged within a certain period of time. Moreover, the heap has good wind erosion resistance, water erosion resistance, and freeze–thaw resistance after spraying dust suppressant. To sum up, the stockpile dust suppressant developed in this study is an environmentally friendly polymer chemical dust suppressant, which has ideal dust suppression performance, can effectively prevent wind erosion and rain, has good freeze–thaw resistance, can adapt to the actual use environment of different climates, has a good dust suppression effect and long retention time, and has broad application prospects.

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Notes
The authors declare no competing financial interest.

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