Experimental study on the influence of longitudinal slope on airflow-dust migration behavior after tunnel blasting

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Abstract

In this paper, a 1:21 model experiment was conducted to discuss the dust dispersion efficiency and liner trolley obstruction effect inside the tunnel at -9° to 9°, the effect of different initial dust concentrations on dust dispersion and liner trolley obstruction effect at 6° slope, and the effect of different return air velocity on dust dispersion at 6° slope. The results show that as the slope of the tunnel changes from 0° to -9°, the average dust dispersion time decreases by 3.7% at the working face and the dust concentration difference between the front and rear of the trolley is improved by 2.7%. When the slope of the tunnel changes from 0° to -9°, the average dust dispersion time increases by 7.2% at the working face and the dust concentration difference between the front and rear of the trolley is improved by 17.9%. With each 100mg/m³ increase in the initial dust concentration, the dust dispersion time at the working face and the tunnel exit increases by 9.15% and 8.17% on average, and the lining trolley obstruction time increases by 23.33s on average. The dust dispersion times take an average reduction rate of 15.7%, with the increase of return air velocity. The recommended return air velocity is greater than 1m/s for large slope tunnels. When the slope changes from 0° to 9°, the hindrance rate of slope on dust dispersion is 2.88462%, 8.65385%, and 16.34615% respectively. Dust dispersion efficiency will be reduced as the tunnel slope changes from 0° to 9°. The growth rate of slope on dust dispersion is -0.96154%, -2.88462%, and -6.73077% respectively.

1 Introduction

With the effective depth of the "Western Development" policy, the continuous promotion of infrastructure construction in the western region of China, and high-speed railroad construction in western China in an orderly manner, China's western terrain is dominated by mountains, plateaus, and basins, with large topographic relief. In the technical background of the traditional drill and blast method as the main boring process, large slope tunnels and spiral tunnels are mostly used to solve the problem of large driving detour distances and slopes between high-altitude areas and low-altitude areas. According to the current specification, the slope of the tunnel main tunnel is generally bounded by 3°, while in recent years some tunnel cross passage and inclined shaft projects have extremely large slope cases such as -14° and 38°. When in large slope tunnel and tunnel construction, the buoyancy and gravity of the smoke will no longer be perpendicular to the ground, which makes the buoyancy and gravity become an additional driving force for the smoke to spread in the tunnel, which has an important impact on the pollutant concentration distribution. Construction ventilation, as the main way of air purification in underground space operations, is one of the key indispensable technical aspects of tunnel construction. At the same time, if the exhaust gas, toxic gas, dust, and other pollutants generated from drilling, blasting, slurry spraying, slagging, and other operational processes cannot be discharged from the tunnel in time, it will seriously threaten the physical and mental health and life safety of the tunnel workers.

At present, the research on the construction ventilation of long tunnels has achieved considerable results. These studies mainly focus on dust dispersion characteristics, temperature variation characteristics,
optimization of ventilation parameters, etc. Some of these scholars have mainly used numerical simulations and field tests to study slope tunnel construction ventilation. Kong et al. used NSYS to establish the ventilation model for tunnels with different slope changes, the flow field characteristics near the jet fan and the effect of tunnel slope on the ventilation efficiency were studied; Zhang et al. simulated the smoke dispersion effect of the shaft under the influence of longitudinal ventilation and slope to study the change in the rate of smoke emission from the shaft in the tunnel; Li et al. carried out a field test in an underground sloping tunnel and the results showed that the temperature decreases in the form of exponent; Rafael et al. learned influence of the slope in the ventilation semi-transversal system of an urban tunnel; Song studied the influence of slope and radius of curvature of the spiral tunnel on the dispersion pattern of pollutants.

A large number of ventilation studies have also been conducted through model experiments, many of these scholars have also addressed the issue of the characteristics of operation ventilation and fire smoke exhaust of large slope tunnels by using model experiments. Where Chow et al. used a 1/50 tunnel model with an adjustable angle to learn the fire smoke dispersion pattern under 5°, 10° and 15° slopes; Lei used numerical simulation with branch slopes of 0%, 3%, 6%, and 9% to estimate the mass and heat flux into the branch; Gao et al. learned the effect of longitudinal slope on the smoke propagation and ceiling temperature characterization in sloping tunnel fires under natural ventilation; Tao et al. based on the temperature and smoke distribution, ventilation schemes before and after the opening of the transverse passage are proposed; Zhou provided a reference for the optimal design and management of natural ventilation system and contribute to improving the air quality and controlling the pollutant concentration in single and gable sloping city tunnels; Li used a 1/8 reduced-scale tilted tunnel model was built for the experimental to carry out the smoke movement about the fire source due to buoyancy along the longitudinal tunnel axis. This research provides excellent results for the study of ventilation in large slope tunnels and examples of model tests for reference.

In summary, a wealth of information on the study of smoke dispersion patterns in sloped tunnel fires. Few studies are carried out on the construction ventilation of large slope tunnels, and few studies on the effect of large slope on the change of dispersion of pollutants distribution using model experiments. Therefore, because of the complex construction environment of sloped tunnels, an in-depth study of the spatial and temporal distribution of pollutants during the construction period, the investigation of their transport characteristics and derivative development mechanisms under the coupling effect of wind and flow fields, and the formulation of the effect of slope on the transport efficiency of pollutants to achieve efficient and safe construction with green construction as the core concept are the key issues that need to be solved in tunnel construction today.

In this paper, a 1:21 model experiment was conducted to discuss the dust dispersion efficiency and liner trolley obstruction effect inside the tunnel at -9° to 9°, the effect of different initial dust concentrations on dust dispersion and liner trolley obstruction effect at 6° slope and the effect of different longitudinal return air velocities on dust dispersion at 6° slope.
2 Model Building And Working Condition Setting

2.1 Similarity theory

Similarity experiments are based on the principle of similarity, according to a certain scale to make a
model with a similar scale to the prototype for experimental studies, in order to predict the flow
phenomenon that will occur in the prototype, the core of the modeled similarity experiments is to
reproduce the physical nature of the phenomenon of motion. In the case of experimental conditions, the
model experiment is more effective instead of theoretical calculations.\(^{28,29}\)

To ensure that the ventilation model for two-line railroad tunnel construction is similar to the actual
situation flow, the model experiment should satisfy geometric similarity, kinematic similarity, and
dynamic similarity. Generally speaking, the geometric similarity is the premise and basis of motion
similarity and dynamic similarity, and dynamic similarity is the dominant factor of flow similarity. In
tunnel gas-solid two-phase flow simulation experiments, it is almost impossible to make the model and
the prototype meet seven similarity criteria and several single-value conditions at the same time, and the
study of solid particles in the flow is difficult to realize the modal conditions, which are usually solved by
approximate imitation\(^ {30,31}\), so only the similarity criteria that play a major role are considered in the
experimental design. Among them, Euler’s criterion is the pressure similarity condition, and Euler’s
criterion is naturally satisfied when the prototype and model flow patterns are similar; the actual dust
particles in the cavity group and the dust particles in the experimental model are small, and Froude’s
criterion can also be ignored; the model and prototype ventilation gas is air, which can be regarded as
incompressible airflow with constant density and viscosity, and the flow resistance consists of viscous
resistance and inertia force, and the model experiment mainly Reynolds criterion must be satisfied:

\[
Re = \frac{wd}{\nu}
\]

1

\[
\frac{\rho_p v_p L_p}{\mu_p} = \frac{\rho_m v_m L_m}{\mu_m}
\]

2

\[
Re_p = Re_m
\]

3

where \( Re \) is Reynolds number; \( w \) is fluid velocity; \( d \) is the equivalent diameter; \( \nu \) is fluid viscosity
coefficient; \( p \) is density; \( L \) is length and \( \mu \) is fluid dynamic viscosity coefficient.
And because the model is proportional to the prototype spatial geometry, ideally the criterion similarity should apply to a single particle size, but the distribution of dust particle sizes in the actual construction process is a mixed distribution, for which a certain characteristic size of the multi-grain mixed dust that obeys the same distribution law as the prototype particle size distribution is used as the equivalent diameter for simulation. For isothermal flow, the model is automatically satisfied by the similarity of the relevant physical parameters of the fluid at the corresponding point within the prototype. Since viscous flow has stability, the flow at a certain distance from the wall has little effect on the flow state and flow velocity distribution, so the wall roughness similarity can be disregarded. Boundary conditions: No matter how the inlet velocity is distributed, the velocity distribution tends to be the same for the model and the prototype after a certain distance, so the similarity of the fluid velocity distribution at the inlet and outlet is automatically satisfied.

2.2 Experimental Model Building

The tunnel construction operation area based on the drill and blast method mainly refers to the second lining step range from the working face to the lining trolley, as shown in Fig. 1. As this section is the main concentration area of the tunnel construction workers, its environmental quality is required to be high, so we take the operation section of the grown-up railroad tunnel as the research object and construct an equal scale scaled-down model to investigate the key parameters affecting the dust dispersion and dispersion.

The tunnel model refers to the standard section of a double-line railroad tunnel, and the scaled-down model is constructed within 250m$^2$ of the construction section, with a proposed prototype section area of 150m and a model similarity ratio of 1:21, the specific dimensions of the section are shown in Fig. 2. To achieve better observation effect, the experimental model is made of 2mm thick transparent acrylic plate custom splicing, the length of single section model is 1.2m, a total of 10 sections, the total length of the model is 12m, using a 0.5m high platform to support the placement. To ensure overall airtightness during the experiment, the edges of every single section of the model are managed to be sealed with aluminum foil tape, and the schematic diagram of the model construction is shown in the following figure. To build a more realistic structure of the internal environment of the tunnel section, consider adding a simple lining trolley model, which is made of 1mm rigid cardboard, 0.47m long, and placed at 9.5m from the working face of the tunnel model (200m from the prototype).

The ventilation system of the model experiment adopts a small axial fan of SF4-4R type, meanwhile, in order to ensure the ventilation effect, on the basis of not exploring the air leakage of the duct and its form on the overall impact of the experiment, it is proposed to use 1mm thick PVC rigid pipe as the air flow path of the whole model experiment (i.e. the prototype duct), with 1800mm diameter duct as the prototype to build the model, with an inner diameter of 85mm, and the air supply system through canvas. At the same time, SZ-J/0.75G-A2 fan speed control switch is used to control the axial fan speed to obtain the predetermined return air speed in the tunnel with 0.75kW power; the air duct outlet distance from the
palm surface is 0.95m (20m for the prototype), and the model ventilation system is shown in Fig. 3, and its main equipment performance parameters are shown in Table below.

To build a more realistic structure of the internal environment of the tunnel section and to explore the obstructing effect of the lining trolley on dust dispersion, a simple lining trolley model was added. The trolley model was made of 1mm rigid cardboard, 0.47m long, and placed at 9.5m (200m of the prototype) from the working face of the tunnel model.

2.2 Experimental dust setting

In the construction of the drill and blast method, drilling, blasting, slag transportation, shotcrete, and other construction processes will generate a large amount of dust, according to the source is divided into the original dust, blasting dust and process dust, blasting dust and process dust is 80–90% of the total dust production. The dust generated by blasting is mainly the dust formed by the rock being broken, accompanied by the dust caused by the huge blast force; the source of dust from slag transportation is mainly the transfer of slag and dust from operating machinery; the dust generated by shotcrete is mainly generated by the dispersion of concrete powder, the collision between high-speed concrete and tunnel walls and mutual collision. Tunnel blasting dust particle size is generally 0 ~ 75\textsuperscript{32,33}.

The standard port 50ml constant pressure funnel with tetrafluorine piston valve is used as a dust generator to circumvent the disturbance of its initial distribution field morphological characteristics during the large-scale non-uniform intake of dust particles and restore the original state of blasting floating dust after stagnation as much as possible. To simulate the initial dust concentration field of different scales during the experiment, the sieved dust was introduced into the constant pressure funnel, the piston was opened, and the dust particles entered the model tunnel at a uniform speed and in equal amounts. The ventilation dust concentration monitoring device is placed at the front of the tunnel model, and when the concentration near the palm surface reaches the predetermined experimental working condition, the ventilation system is turned on and the experimental monitoring is carried out. Experimental dust disposal progress and equipment are shown in Fig. 4.

2.3 Monitoring setting

To investigate the dust distribution law under the coupling effect, the test uses return air velocity and dust as the main monitoring indexes, and monitors the return air velocity and dust volume concentration in real-time, in which the XZ4451D-500MT-05088 type hot film return air velocity sensor is used to determine the section return air velocity with a range of 0 ~ 5m/s and a precision of 3%. The test device is shown in Fig. 5. Each condition will ventilate the 1200s and monitoring data were recorded once every ten seconds. The ambient temperature of the laboratory where the experiment was conducted was 19°C to 22°C and the atmospheric pressure was 101kPa.

2.4 Working condition setting
The experiment intends to explore the key factors affecting the dust migration characteristics during the tunnel construction period, taking the dust particle size, initial concentration, return air velocity, and second lining step as the main research objects, and measuring the spatial and temporal distribution of dust at different particle sizes, different sizes of initial dust concentration fields, different return air rates and different second lining steps. The monitoring contents and working conditions are listed in Table.1 below, with 13 working conditions in total.

**Table 1**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Consideration</th>
<th>Slope(%)</th>
<th>Air Velocity(m/s)</th>
<th>Dust Concentration(mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–1</td>
<td>Slope</td>
<td>0</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>1–2</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–3</td>
<td></td>
<td>-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–4</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–5</td>
<td></td>
<td>-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–6</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–7</td>
<td></td>
<td>-9</td>
<td></td>
<td></td>
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<tr>
<td>2–1</td>
<td>Return air velocity</td>
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<td>200</td>
</tr>
<tr>
<td>2–2</td>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>2–3</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2–4</td>
<td></td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3–1</td>
<td>Initial dust concentration</td>
<td>6</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>3–2</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>3–3</td>
<td></td>
<td></td>
<td></td>
<td>300</td>
</tr>
<tr>
<td>3–4</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
</tr>
</tbody>
</table>

According to current specifications and engineering examples, the slope of tunnels, auxiliary passages, and inclined shafts generally does not exceed 3°, and there are few cases of large slopes. In this study, to investigate the extreme cases, we set the slope of ± 3°, ± 6°, ± 9°, and 0° as the tunnel slope variables, where positive and negative represent the downhill and reverse slope cases, with 7 control groups. Also, for the field measurement results of relevant long-drawn railroad tunnels, subject to various unfavorable factors in the actual ventilation system deployment and implementation, and the cross-sectional area is relatively large, the cross-sectional return return air velocity of long-drawn tunnels is generally less than 2m/s and maintained at 0.4 ~ 0.8m/s level. Therefore, 0.5m/s, 0.8m/s, 1.0m/s, 1.5m/s, and 2.0m/s are
taken as the return air velocity variables, and a total of 5 sets of working conditions are set. The dust concentration after tunnel working face blasting is determined by the construction environment, surrounding rock conditions, explosive type, dosage, etc. The initial dust concentration of 100mg/m$^3$, 200mg/m$^3$, 300mg/m$^3$, and 400mg/m$^3$ is used as the initial dust concentration variables in this study.

3 Result And Discussion

3.1 Impact of different slopes

To investigate the effect of different slopes on the dust dispersion law, the experiment was designed with seven groups of comparison conditions, and the tunnel slopes were 0°, ±3°, ±6°, and ±9° for a total of seven different particle size ranges of dust for the control experiment, ensuring the same initial concentration of 200 mg/m$^3$, controlling the model internal return air velocity of 1.0 m/s by adjusting the transformer. The variation of dust concentration with ventilation time at the location of the monitoring point was recorded and is shown in Fig. 6 below.

As shown in the figure, comparing the changes in dust concentration with time at each slope, it can be seen that the effect of different tunnel slopes on dust dispersion is mainly manifested by the increase of dust peak and the increase of time required for dust discharge with the increase of slope. Under various working conditions, the concentration of monitoring surface 1 has a small local rebound. The above situation is because as the slope of the model becomes larger, the dust is more likely to gather in the tunnel during ventilation, making it difficult for some of the dust to settle inside the tunnel or be discharged under the action of gravity. According to the comparison of the concentration data of the two supervisory surfaces at the front and rear ends of the trolley, the lining trolley has a significant hysteresis effect on dust dispersion. By processing the test data of the two monitoring points, the average dust concentration difference and dust dispersion lag time comparisons for each slope in Table.2 were obtained. From the table, it can be seen that the concentration difference from −9° to 0° is slowly increasing with an average increase of 2.7%, dust dispersion lag time shows consistency, with reduced dust lag time at -9° operating conditions. The concentration difference from 0° to 9° is significantly increasing with an average increase of 17.9%, and dust lag time improved by 20s on average from 3° to 9°.
Table 2
Comparison of dust dispersion before and after lining trolley at different slopes

<table>
<thead>
<tr>
<th>Working Conditions</th>
<th>Average Dust Concentration Difference (mg/m³)</th>
<th>Dust dispersion Lag Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-9°</td>
<td>6.01</td>
<td>20</td>
</tr>
<tr>
<td>-6°</td>
<td>6.19</td>
<td>30</td>
</tr>
<tr>
<td>-3°</td>
<td>6.438</td>
<td>30</td>
</tr>
<tr>
<td>0°</td>
<td>6.508</td>
<td>30</td>
</tr>
<tr>
<td>3°</td>
<td>7.753</td>
<td>30</td>
</tr>
<tr>
<td>6°</td>
<td>8.95</td>
<td>50</td>
</tr>
<tr>
<td>9°</td>
<td>10.65</td>
<td>70</td>
</tr>
</tbody>
</table>

From the Fig. 7, the maximum dust concentration is 187.7, 186.2, 181.9, 182.2, 185.7, 181.9, and 188.0mg/m³ respectively, there is no major difference between the operating conditions. The dust concentration at each monitoring section near the working face gradually rises with time until the peak under the coupling effect of the wind flow field and then decreases with a decreasing trend of decreasing rate, and the monitoring section concentration at the working face under the slope of -9°, -6°, -3°, 0°, 3°, 6°, and 9° working conditions reaches the specified threshold value with return air velocity increments of 350s, 370s, 370s, 390s, 400s, 440s, 480s respectively. It can be found that from 0° to -9°, the dust dispersion rate is partially increased, with a maximum difference of 50 s and an average growth rate of 3.7%; while from 0° to 9°, the dust dispersion rate is significantly reduced, with a maximum difference of 90 s. The average reduction rate is 7.2%.

3.2 Impact of different initial dust concentration

To investigate the effect of different slopes on the dust dispersion law, the experiment was designed with seven groups of comparison conditions, and the tunnel slopes were 100mg/m³, 200mg/m³, 300mg/m³, and 400mg/m³, for a total of seven different particle size ranges of dust for the control experiment, controlling the tunnel slope as 6° by adjusting the support frame and return air velocity of 1m/s by adjusting the transformer. The variation of dust concentration with ventilation time at the location of the monitoring point was recorded and is shown in Fig. 8 below.

The effect of initial dust concentration on dust dispersion mainly shows that the concentration peak rises with the increase of concentration field, the dust spreading rate decreases, and the lag degree of monitoring section position increases before and after the trolley, with each 100mg/m³ increase in the initial dust concentration, the lining trolley obstruction time increases by 23.33s on average. Under different initial dust concentrations, the overall change pattern of dust concentration with time gradient
did not change significantly, and it showed a short time rise to the peak with the increase of time, and then the rate decreased. The initial dust concentration affects the peak concentration of the cross-section, which shows that the initial dust volume rises, the peak concentration rises, and the time of the peak concentration then lags, and the time used to reduce to the maximum allowable concentration lags accordingly. To further explore the effect of the initial dust volume on the dust dispersion efficiency of the tunnel, the following: monitoring point 1 and monitoring point 4 were selected to compare the variation of dust concentration in the internal section with time at different initial concentrations.

It can be seen from the Fig. 9 that the time of maximum concentration of each condition is relatively consistent. As the initial dust concentration increases in monitoring point 1, there is a significant rebound in dust concentration after ventilation starts. The dust dispersion time increases significantly as the initial dust concentration increases, the dust dispersion time is 400s, 440s, 470s, and 520s respectively with an average growth rate of 9.15%. The dust arrival time at the outlet is not much different for each working condition, while the dispersion time also increases significantly with the increase of the initial dust concentration, the dust dispersion time is 590s, 660s, 690s, and 750s respectively with an average growth rate of 8.17%. This is mainly due to the increase in the initial dust concentration, the more stable the dust community, the relatively small effect of dispersion by the wind flow, requiring longer ventilation time to dilute and diffuse the dust.

### 3.3 Impact of different wind velocity

To investigate the effect of different slopes on the dust dispersion law, the experiment was designed with seven groups of comparison conditions, and the return air velocity were 0.2m/s, 0.5m/s, 1m/s, and 2m/s, for a total of 4 different particle size ranges of dust for the control experiment, ensuring the same initial concentration of 200mg/m$^3$, controlling the tunnel slope as 6° by adjusting the support frame. The overall trend of dust concentration with time gradient in each monitoring section under the coupling effect of the wind flow field is: rising to the peak within a short time, and then gradually decreasing with time in a power function-like trend, i.e., the rate of decrease is first fast and then slow and gradually decreasing. The key characteristics of monitoring point 1 and monitoring point 4 are compared and analyzed under different return air velocity, see Fig. 10 and Fig. 11 below, it can be seen that the influence of different longitudinal wind return rates on its concentration changes is mainly manifested as the increase in return air velocity, the peak concentration of each monitoring section decreases, and the peak occurs earlier; at the same time, the reduction rate of the section concentration is enhanced to a certain extent. The peak dust concentration represents the overall dust pollution level in the tunnel, the time of peak appearance can represent the dust dispersion rate in the tunnel, and the time taken to reduce to the allowable concentration can reflect the dust removal efficiency under the existing ventilation system. The effects of return air velocity on the above three parameters are studied separately, mainly as follows.

Figure 10 shows the time of peak dust concentration at different return air velocitys near the working face, from the figure, it can be seen that the time of peak concentration near the working face decreases with the increase of return air velocity, and the rate of decline increases with a certain weak trend, and the
rising trend becomes more and more significant when the return air velocity is greater than 1.0 m/s. The average reduction rate was 26.7%, and the dust dispersion time was 700s, 550s, 440s, and 270s for the return air velocity rate of 0.2 m/s to 2 m/s, respectively, which showed a significant increase in dust removal effect. In Fig. 11, it can be found that the dust dispersion time and the peak concentration at the exit of the dust model are decreasing from 0.2 m/s to 2 m/s. The dust dispersion times are the 1060s, 970s, 830s, and 680s, with an average reduction rate of 15.7%. The dust dispersion efficiency at 1 m/s and 2 m/s was significantly improved, with 14.4% and 24.7%, respectively. This indicates that the increase of the ventilation return air velocity can promote the transport of dust in the tunnel and accelerate the reduction of dust concentration, which means maintaining a longitudinal return return air velocity of more than 1 m/s in the tunnel under large slope conditions can significantly improve the efficiency of dust dispersion and improve the construction environment in the tunnel.

### 3.4 Impact of dust dispersion influence factor

To specifically quantify the effect of tunnel slope on dust dispersion efficiency, select data for different slopes at monitoring point 4, and the dimensionless number \( \eta \) is defined to represent the dust dispersion influence factor. \( \eta \) is mainly expressed in the experiment as the length of dust discharge time and the time of maximum dust concentration appearance, also compares dust dispersion efficiency at 0°. When \( \eta \) is a positive number means that it hinders dust dispersion while a negative number means that it has a positive effect on dust dispersion. Therefore, in order to explore the relationship between the tunnel slope \( \alpha \) and \( \eta \), the relationship equation of \( \eta \) is defined as follows:

\[
\eta = \frac{t_i}{t_0} \cdot \frac{T_i}{T_0} - 1
\]

where \( t \) is the time of maximum dust concentration; \( T \) is the total time for dust dispersion in the lining trolley section.

The data from the exit monitoring points \( t_i \) and \( T_i \) at each slope are brought into Eq. (3) to obtain the data, and the curve is fitted using a polynomial, as shown in Fig. 12. The relationship equation between \( \eta \) and slope \( \alpha \) is:

\[
\eta = -0.45818 - 0.64619a + 0.05597a^2 - 0.00791a^3
\]

where \( a \) is the slope of the tunnel; \( \eta \) is the total time for dust dispersion in the lining trolley section.

The fit coincidence \( R^2 \) is 0.99462. It can be seen from the figure that compared to the no-slope case, the hindering effect of dust dispersion under the downhill longitudinal slope is greatly increased. The reverse slope situation has a negative effect on dust dispersion as the growth rate of \( \eta \) in 3°, 6°, and 9° are 2.88462%, 8.65385%, and 16.34615% respectively. The resistance to dust dispersion increases with the increase of tunnel slope, \( \alpha \) shows a positive significance for dust dispersion efficiency, while the \( \eta \) in -3°, -6° and -9° are -0.96154%, -2.88462%, and -6.73077% respectively.
4 Conclusion

This paper reveals the understanding about the influence of longitudinal slope on airflow-dust migration behavior after tunnel blasting. A series of model tests with a scale of 1:21 are carried out to investigate the effect of the different slopes, initial dust concentration and return air velocity in the tunnel on the dust dispersion efficiency. The main results are as follows:

(1) As the slope of the tunnel changes from 0° to -9°, the dust dispersion efficiency in the tunnel improves. The average dust dispersion time decreases by 3.7% at the working face and the dust concentration difference between the front and rear of the trolley is improved by 2.7%. When the slope of the tunnel changes from 0° to 9°, dust dispersion in the tunnel is significantly lagging. The average dust dispersion time increases by 7.2% at the working face and the dust concentration difference between the front and rear of the trolley is improved by 17.9%.

(2) When the tunnel slope is 6°, the initial dust concentration affects the time of the peak concentration then lags, and the time used to reduce to the maximum allowable concentration lags as the initial dust concentration increases. With each 100mg/m³ increase in the initial dust concentration, the dust dispersion time at the working face and the tunnel exit increases by 9.15% and 8.17% on average, and the lining trolley obstruction time increases by 23.33s on average.

(3) When the tunnel slope is 6°, with the increase of return air velocity, the dust dispersion times take an average reduction rate of 15.7%. The dust dispersion efficiency is significantly improved while the return air velocity is 1m/s and 2m/s with the dust dispersion efficiency improved by 14.4% and 24.7% respectively. The recommended return air velocity is greater than 1m/s for large slope tunnels.

(4) The dust dispersion influence factor $\eta$ represents the influence of the slope of the tunnel on the dispersion of dust to the exit. The results show that when the slope changes from 0° to 9°, the hindrance rate of slope on dust dispersion is 2.88462%, 8.65385%, and 16.34615% respectively. Dust dispersion efficiency will be reduced as the tunnel slope changes from 0° to 9°, The growth rate of slope on dust dispersion is -0.96154%, -2.88462%, and -6.73077% respectively.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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References


8. Xie, F. Research on Construction Technology of Reverse-slope Drainage of Large-slope Inclined Shaft in Water-rich Tunnels-Taking Water-rich and Large-slope Inclined Shaft Construction Project of Taiyueshan Tunnel on Lihuo Expressway as an Examp. Engineering and Technological Research 7(18):65-67 (2022)


25. Tao, L., Zhang, Y., Hou, K., Bai, Y., Zeng, Y., Fang, Y. Experimental study on temperature distribution and smoke control in emergency rescue stations of a slope railway tunnel with semi-transverse


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