Suppression Effect of Waterborne Polymer on Soil Used for Backfilling at Construction Site

Sheng Yang 1,2,3, Zhiyuan Qin 1 and Fuqiang Zhang 1,3,*

1 Hebei Key Laboratory of Functional Polymer; School of Chemical Engineering and Technology, Hebei University of Technology, Tianjin 300130, China; yspoly@126.com (S.Y.); zyqin2021@163.com (Z.Q.)
2 Kalavinka (Tianjin) Environment Technology Co., Ltd., Tianjin 301700, China
3 Tianjin Key Laboratory of Materials Laminating Fabrication and Interface Control Technology; Research Institute for Energy Equipment Materials, Hebei University of Technology, Tianjin 300130, China
* Correspondence: fqzhang@hebut.edu.cn

Abstract: To improve the dust control efficiency of soil for backfilling at construction sites, a novel waterborne polymer was used as a dust suppressant, and the dust emission model was created to control the effect of a large-scale field. The results showed that the waterborne polymer could improve the water retention efficiency of soil for backfilling, and the average water content was 2.18 times that of the watered samples, significantly delaying water evaporation. The compressive strength of soil for backfilling reached 4.91 MPa and improved the wind erosion resistance of the consolidation layer, effectively resisting wind damage. At a construction site, the waterborne polymer was sprayed on soil for backfilling, and the concentration of PM$_{10}$ was reduced by 67.41%, confirming the effectiveness for large-scale utilization.

Keywords: construction site; soil for backfilling; PM$_{10}$ dust suppressant; soil stability

1. Introduction

Growing urbanization has led to significant dust generation at construction sites, adversely affecting the air quality and workers’ health. Particulate matter $\leq$10 $\mu$m in aerodynamic diameter (PM$_{10}$) can enter the nasopharynx, and particulate matter $\leq$2.5 $\mu$m in aerodynamic diameter (PM$_{2.5}$) can infiltrate deep into the alveolar areas of the human lungs [1]. At 27 °C, 73% relative humidity (RH), and 1.0 m/s wind speed, the average daily PM$_{10}$ concentration at construction sites can be as high as 270.70 $\mu$g/m$^3$ [2]. The contribution rate of construction sites to the PM$_{10}$ concentration in urban ambient air is more than 10%. In 2015, the concentrations of PM$_{10}$ and PM$_{2.5}$ at national control monitoring points affected by construction sites in Beijing reached 17.5 $\mu$g/m$^3$ and 6.2 $\mu$g/m$^3$, contributing 17.2% and 7.8% [3], respectively, to the total air pollution of the city. Water spraying is a common measure for dust suppression, yet it is inefficient and hard to provide longstanding dust suppression due to the easy moisture evaporation on watered pavements in open and dry environments [4]. The dust suppression effect can be significantly improved by adding dust suppressants into the spraying water [5–7].

Traditional chemical dust suppressants mainly include wetting, condensed, and bonding chemical dust suppressants [8]. Condensed chemical dust suppressants, such as sodium chloride and calcium chloride, can postpone moisture evaporation and increase density by wet-dust suppression, retaining moisture in powder particles for a longer time [9–11]; nevertheless, they can severely harm plant growth. Organic polymers, such as polyvinyl alcohol, can bond and seal powder to improve its stability by dry dust suppression [12,13], but there is still room for improvement in moisture retention.

Traditional dust suppressants can mainly be used for a single purpose and exhibit poor comprehensive performance, while some may cause detrimental environmental effects. Therefore, developing multifunctional, environmentally friendly dust suppressants...
attracted extensive research attention [14–16]. Li [17] extracted carboxymethyl cellulose from waste paper and prepared a dust suppressant by reacting it with polyvinyl alcohol and N-vinylpyrrolidone. The suppressant crusted on the surface of pulverized coal and improved the wetting effect of water. Wu [18] prepared a multifunctional, environmentally friendly dust suppressant with a semi-interpenetrating network structure, providing the wetting, moisture retention, and consolidation of pulverized coal. Zhao [19] synthesized an Enteromorpha-based dust suppressant exhibiting satisfactory permeability to pulverized coal and reaching a compressive strength of consolidated coal dust of 122.6 kPa. Zhu [20] developed a compound fluid dust suppressant of starch and organobentonite possessing good biodegradability and dust suppression effects. Recently, dust has been consolidated through enzyme-induced carbonate precipitation. Wu [21] and Zhu [22] both used urease to decompose urea to generate carbon dioxide, which then reacted with calcium chloride, penetrating the pulverized coal to form calcium carbonate crystals, consolidating a large amount of pulverized coal, and improving its resistance to wind erosion. These research studies have greatly expanded the functions of dust suppressants. However, the employed preparation methods of dust suppressants are complex, causing high costs and limiting their large-scale applications. Moreover, the lack of a systematic performance evaluation method affects the application field [23].

Waterborne acrylate polymers are widely used in the coating and adhesive industries due to large availability, low cost, and no pollution effects [24]. Additionally, acrylic acid (AA) is one of the main monomers used to prepare water-absorbent resins. For this reason, a waterborne polymer dust suppressant is adopted in this paper to stabilize soil for backfilling and to restrain the dust from construction sites. The changes in the moisture content of the stabilized soil for backfilling are tested under constant temperature and humidity, and the dust suppression efficiency is estimated using an emission factor model, thus evaluating the wet dust suppression performance of the polymer. The drying changes in the stabilized soil for backfilling at room temperature are studied, and the dry dust suppression performance is evaluated using 28-day compression strength. In addition, a new evaluation method of soil stabilization for large-scale dust suppression is applied to test the dust suppression efficiency of the dust suppressant at a construction site and to evaluate the stability effect and environmental safety of soil for backfilling at the construction site.

2. Materials and Methods

2.1. Preparation of Dust Samples

The experimental powder was vacuum-collected from the surface of a backfill yard at a construction site in Hongqiao District, Tianjin, China; dried at 105 °C after debris removal; and then sieved through a 20-mesh filter cloth (850 µm). The silt content in the backfill powder was 3.5%, according to the AP-42 test method [25]. The calculated silt loading was 89 g/m² based on the sampling area and the sampling mass. Silt accounted for most of the powder sieved through a 200-mesh filter cloth (75 µm), and its particle size distribution was measured with a laser particle size analyzer (Mastersizer 2000, Malvern Ltd., Leamington Spa, UK) at 25 °C. As shown in Figure 1, the median diameter was 26.00 µm. An X-ray fluorescence spectrometer (ARL QUANT, Thermo Fisher Scientific Ltd., Waltham, MA, USA) was used to determine the mass contents of SiO₂, Al₂O₃, CaO, Fe₂O₃, MgO, K₂O, Na₂O, TiO₂, SO₃, and P₂O₅, and they were 59.93, 14.55, 10.22, 5.67, 3.93, 3.09, 1.05, 0.86, 0.26, and 0.12%, respectively, while other components accounted for 0.32%.
2.2. Preparation of Dust Suppressants

The main experimental reagents are shown in Table 1. Amounts of 2.0 g AA, 6.0 g MMA, 30.0 g BA, and 14.0 g St were mixed. Then, 110 mL water, 2.0 g emulsifier, and 8.0 g polyacrylic acid resin were added into a 250 mL four-necked flask equipped with mechanical stirring, a condenser tube, and a constant pressure dropping funnel, and an appropriate amount of NaOH was added for neutralization. A certain amount of APS initiator was added to the solution at 70 °C. After 8 min, the mixed monomers were added dropwise using a power feed technique, and St was added using a constant-flow pump. Afterward, APS initiator was added every 30 min, and the adding speed of St was adjusted from slow to fast. After 180 min, all the monomers were added. The solution was kept at 90 °C for 1 h before being cooled down to room temperature, neutralized with 5.0% NaOH, and sieved through a 200-mesh filter cloth (75 μm) to obtain a final aquasol product with a pH value of 6.7 and a solid content of 39.7% at 105 °C [26].

Table 1. Main experimental reagents.

| Name                             | Purity          | Manufacturer                                      |
|----------------------------------|-----------------|---------------------------------------------------|
| Acrylic acid (AA)                | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Butyl acrylate (BA)              | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Methyl methacrylate (MMA)        | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Styrene (St)                     | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Emulsifier (EC)                  | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Ammonium persulfate (APS)        | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Polyacrylic acid resin (PMMA)    | Industrial grade| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |
| Sodium peroxide (NaOH)           | Analytically pure| Hebei Richu Chemical Co., Ltd., Cangzhou, Hebei, China |

2.3. Experimental Instruments and Test Methods

Contact angle: A pellet with a diameter of 13 mm and a height of 3 mm was made from 0.8 g soil dust under 20 MPa pressure. The contact angles between droplets and soil dust were measured with an optical contact angle instrument (DAS30, Kruss Ltd., Hamburg, Germany) at a titration speed of 100 μL/min and a droplet volume of 4 μL.

Zeta potential: The Zeta potential was measured using a nanoparticle size and potential analyzer (Nano-ZS90, Malvern Ltd., Leamington Spa, UK), and the mass concentration of the powder suspension was 0.1 wt.%

Moisture content: Soil for the backfilling powder with an initial mass $W_0$ of 20.0 g was filled and leveled out in a culture plate with a diameter of 100 mm and sprayed with a dust suppressant solution until the sample surface was fully wet. The obtained samples were referred to as suppressed samples, and the mass of the dust suppressant was 1.05%. Other
dust samples were sprayed with the same amount of distilled water as a control group, referred to as watered samples. The watered samples were placed in an incubator (WS-70 constant temperature and humidity incubator, Shanghai Zhuli Instrument Ltd., Shanghai, China) with constant temperature and humidity of 35 °C and 45% RH, respectively. The mass \( W_t \) (g) at different times \( t \) was recorded, and the moisture content \( P \) at time \( t \) was expressed as follows:

\[
P = \frac{W_t - W_s}{W_s} \times 100\%
\]

where \( P \) is the moisture content (%), \( W_s \) is the initial mass of the soil for the backfilling powder (g), and \( W_t \) is the mass of the suppressant sample or watered sample at different drying times (g).

Compression strength: A total of 50.0 g of dust suppressant solution with a concentration of 3.0% was mixed and stirred with 141.0 g of soil for the backfilling powder, poured into a brass mold (40 mm × 40 mm × 40 mm) to form, and then stripped before being dried at room temperature. For comparison, the above operation was repeated with the same amount of distilled water. After 1, 3, 7, 14, 21, and 28 days, the compressive strength was tested with a microcomputer-controlled electron universal testing machine (UTM-5305, Shenzhen Sansi Testing Technology Ltd., Shenzhen, China) following the GB/T 17671-1999 Method of Testing Cements-Determination of Strength (ISO).

Microstructure: The morphological structure of the soil for backfilling was examined using a field emission scanning electron microscope (Nova Nano SEM450, FEI Ltd., Hillsboro, OR, USA), and the sample surface was sputtered with Au before measurement.

Field application: The meteorological information, including the particle concentration, temperature, and humidity at a height of 2.5 m on the construction site, was monitored in real-time with an online dust-monitoring system produced by Shijiazhuang Zhaorong Technology Co., Ltd. (Shijiazhuang, China). The dust suppressant was sprayed with a multipurpose anti-dust truck. The dust monitoring points were established according to the HJ 664—2013 Technical Regulation for Selection of Ambient Air Quality Monitoring Stations (on trial). The concentration of suspended particles was recorded with an aerosol monitor (Dust Trak 8530, TSI Ltd., St. Paul, MN, USA) placed 1.5 m from the ground and calibrated according to regulations before use.

3. Results

3.1. Interaction between Polymers and Soil for Backfilling

Improving the stability of soil dust is the fundamental method for reducing wind-blow dust. The intensity of PM\(_{10}\) emission decreases with the particle size of soil dust aggregates [27]. Under suspension conditions with known values of gravitational acceleration \( g \), air density \( \rho_0 \), air viscosity \( \gamma \), and particle density \( \rho \), the dust settling velocity \( u_s \) is determined using the diameter \( D \) [28] according to Equation (2); the increase in the latter leads to fast dust falling, short retention in the air, and a small drift range.

\[
u_s = \frac{g(\rho - \rho_0)D^2}{18\gamma}
\]

3.1.1. Wettability of Soil for Backfilling with Dust Suppressants

Wetting is necessary to agglomerate fine particles and increase particle size. Enriched with black carbon and organic matter on the surface, backfill particles contain mineral ions, such as Ca\(^{2+}\) and Mg\(^{2+}\), and high-valent ions, such as Fe\(^{3+}\), from car exhaust and coal emissions, resulting in low polarity of the surface and hindered water wetting. Since AA is a functional monomer, the effect of the AA dosage on wettability was studied based on the percentage of AA in the monomer mass. The results are shown in Figure 2a.
watered samples. In the dry state, the moisture content remained stable. The equilibrium moisture content of the suppressed samples continually decreased with time, but it was always higher than that of the watered samples. It was observed in the PM10 emission test that the moisture content of the watered samples was 0.99%, while that of the suppressed samples was 46.9% when the moisture content increases by 1.0% [29].

3.1.1. Wettability of Soil for Backfilling with Dust Suppressants

Since AA is a functional monomer, the effect of the AA dosage on wettability was studied based on the percentage of AA in the monomer mass. The results are shown in Figure 2a. The carboxyl group content of the polymers decreased with the mass ratio of MMA/AA. At a certain chemisorption capacity of soil dust, the higher the MMA/AA mass ratio, the greater the adsorption capacity, causing a slow increase in the negative Zeta potential value to −46.9 mV when the MMA/AA mass ratio was 3. However, as the MMA/AA mass ratio further increased, the carboxyl group content was further reduced, and the adsorption capacity decreased. This indicates that the carboxyl groups of polymers were cross-linked with Ca2+, Mg2+, and Fe3+ ions on the surface of the soil dust particles, promoting the chemisorption of polymers on the surface of the particles and improving the dispersion of the soil dust particles. Therefore, a polymer with an AA content of 2.0% and an MMA/AA mass ratio of 3 was selected for the following study.

3.1.2. Zeta Potential of the Stabilized Backfill Powder

The interaction between particles drives the particle size to increase, mainly via capillary and chemical cementing forces [29], both of which are related to Zeta potential. The influence of the mass ratio of hydrophilic monomers MMA/AA on the Zeta potential of soil dust was studied at a constant monomer dosage. As shown in Figure 2b, the Zeta potential of the unstabilized soil for backfilling in a neutral aqueous medium was −10.5 mV, and it increased after stabilization.

Figure 2. (a) Effect of AA mass concentration on contact angles, and (b) effect of the MMA/AA mass ratio on the Zeta potential of stabilized soil dust.

The contact angle between the polymer solution and soil dust decreased to 39.1° as the AA dosage increased to 2.0%. After polymerization, the charge capacity and cationic affinity of the polymers were increased via the carboxyl groups of AA, and the spreading ability of droplets on the surface of the soil dust was improved. Hence, the trapping efficiency and aggregation ability of dust were enhanced.

3.2. Wet Dust Suppression Performance of Polymers

3.2.1. Change in the Moisture Content of Soil for Backfilling during Drying

High moisture content plays an important role in soil dust stabilization. The PM10 emission can be reduced by 410–1500 µg/g when the moisture content increases by 1.0% [29]. As seen from Figure 3, during drying at 35 °C and 45% RH, the moisture content of the suppressed samples continually decreased with time, but it was always higher than that of the watered samples. In the dry state, the moisture content remained stable. The equilibrium moisture content of the watered samples was 0.99%, while that of the suppressed samples...
was 3.25%. The results show that the used polymers enhanced the moisture retention capacity of the soil for backfilling.

![Figure 3](image1.png)

**Figure 3.** The changes in the moisture content at 35 °C and 45% RH for watered and suppressed samples.

3.2.2. Effect of Polymers on the Equilibrium Moisture Content

The results showed that the drying process in Figure 3 conformed to the following law [30]:

\[
P = Ae^{-Bt}
\]

where \( A \) and \( B \) are constants and \( t \) is drying time (h).

The natural logarithm of Equation (3) gives Equation (4), and the linear regression results are shown in Figure 4.

\[
\ln P = \ln A - Bt
\]

![Figure 4](image2.png)

**Figure 4.** Regression equation of the natural logarithm of Equation (4).
In Figure 3, the drying time spans from $t_0$ to $t_e$, and the average moisture content $P_{av}$ during drying is given as follows:

$$P_{av} = \int_{t_0}^{t_e} P \, dt / (t_e - t_0) = \frac{A \int_{t_0}^{t_e} e^{-Bt} \, dt}{t_e - t_0} = \frac{A}{t_e - t_0}$$ (5)

The drying times of the watered and suppressed samples in Figure 3 were 9 h and 17 h, respectively. According to Equation (5), the average moisture content of the watered samples was 6.38%, while that of the suppressed samples was 13.93%, which was 118.8% higher.

### 3.2.3. Dust Suppression Efficiency of Waterborne Polymers

Construction sites are typical fugitive emission sources, with complex compositions of soil for backfilling, large randomness of the dusting process, and strong individual characteristics of the site space, which altogether hamper the calculation of the emission factor. Nankai University established a PM$_{10}$ emission factor $EF$ (g/m$^2$h) model at a construction site by taking the dust area rate $D$, wind speed $u$ (m/s), moisture content $M$ (%) of the soil for backfilling, silt loading $S$ (g/m$^2$), and vehicle activity $N$ (number of vehicles) as key factors [31]:

$$EF = 0.02534D u^{1.983} M^{-1.993} S^{0.745} N^{0.684} \quad R^2 = 0.971$$ (6)

The particle size coefficient of TSP was 1.0, PM$_{10}$ was 0.49, and PM$_{2.5}$ was 0.1. The Ministry of Environmental Protection adopted this model because it embodied both the powder nature and the dust emission mechanism [5], and it was used for evaluating the wet dust suppression performance in this paper.

During the collection of backfill powder with $D = 30\%$, the $S$ was determined to be 89 g/m$^2$. When $N$ was 5 and $u$ was 7 m/s, the PM$_{10}$ emission factor $EF_b$ of the watered samples was 0.76 g/m$^2$h, and that of the suppressed samples was 0.16 g/m$^2$h, as calculated using Equation (6). As defined by Equation (7), the dust suppression efficiency ($\eta$) of waterborne polymers on the backfill powder PM$_{10}$ was 78.95%.

$$\eta = \left(1 - \frac{EF_S}{EF_b}\right) \times 100\%$$ (7)

### 3.2.4. Dust Suppression Duration of the Stabilized Soil for Backfilling

The suppressed samples were sprayed with the same quantity of distilled water after drying, and then the changes in the moisture content during the second drying were tested. The process of drying and spraying was repeated six times, and the results of the regression treatment of the data for each cycle are shown in Table 2.

| Time | ln$A$ | $B$ | $R^2$ |
|------|-------|-----|--------|
| 1    | 3.730 | 0.1654 | 0.9890 |
| 2    | 3.638 | 0.1614 | 0.9869 |
| 3    | 3.617 | 0.1653 | 0.9804 |
| 4    | 3.721 | 0.2038 | 0.9757 |
| 5    | 3.707 | 0.2177 | 0.9823 |
| 6    | 3.673 | 0.2403 | 0.9866 |
| 7    | 3.701 | 0.2620 | 0.9689 |

It can be seen from Table 3 that the dust suppression efficiency values of PM$_{10}$ in the first two cycles were higher than 70%, exhibiting little change, followed by an obvious decrease in later cycles. The dust suppression efficiency of the fifth cycle was lower than 60%, which might be related to the aging of the polymers.
Table 3. PM$_{10}$ emission factors and dust suppression efficiency during continuous use.

| Time | $P_{av}$/% | $EF$/g/m$^2$h | $\eta$/% |
|------|------------|---------------|----------|
| 1    | 13.93      | 0.16          | 78.95    |
| 2    | 12.97      | 0.19          | 75.0     |
| 3    | 12.44      | 0.20          | 73.68    |
| 4    | 11.54      | 0.23          | 69.74    |
| 5    | 10.74      | 0.27          | 64.47    |
| 6    | 9.47       | 0.35          | 53.95    |
| 7    | 8.99       | 0.39          | 48.68    |

3.3. Dry Dust Suppression Performance of Waterborne Polymers

The density and wet dust suppression effect of the dried backfill powder decreased, so the dry dust suppression ability of the waterborne polymer became obvious. This study showed that the dust flux at a height of 1.8 m for powdered bare soil was nine times higher than that for crusted soil after closing the powder surface via crustation by strengthening the cohesion between particles [32]. The changes in the compression strength of the soil for backfilling during crustation are shown in Figure 5.

![Figure 5. The changes in the compression strength of the soil for backfilling with time at room temperature.](image)

3.4. Safety of Polymer Dust Suppressants

The precipitation washing of the suppressed samples was simulated, and the surface water was collected [33]. Then, the water quality was measured for safety purposes based on the GB 11914-1989 Water Quality Chemical Oxygen Demand and GB/T 9732-2007 General Rule for Determination of Ammonium. The results (Table 4) indicate that the dust suppressants had no adverse effects on the environment and helped restore the soil.

Table 4. Effect of dust suppressants on the quality of surface water.

|                        | Water-Spraying Treatment | Polymer Stabilization |
|------------------------|--------------------------|-----------------------|
| Appearance             | Light yellow and transparent | Colorless and transparent |
| Ammonia nitrogen/mg L$^{-1}$ | <1                       | <0.4                  |
| COD/mg L$^{-1}$        | 26.3                     | 24.6                  |
The overall safety was evaluated according to the GB 18582 Indoor Decorating and Refurbishing Materials—Limit of Harmful Substances of Interior Architectural Coatings, and the dust suppressants were identified as harmless to humans and animals, as shown in Table 5.

Table 5. Contents of hazardous substances in dust suppressants.

| Items                                | Detection Limits | Specified Limits | Detection Results |
|--------------------------------------|------------------|------------------|------------------|
| Volatile organic compounds (VOCs) / g L\(^{-1}\) | 2                | 120              | 3.24             |
| Totals of benzene, methylbenzene, ethylbenzene, and xylene / mg kg\(^{-1}\) | 50               | 300              | Not detected     |
| Free formaldehyde / mg kg\(^{-1}\)     | 5                | 100              | Not detected     |
| Soluble heavy metals / mg kg\(^{-1}\) | 1                | 60               | Not detected     |

3.5. Effect of Dust Suppression at a Construction Site

Large-scale dust suppression was conducted at a construction site in Hongqiao District, Tianjin, China, to prove the above laboratory results. As shown in Figure 6, the area was 20,000 square meters large, surrounded by roads on three sides and another construction site to the north. A waste soil yard at the north side of the construction site mixed with bricks and tiles was set as monitoring point C1. As the main dust suppression area, the bare ground and the soil of the backfilling yard at the west side (waste body: 60 m × 200 m; maximum vertical height: 4.2 m) were set as monitoring points for fugitive dust C2, C3, and C4. The bare ground at the east was used as a control area, with monitoring points B1 and B2 for comparison. The particle concentration in the dust suppression and control areas was calculated as the average value of the monitoring points. At 13:00 h on June 26, 2017, the temperature was 35.6 °C, the relative humidity was 46.9%, and the speed of the southwest wind was 4.86 m/s. After using a mist cannon for spraying, the measured results were as follows: the mass concentration of the dust suppressants was 1.0%, the amount for the waste area was about 1.0 kg/m\(^2\), and that for the ground was about 1.3 kg/m\(^2\). The construction and water spraying were ongoing during the field dust suppression. According to Table 6, the dust concentration in the dust suppression area was similar to that in the control area before spraying (0 h).

Figure 6. The layout of dust suppression areas at the construction site. C1 is the monitoring point. C2, C3 and C4 are monitoring points in the dust suppression area. B1 and B2 are the monitoring points in the control area.
According to Figure 7a, the dust suppression efficiency for PM$_{10}$ 24 h after stabilization was 67.41%, exhibiting a difference of 11.54% from the estimated result, while that of PM$_{2.5}$ was 53.68%, differing from the estimated result by 25.27%. It can be concluded that the estimated results were in line with the actual results, and the performance evaluation method used in this paper was feasible, given the monitoring errors and differences in the temperature, humidity, and test conditions at the construction site.

According to Figure 7a, the dust suppression efficiency for PM$_{10}$ 24 h after stabilization was 67.41%, exhibiting a difference of 11.54% from the estimated result, while that of PM$_{2.5}$ was 53.68%, differing from the estimated result by 25.27%. It can be concluded that the estimated results were in line with the actual results, and the performance evaluation method used in this paper was feasible, given the monitoring errors and differences in the temperature, humidity, and test conditions at the construction site.

### Table 6. Concentration of suspended particles at the dust suppression site ($\mu$g/m$^3$).

| Time/h | Dust Suppression Area | Control Area | Dust Suppression Area | Control Area |
|--------|-----------------------|--------------|-----------------------|--------------|
| 0      | 37.00                 | 36.50        | 57.75                 | 56.50        |
| 24     | 15.75                 | 34.00        | 18.25                 | 18.00        |
| 48     | 17.88                 | 37.50        | 18.00                 | 46.00        |
| 72     | 32.75                 | 58.00        | 34.75                 | 65.00        |
| 96     | 26.25                 | 34.50        | 41.50                 | 55.00        |
| 120    | 25.75                 | 31.50        | 34.00                 | 44.00        |
| 144    | 25.25                 | 29.00        | 31.00                 | 35.50        |
| 168    | 47.50                 | 51.50        | 48.25                 | 54.50        |

Since the construction site was fully open and the stable area was limited, the external factors greatly affected the dust suppression efficiency, which decreased continuously with time. The dust suppression efficiencies for PM$_{10}$ after stabilizations of 48 and 72 h were 60.87 and 46.54%, respectively, and the average dust suppression efficiency for PM$_{2.5}$ after 72 h was 50.18%. Figure 7b shows the surface state of the waste area on day 15 after stabilization, with a stable crusting effect and normal plant growth.

### 4. Discussions

According to the wet dust suppression performance of polymers, the drying of the soil for backfilling lasted about 17 h after spraying with the polymer dust suppressant. Due to an increase in humidity and a decrease in temperature at the construction site overnight, as well as the moisture absorption of both the soil and the polymers [34,35], a high dust suppression effect could be maintained within 24 h. Continuous use of five cycles was equivalent to five days. Therefore, the wet dust suppression performance was evaluated for a continuous duration with a dust suppression efficiency of at least 60%. Taking the test errors and safety factors into account, the determined index was a dust suppression time no less than 5 days. The dust suppression efficiency was calculated based on the average moisture content under constant temperature and humidity conditions using the backfill powder from the construction site. The test objects were the same as the field application.
objects, which reduced the difference between the test data and the real study and helped improve the field stabilization effect.

The soil for backfilling exhibited a three-phase structure consisting of mineral particles [36], water, and air. At the saturated moisture content, all the pores were filled with water. During drying, moisture was first released from the soil pores ≥100 µm, enhancing cohesion and increasing the compression strength of the soil for backfilling (Figure 5). The bigger pores (>75 µm) lost moisture from day 3 to day 14 (Figure 8). At this time, the polymer promoted the aggregation of fine particles less than 10 µm and improved the compression strength [37]. From day 14 to day 21, water loss mainly occurred in the middle-sized pores (30–75 µm), and bigger particles in the watered samples began to aggregate spontaneously. In Figure 5, the strength of the watered samples on day 21 was 1.94 MPa, reaching 5.38 MPa when the agglutinated powder particles of the polymer and their surfaces were crusted. As the pores did not contain remaining water anymore, the effect became exhausted. The compression strength on day 28 for the watered samples dropped back to 1.26 MPa, while that of the suppressed samples remained at 4.97 MPa.

![Figure 8. Aggregation state of suppressed soil.](image)

According to edaphology, soil is an aggregate of silt and clay [38]. Therefore, the waterborne polymer dust suppressant can prolong the water evaporation mainly by reinforcing the interaction between powder particles. The average particle size of the aggregate is reduced by anionic carboxyl radicals through the charge repulsion dispersion effect, while the powder cohesion is improved by hydrogen-bonding interactions between the aggregate and the Si-O and Al-O bonds on the powder surface [39]. Figure 9a, b shows the surface morphologies of watered and suppressed samples, respectively. The particles in Figure 9a were more evident and bigger, exhibiting high porosity, rapid volatilization, and low strength compared to the particles in Figure 9b, which were smaller and exhibited dense surfaces due to the dispersion effect and intensified cohesion, respectively. They possessed consolidation layers similar to clingfilm to inhibit water evaporation and enhance the moisture content and compression strength.

The compressive strength on coal surfaces is no more than 30 kPa during railway transportation [40]. Accordingly, the compression strength on day 28 could be used as an evaluation parameter for dry dust suppression performance, and strength above 1.5 MPa was sufficient to suppress the generation of wind-blown dust in inland areas.
5. Conclusions

(1) The contact angle between the waterborne polymer dust suppressant and the soil for backfilling at construction sites, as well as the Zeta potential of the stabilized soil for backfilling, were studied. The polymer improved the interaction between the backfill particles, the average moisture content during drying increased by 118.8%, and the stability of the backfill was significantly enhanced.

(2) The wet dust suppression performance was evaluated against time, where the dust suppression efficiency was at least 60%. With a polymer mass of 1.04%, the dust suppression efficiency of PM\(_{10}\) at 35 °C and 45% RH reached 78.95%, and the dust suppression efficiency lasting until day 5 was 64.47%.

(3) The dry dust suppression performance was examined with compression strength at room temperature. The waterborne polymer promoted the aggregation and cohesion of fine particles below 10 μm, and the strength on day 28 reached 4.97 MPa, which was 3.94 times higher than that of the watered samples. It was, therefore, concluded that the waterborne polymer could effectively resist wind-blown dust, and the stabilized soil for backfilling exhibited high stability.

(4) According to the results at the construction site, the dust suppression efficiencies for PM\(_{10}\) and PM\(_{2.5}\) reached 67.41 and 53.68%, respectively, which was consistent with the estimated results. It confirmed the feasibility of the evaluation method used in this paper and the onsite stabilization effect of the polymer.

(5) At 15 days after stabilization, the surface crust of the soil for backfilling was stable, and the plant growth was unaffected, so the polymer exhibited good environmental safety. The above results provide material and method support for dust suppression at construction sites.

Author Contributions: Field work and experiment, S.Y. and Z.Q.; data analysis, S.Y.; writing—original draft preparation, S.Y.; writing—revision and editing, S.Y. and F.Z.; project administration, F.Z.; funding acquisition, F.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Program of Tianjin, China (16ZXCXSF00010), and the Science and Technology Program of Hebei Province (17273703D).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful for the comments of the anonymous reviewers, which greatly improved the quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aslam, A.; Ibrahim, M.; Shahid, I.; Mahmood, A.; Irshad, M.K.; Yamin, M.; Ghazala; Tariq, M.; Shamshiri, R.R. Pollution Characteristics of Particulate Matter (PM\(_{2.5}\) and PM\(_{10}\)) and Constituent Carbonaceous Aerosols in a South Asian Future Megacity. Appl. Sci. 2020, 10, 8864. [CrossRef]
2. Borja, L.; César, S.; Cunha, R.; Kiperstok, A. Quantitative Method for Prediction of Environmental Aspects in Construction Sites of Residential Buildings. *Sustainability* **2018**, *10*, 1870. [CrossRef]

3. Xu, Y.; Zhou, Z.; Huang, Y.; Wang, K.; Nie, T.; Nie, L.; Qin, J. Fugitive Dust Emission Characteristics from Building Construction Sites of Beijing. *Environ. Sci. 2017*, *38*, 2231–2237. (In Chinese) [CrossRef]

4. Wei, D.; Du, C.; Lin, Y.; Chang, B.; Wang, Y. Temporal-Spatial Distribution of Vehicle Transportation Pavement Dust Migration in an Open-Pit Mine. *ACS Omega* **2020**, *5*, 16030–16036. [CrossRef] [PubMed]

5. MEPC. Technical Guidelines for the Preparation of Dust Source Particulate Matter Emission Inventory (On Trial); MEPC: Beijing, China, 2014; Available online: [https://www.mepc.gov.cn/gkml/hbb/bgg/201501/W020150107594588131490.pdf](https://www.mepc.gov.cn/gkml/hbb/bgg/201501/W020150107594588131490.pdf) (accessed on 25 April 2017).

6. Ikeagwuanu, C.C.; Nwou, D.C. Emerging trends in expansive soil stabilisation: A review. *J. Rock Mech. Geotech. Eng.* **2019**, *11*, 423–440. [CrossRef]

7. Mirzababaei, M.; Arulrajah, A.; Ouston, M. Polymers for Stabilization of Soft Clay Soils. *Proc. Eng.* **2017**, *189*, 25–32. [CrossRef]

8. Parvej, S.; Naik, D.L.; Sajid, H.U.; Kiran, R.; Huang, Y.; Thanki, N. Fugitive Dust Suppression in Unpaved Roads: State of the Art Research Review. *Sustainability 2021*, *13*, 2399. [CrossRef]

9. Lu, Z.; Lei, Z.; Zafar, M.N. Synthesis and performance characterization of an efficient environmental-friendly Sapindus mukorossi saponins based hybrid coal dust suppressant. *J. Clean. Prod.* **2021**, *306*, 127261. [CrossRef]

10. Katra. Comparison of Diverse Dust Control Products in Wind-Induced Dust Emission from Unpaved Roads. *Appl. Sci.* **2019**, *9*, 5204. [CrossRef]

11. Rica, H.C.; Saussaye, L.; Boutoulil, M.; Leleyter, L.; Baraud, F. Stabilization of a salty soil: Effects of disruptive salts. *Eng. Geol.* **2016**, *208*, 191–197. [CrossRef]

12. Xu, L.; Pei, Z. Preparation and Optimization of a Novel Dust Suppressant for Construction Sites. *J. Mater. Civ. Eng.* **2017**, *29*, 04017051. [CrossRef]

13. Tong, Y.; Lü, Y.; Su, L.; Ji, Y.; Zhang, F. Adhesion of VAC copolymer emulsion to road floating dust. *China Adhes.* **2018**, *27*, 21–23. (In Chinese) [CrossRef]

14. Fan, T.; Zhou, G.; Wang, J. Preparation and characterization of a wetting-agglomeration-based hybrid coal dust suppressant. *Process Saf. Environ. Prot.* **2018**, *113*, 282–291. [CrossRef]

15. Wang, Y.; Du, C.; Cui, M. Formulation Development and Performance Characterization of Ecological Dust Suppressor for Road Surfaces in Cities. *Appl. Sci. 2021*, *11*, 10466. [CrossRef]

16. 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]

17. Li, S.; Zhou, G.; Liu, Z.; Wang, N.; Wei, Z.; Liu, W. Synthesis and performance characteristics of a new ecofriendly crust-dust suppressant extracted from waste paper for surface mines. *J. Clean. Prod.* **2020**, *258*, 120620. [CrossRef]

18. Mingyue, W.; Xiangming, H.; Qian, Z.; Wei, L.; Yanyun, Z.; Zhenglong, H. Study on preparation and properties of environmentally-friendly dust suppressant with semi-interpenetrating network structure. *J. Clean. Prod.* **2020**, *259*, 120870. [CrossRef]

19. Zhao, Z.; Zhao, Y.; Hu, X.; Cheng, W.; Hou, J.; Song, C. Preparation and performance analysis of entombora-happlied environmentally friendly dust suppressant. *Powder Technol.* **2021**, *393*, 332–333. [CrossRef]

20. Zhu, Y.; Cui, Y.; Shan, Z.; Dai, R.; Shi, L.; Chen, H. Fabrication and characterization of a multi-functional and environmentally-friendly starch/organo-bentonite composite dust suppressant. *Powder Technol.* **2021**, *391*, 532–543. [CrossRef]

21. Wu, M.; Hu, X.; Zhang, Q.; Zhao, Y.; Sun, J.; Cheng, W.; Fan, Y.; Zhu, S.; Lu, W.; Song, C. Preparation and performance evaluation of environment-friendly biological dust suppressant. *J. Clean. Prod.* **2020**, *273*, 123162. [CrossRef]

22. Zhu, S.; Hu, X.; Zhao, Y.; Fan, Y.; Wu, M.; Cheng, W.; Wang, P.; Wang, S. Coal Dust Consolidation Using Calcium Carbonate Precipitation Induced by Treatment with Mixed Cultures of Urease-Producing Bacteria. *Water Air Soil Pollut.* **2020**, *321*, 442. [CrossRef]

23. Yan, H.; Ding, G.; Li, H.; Wang, Y.; Zhang, L.; Shen, Q.; Feng, K. Field Evaluation of the Dust Impacts from Construction Sites on Surrounding Areas: A City Case Study in China. *Sustainability 2019*, *11*, 1906. [CrossRef]

24. Jiao, C.; Sun, L.; Shao, Q.; Song, J.; Hu, Q.; Naik, N.; Guo, Z. Advances in Waterborne Acrylic Resins: Synthesis Principle, Modification Strategies, and Their Applications. *ACS Omega* **2021**, *6*, 2443–2449. [PubMed] [CrossRef]

25. Teng, H.; Kwizigile, V.; Karakouzian, M.; James, D.E. Etyemezian, V. Investigation of the AP-42 Sampling Method. *J. Air Waste Manage. Assoc.* **2012**, *58*, 1422–1433. [CrossRef]

26. Su, L.; Ji, Y.; Zhang, F.; Yang, S.; Yang, H.; Xiao, Q. Dust suppression performance and field application of waterborne polymer on iron ore powder. *Chin. J. Environ. Eng.* **2013**, *18*, 2181–2188. (In Chinese) [CrossRef]

27. Mendez, M.J.; Aimar, S.B.; Buschiazzo, D.E. PM_{10} emissions from aggregate fractions of an Entic Haplustoll under two contrasting tillage systems. *Aeolian Res.* **2015**, *19*, 195–201. [CrossRef]

28. Katra, I.; Elperin, T.; Fominykh, A.; Krasovitov, B.; Yizhaq, H. Modeling of particulate matter transport in atmospheric boundary layer following dust emission from source areas. *Aeolian Res.* **2016**, *20*, 147–156. [CrossRef]

29. Aimar, S.B.; Mendez, M.J.; Funk, R.; Buschiazzo, D.E. Soil properties related to potential particulate matter emissions (PM_{10}) of sandy soils. *Aeolian Res.* **2012**, *3*, 437–443. [CrossRef]

30. Bae, S.; Inyang, H.I.; De Brito Galvão, T.C.; Mbamalu, G.E. Soil desiccation rate integration into empirical dust emission models for polymer suppressant evaluation. *J. Hazard. Mater.* **2006**, *132*, 111–117. [CrossRef]
31. Zhao, P.; Feng, Y.; Zhang, Y.; Zhu, T.; Jin, J.; Zhang, X. Modeling and impact study of fugitive dust emissions from building construction sites. *China Environ. Sci.* 2009, 29, 567–573. (In Chinese)

32. Avecilla, F.; Panebianco, J.E.; Buschiazzo, D.E. Meteorological conditions during dust (PM$_{10}$) emission from a tilled loam soil: Identifying variables and thresholds. *Agric. For. Meteorol.* 2017, 244, 21–32. [CrossRef]

33. Li, M.; Chai, S.; Du, H.; Zhang, J.; Wang, Z. Use of SH dust-depressor for rain erosion control of soil in construction. *Chin. J. Environ. Eng.* 2016, 10, 3105–3110. (In Chinese) [CrossRef]

34. Hoffmann, C.; Funk, R. Diurnal changes of PM$_{10}$-emission from arable soils in NE-Germany. *Aeolian Res.* 2015, 17, 117–127. [CrossRef]

35. De Oro, L.A.; Colazo, J.C.; Avecilla, F.; Buschiazzo, D.E.; Asensio, C. Relative soil water content as a factor for wind erodibility in soils with different texture and aggregation. *Aeolian Res.* 2019, 37, 25–31. [CrossRef]

36. Madden, N.M.; Southard, R.J.; Mitchell, J.P. Soil water and particle size distribution influence laboratory-generated PM$_{10}$. *Atmos. Environ.* 2010, 44, 745–752. [CrossRef]

37. Alfaro, S.C. Influence of soil texture on the binding energies of fine mineral dust particles potentially released by wind erosion. *Geomorphology* 2008, 93, 157–167. [CrossRef]

38. Tadayonnejad, M.; Mosaddeghi, M.R.; Dashtaki, S.G. Changing soil hydraulic properties and water repellency in a pomegranate orchard irrigated with saline water by applying polyacrylamide. *Agric. Water Manag.* 2017, 188, 12–20. [CrossRef]

39. Andry, H.; Yamamoto, T.; Irie, T.; Moritani, S.; Inoue, M.; Fujiyama, H. Water retention, hydraulic conductivity of hydrophilic polymers in sandy soil as affected by temperature and water quality. *J. Hydrol.* 2009, 373, 177–183. [CrossRef]

40. Lai, S.L.; Chai, Q.; Wang, B.; Yang, N. Preparation and Application of Polymer Dust Suppressants in Coal Transportation under Microwave Irradiation. In Proceedings of the International Conference on Chemical, Material and Metallurgical Engineering (ICCMME 2011), Beihai, China, 23–25 December 2011; pp. 1632–1635. [CrossRef]