ABSTRACT: To investigate the dust source of the most polluted equipment in the open-pit mine, this paper studied the temporal–spatial distribution laws of dust migration in the vehicle transportation pavements in the open-pit mine via theoretical analysis and a field test. The results show that the dust concentration of the same horizontal distance from the pavement centerline remains roughly stable, which proves that the dust above the pavements is a continuous line source. In the horizontal direction, the maximum dust and baseline concentration reached heights of 1–3 and 20 m away from the wheels, respectively, while they are obtained at heights of 0.5 and 2.2 m away from the pavement in the vertical distance, respectively. The spatial concentration distribution of the dust clearly proves that the dust movement mode is a jumping mode. It takes 6 and 30 s after the vehicle had passed to achieve the maximum dust and baseline concentration, respectively. The dust concentration of a fully loaded vehicle is 2–3 times greater than that of a no-load vehicle. Meanwhile, the dust concentration of a sprinkling pavement is as 10% as that of an un-sprinkling pavement. The results of the migration of transportation dust and temporal–spatial distribution provide useful references for the analysis of dust source intensity and pollutant diffusion in open-pit mines. Furthermore, the efficient and low-cost moisturized dust suppressant would be the future direction to develop in different mining areas.

1. INTRODUCTION

In the past few decades, the increase of dust pollution above the transportation pavements emerged with the acceleration of industrialization, and the size of the pavement dust particulate matter (PM) is closely related to air pollution and the health of workers in workfaces. The particle size analysis and PM inhalation model study provide helpful methods to better figure out the health effects of PM produced in open-pit mining, and the measured PM concentration shows a strong consistency with the results of artificial neural network modeling. Based on the investigation using computational fluid dynamics–discrete element method (CFD-DEM) coupling and CALPUFF diffusion models, the diffusion distance of dust particles in the mining area exhibited a linear increasing trend versus time, while the maximum diffusion velocity decreased logarithmically with respect to the diffusion distance. The dust particles with various sizes showed a similar average escape time, while the maximum escape time and escape rate decreased with the increase of particles. Diego et al. reported that the total diffused dust can be obtained quantitatively by introducing a subroutine describing particle trajectory into CFX and can verify the timeliness of results and utilization of the natural environment in an open-pit mining area from satellite monitoring. Andrade et al. pointed out that the comprehensive environmental impact index was proposed after the field study in the impact on air quality by five open-pit mines, which is applicable to the impact of each air source nearby.

Based on the wind tunnel experiments and field tests, the emission factor of PM10 near four typical construction sites, which is obtained from the emission factor formula and exposure analysis experiment methods of PM10 for the soil transportation pavement, was 2–10 times higher than that of normal pavements. However, the dust intensity of a single vehicle can be reduced by half after sprinkling on the open-pit mine pavements. The dust, exhausted by vehicle transportation, depends on the speed and roadbed materials, which means that the dust concentration can be achieved to the highest at 1.7 m behind the vehicles at high speed. At the same time, PM10 is highly sensitive to pavement conditions.

The vehicle transportation contributes 89% of the total dust produced by equipment annually among the dust sources of
equipment in the open-pit mining, making it the most polluted dust source. The main transportation method in open-pit mining is vehicle transportation, which is characterized by the unique location of operation and the large scale of activity. Based on that, the air dust management in open-pit mines focused on the dust emitted by the vehicle transportation. This paper did some theoretical analysis and field tests to study the temporal—spatial distribution laws of vehicle transportation pavement dust migration in the open-pit mine, and thus, the spatial diffusion and migration laws of dust on the pavements in the open-pit mine were obtained.

2. EXPERIMENTAL SECTION

The pavement dust particles will be lifted off the ground because of vehicle disturbances. If the disturbance-induced complex turbulence is not considered and the influence of ambient wind speed is ignored, then the dust flying speed can be divided into the three directions: the horizontal (X in Figure 1), perpendicular (with respect to the horizontal direction; Y in Figure 1), and vertical direction (Z in Figure 1). The two partial velocities in the horizontal and perpendicular direction is caused by the disturbance of the air stream, while the velocity in the vertical direction is induced by the rising and falling of particles due to the turbulence, gravity, and air resistance. The trajectory of motion is shown in Figure 1.

2.1. Selection of Test Sites. Four sections of the highway were selected as the measurement site, according to the topographic data of the mining area (Figure 2 and Table 1).

2.2. Test Equipment. At present, the dust concentration, expressed as mass concentration, is mainly measured by the filter paper weight and photoelectric direct reading method.

The former method has a low cost, but it needs to weigh the filter paper, which is inconvenient to measure. In addition, the measurement error of dust concentration with low concentration in a short time is large. Therefore, it is used to measure the concentration distribution of the pavement dust. As for the latter, which is not only fast, accurate, and sensitive but also can directly display the mass concentration, can be used to measure the influence of different factors on dust concentration.

The two instruments above were placed at the same place at the tested site, and the mass concentration conversion coefficient $K$ of the pavement dust was measured to be 0.4213 by multigroup measurement calculation; thus, the mass concentration of dust can be obtained. For the pavement dust, the dust concentration can be calculated by the following formula

$$C = 0.4213 \cdot R \quad (1)$$

where $C$ is the dust concentration in mg·m$^{-3}$ and $R$ is the value measured by the digital dust sampler in CPM.

2.3. Measurement of Spatial Distribution of Dust Concentration. The spatial distribution test of pavement dust concentration mainly measured the dust concentration distribution at different heights and the downwind distance from the dust source. The section with less influence of wind was selected as the measurement site.

2.3.1. Dust Concentration in the Parallel Direction of the Pavement Centerline. After the repeated measurement at different sites and analyses of different results, five measuring points were selected in the horizontal direction of the pavement centerline. The interval of measurement points was 10–20 m. A measuring point of baseline concentration was set 25 m away from the pavement centerline in the vertical direction to record the variation of the dust concentration in the natural environment. The test data was measured under the same natural conditions when different vehicles passed by. The average acquisition time for each sample was 6 s, and the layout of the measuring points is shown in Figure 3a.

2.3.2. Dust Concentration in the Vertical Direction of the Pavement Centerline. The arrangement of measuring points in the vertical direction of the pavement centerline is shown in Figure 3a. The sampling points were 2, 5, 7, 10, 15, 20, 25, and 30 m away from the vehicle edge, and the sampling height was 0.1 m. At the same time, the measuring point of the baseline concentration (labeled as 14) was also set 25 m away from the pavement centerline.

2.3.3. Dust Concentration in the Perpendicular Direction of the Pavement Centerline. The measuring points selected in the perpendicular direction were 3 m away from the pavement centerline with the heights of 0.15, 0.5, 1, 1.5, and 2 m. In

![Figure 1. Dust movement trajectory diagram.](image)

![Figure 2. Distribution of measuring pavement.](image)
addition, the natural dust concentration was measured 15 m away from the pavement centerline.

2.3.4. Measurement of Dust Concentration over Time. The law of dust concentration changing with time was measured by fixed-point measurement. When the vehicle is fully loaded, the dust accumulation was measured by an interval of 6 s. The measuring point was set at the rear of the vehicle near the pavement centerline (Figure 3b), which was 1.5 m higher from the pavement. The minimum sampling time of the P-L2C digital dust sampler was 0.1 min. Therefore, after the vehicle passed through the measuring point, the dust concentration was continuously sampled 10 times in 0.1 min. The dust concentrations of each sampler as well as other relevant parameters were recorded.

2.3.5. Measurement of Vehicle Speed. The distance–time method was used to measure the on-site vehicle speed, which means to measure the time needed for a vehicle to pass a certain distance. If the driving distance (L) is too large, then the uneven driving speed will lead to an inaccurate measured speed. On the contrary, time (t) decreases with the L if L is too short. Minor errors will also bring great changes to the speed measurement so that L should be set as 40 m.

3. RESULTS AND DISCUSSION

3.1. Spatial Distribution of Dust Concentration. The environmental conditions of the field test are as follows: the average wind speed, the temperature, the humidity, the natural dust concentration, and the average speed were 0.92 m s\(^{-1}\), 25.1 °C, 21.3%, 7.1 mg m\(^{-3}\), and 4 m s\(^{-1}\), respectively. The spatial distribution of dust concentration is shown in Figure 4 when nine vehicles passed in 30 min.

The dust concentration was stable at \(\sim 56.7598 \text{ mg m}^{-3}\) at one measuring point, except for some slight fluctuations along the X axis paralleled to the pavement centerline, which can be treated equally considering the errors (Figure 4a). Therefore, the dust concentration of the pavement can be regarded as a continuous and uniform linear dust source.

It can be seen from Figure 4b that the dust concentration on the pavement reached the largest dust concentration (60.16 mg m\(^{-3}\)) at a distance of 1 m from the pavement centerline.
when the vehicle is driving, which was similar with that at 3 m from the pavement centerline. The dust concentration will not decrease rapidly, and this may be because the high-speed wheels can raise a large amount of dust. The dust concentration will decrease substantially from 55.37, at 7 m, to 14.37 mg·m⁻³ at 20 m away from the pavement centerline. However, the dust concentration changes slightly at 25 m from the pavement centerline, which can be regarded as the base concentration. It can be considered that the dust concentration measured here was suspended particles in the air with a small flying angle, low moving height, and small diffusion distance. The fitting expression of dust concentration at different distances from the pavement centerline is

\[ C_y = 80.292e^{-0.079y} R^2 = 0.9726 \]  

where \( C_y \) is the dust concentration in the perpendicular direction in mg·m⁻³ and \( y \) is the distance on the Y axis in m.

As shown in Figure 4c, the dust concentration increased first and then decreased with the increased vertical height. The average concentration distribution at different heights from the pavement can be expressed as

\[ C_z = -25.581z^3 + 122.22z^2 - 214.9z^2 + 138.51z + 46.028 R^2 \]

\[ = 0.9824 \]

where \( C_z \) is the dust concentration in the vertical direction in mg·m⁻³ and \( z \) is the distance on the Z axis in m.

The maximum dust concentration of 75.834 mg·m⁻³ appeared at a height of 0.5 m in the vertical direction. When the height is 0.8 m, the dust concentration decreases greatly (to 64.038 mg·m⁻³). The dust concentration is 31.176 mg·m⁻³ at a height of 2 m where the baseline concentration is 7 mg·m⁻³. According to the integral of the generated dust by the vehicle in this process, the vehicle height is 2.26 m when the dust concentration is the same as the natural dust concentration. Therefore, it can be inferred that most of the pavement dust cannot move to this place. The influence range of dust diffusion is mainly restricted below a height of 2.26 m in the vertical direction. The spatial distribution and influence range of dust concentration are shown in Figure 4d.

3.2. Variation of Dust Concentration with Time. The curve between the dust concentration and time was obtained by the fixed-point measurement method (Figure 5). It took a certain time for the dust to be diffused to the measuring point, and the concentration reached the peak in 5–10 s after which it will decline rapidly. Then, the concentration remained stable after 24 s and returned to the initial level at 30 s. This indicated that the raised dust had a different particle size. The dust with the larger particle size moved by leaps with low flying height and fast settling, and it is the main component of the dust. Meanwhile, the dust with the smaller particle size mostly moved as suspension or flotation with slow settlement and floating in the atmosphere for a long time. Although this part only accounted for a small part of the total amount of dust, most of the dust were respirable and suspended for a long time, which would cause great harm to human beings. The relationship between dust concentration and time was fitted as follows

\[ C_t = -1.1742t^4 + 16.265t^3 - 73.304t^2 + 108.09t + 2.385 R^2 \]

\[ = 0.9262 \]

where \( C_t \) is the dust concentration over time in mg·m⁻³ and \( t \) is the time in s.

3.3. Theoretical Analysis of the Pavement Dust in Vehicle Transportation. 3.3.1. Causes of Dust Emission. There were many factors that can cause the generation of pavement dust during vehicle transportation:¹³

1. The impact, friction, and rolling of vehicles resulted in the subsidence of pavement bending and potholes.
2. The standard, quality, and size of the construction as well as the poor routine maintenance of the pavements do not comply with the relevant building laws and requirements.
3. It is difficult to avoid the dropping of load along the pavement, and there are no effective dust control measures, which will lead to the deterioration of the pavement.
4. The gravel stone used for a simple pavement has not been screened and has insufficient strength.
5. The pavement covered by gravel and soil was easy to be destroyed on which the potholes and uneven surface dust will often form. A small amount of sprinkling could not control the dust, while a large amount of sprinkling would further deteriorate the pavement condition.

3.3.2. Mechanical Mechanism of Dust. At present, force, moment, and energy balance models were commonly used to explain the secondary flying of the pavement dust caused by airflow.¹⁵ The common point of the three models was that the mechanical disturbance and aerodynamic disturbance caused by vehicle driving will lead to dust emission. The secondary dust will be generated when the vehicle disturbance was greater than the pavement adsorption. In-depth analysis of the mechanical model showed that the dust adsorption of the pavement was not only related to the characteristics of dust but also depended on its structural connection forces. In the process of dust deposition, there would be an interaction between different properties and energy, and the stronger the force was, the more stable the interaction would be. When the cohesive force was greater than the adhesion force, the contact surface between soil particles and stable objects would be destroyed. The attraction between particles produced by the shear strength will decrease with the increase of soil particle spacing, if the fracture surface of stabilized soil was in the soil material between soil particles, and if the strength of the soil...
material was not enough. When the adhesion force was large, the strength of the soil depended on the cohesive force of soil particles. Therefore, the fracture surface of the stabilized soil was in the soil particles when the shear stress caused by external forces was greater than the original cohesive force. It can be concluded that the stability and bearing capacity of the soil pavement mainly depend on the compaction, material, and shear strength of the pavement.

For the asphalt pavement, the dust caused by the vehicle was a continuous linear dust source. Similar with the soil pavement for the failure mechanism of dust stability, the adsorption of dust on the asphalt pavement depended on the original cohesive force of dust particles, the pavement, and the adhesion force between them. Since the asphalt pavement was rarely damaged, the surface instability of the pavement dust occurred only in or between the dust and pavement. The road surface would be deformed to some extent under the load of the wheels, and a lot of dust would be generated under the repeated rolling of the wheel after the stability was destroyed. When the wheels travel on the uneven pavement, the air in the potholes was compressed but it will be suddenly expanded after the wheels pass, which had a strong effect of empty suction or aggregate effect on the pavement. It would not only damage the pavement but also create a strong shock airflow that raised the dust. Then, the dust was diffused into the atmosphere with the disturbance airflow and natural wind of the vehicle driving, forming air pollution. If the driving speed is too fast, then it will also cause an atmospheric turbulence near the wheel, which will bring up the dust near the wheel, thus greatly increasing the dust concentration.

3.3.3. Motion Model of Dust on the Transportation Pavement. Previous studies have shown the mathematical expression of dust deposition as follows:

\[ V_t = 2r^2 \rho_p (\rho_p - \rho_f) \left(1 + \frac{3\mu}{\theta f}\right) \left[1 + 4\mu/\theta f + 6(\mu/\theta f)^2\right] g \]

where \( V_t \) is the dust settling velocity in \( \text{m/s} \), \( r \) is the particle size of the dust in \( \text{m} \), \( \mu \) is the coefficient of kinematic viscosity, \( \theta f \) is the external friction factor, \( \rho_p \) is the dust density in \( \text{kg/m}^3 \), \( \rho_f \) is the air density in \( \text{kg/m}^3 \), and \( g \) is the gravity coefficient and is determined to be 9.81 N\( \cdot \)kg\(^{-1}\).

The formula only described that the dust settling velocity increased with the increasing of particle size and density. There are three different movements of dust particles on the ground, namely, the surface creep, jumping, and suspension. Obviously, the large and heavy dust particles could only roll along the ground, which was called the surface creep. While the small and light particles hang in the air, the gravitational sedimentation velocity of which is so small that it can be carried by a turbulent vortex. Therefore, its motion track is not smooth. The medium-sized dust particles leap into the airflow and return to the ground along a determined and smooth trajectory under the combined action of gravity and air resistance. Most of the pavement dust are jumping, and the angle between the dust and the ground is generally no more than \( 10^\circ \), so its motion height is low and the distance is short. If the pavement reflection effect is considered, then the dust will bounce back into the air and hit other stationary dust particles on the pavement, causing the movement of these dust particles. Under these two functions, the dust spread further to the roadside. The spatial concentration distribution test of the dust (Figure 4) also fully proved that the dust movement mode is the jumping mode.

3.4. Analysis of Factors Affecting Pavement Dust Concentration. There are many factors that can affect the pavement dust with a complex mechanism. Combined with the actual conditions of the test mine, the vehicles were special mine vehicles with a load of 130 t, and the speed was basically constant at 4 \( \text{m/s} \). In addition, the mining area is often located in the mountain area, which often suffers from a relatively harsh climate. Moreover, the solubility of different salts will also vary depending on the mineral compositions of the recycled water in the mining area. Due to the effects of strong winds, high temperatures, and continuous workload, the salt or brine solution would quickly dry out, and the protective layer formed from the dust suppressant on the pavement would be destroyed, which will increase the cost. Combined with the practical application on the site, it could be seen that sprinkling water was still the commonly used dust removal measure on the mine transportation pavements. Therefore, the pavement with or without sprinkling and the vehicles with no load and fully loaded were considered. The variation of dust concentration with time under two conditions were measured (Figure 6).

The peak dust concentration generated by the fully loaded vehicle was about 2–3 times as that of a no-loaded vehicle (Figures 5 and 6a), and it indicated that the load of the vehicle has a great influence on pavement dust production. The larger the load and the dust concentration are, the longer the dust diffusion time is. The main reason is that, when the vehicle is driving on the rough pavement, the compressed air will be suddenly expanded and raised the dust on the pavement.
Further analysis showed that, when the driving speed was slow, there was less air compression in the potholes and the pressure difference caused by a no-load vehicle was smaller, so the instantaneous release of dust was relatively small. On the contrary, the pressure difference caused by a fully loaded vehicle was relatively large, and as a result, the dust concentration and raising height were relatively large. The fitting formula of dust concentration change under a no-load vehicle was as follows:

$$C_n = 3.7917t^3 - 26.943t^2 + 48.65t + 1.4725R^2 = 0.9429$$

where $C_n$ is the dust concentration under no load in mg·m⁻³ and $t$ is the time in s.

The dust concentration during normal driving was measured under the two conditions: with or without sprinkling on the pavement (Figure 6b), and the results showed that the minimum and maximum dust concentrations of the pavement before sprinkling were 27.65 and 69.26 mg·m⁻³, respectively. The dust concentration varied sharply with the maximum concentration difference being 41.61 mg·m⁻³. Meanwhile, for the condition with sprinkling, the pavement humidity increased, and the minimum and maximum dust concentrations were 2.36 and 7.36 mg·m⁻³, respectively, and the dust concentration changed gently with the maximum difference only being 5 mg·m⁻³.

3.5. Implication to Reduce Dust Concentration of Pavement in the Mining Area. From the results of data analysis (see Section 3.4), the dust concentration after sprinkling was greatly lower than that before sprinkling, and the average dust concentration after sprinkling was only about 10% of that before sprinkling. Meanwhile, the dust concentration after sprinkling was closed to the natural dust concentration. It showed that the pavement sprinkling puts a good effect on dust suppression of the vehicle transportation pavement. However, the pavement moisture after sprinkling was easy to be evaporated in the open-air drying environment, and the duration of the sprinkling effect on dust suppression was relatively short. On the other hand, brine solution was thought to have an effect on dust suppression of the vehicle transportation pavement: whether the vehicle was loaded and whether the water was sprinkled. The dust concentration of a fully loaded vehicle was 2–3 times that of a no-load vehicle. The dust concentration of a sprinkling pavement was 10% of that of an unsprinkling pavement.

(4) According to the theory of fluid dynamics and gas–solid two-phase flow, the transport model and concentration distribution law of the dust were obtained, which laid theoretical and practical significance on the study of dust source strength and pollutant diffusion in open-pit mines.

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Notes

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