Research on anti-freezing and thermal insulation measures of tunnel in cold area

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Abstract—To solve the problem of freezing damage in tunnels in cold areas, based on the investigation and analysis of the existing tunnel insulation measures in cold regions, the Wunvfeng Tunnel is used as a supporting project. First, indoor tests are conducted to analyze the insulation performance, insulation effect and influencing factors of the cold insulation layer. The moisture-proof performance has a great influence on the cold-proof and thermal insulation effect. From the test results, it can be seen that when the thermal insulation layer is immersed in water, its thermal insulation performance decreases rapidly. The temperature behind the thermal insulation layer decreases rapidly with time, and the temperature quickly drops below zero without convergence, trend, the loss of cold-proof and thermal insulation performance. Then, through numerical simulation, the thermal insulation effect of different insulation layer laying methods (intermediate method, double layer method and surface method) was compared and analyzed, and it was concluded that under the same thickness of insulation layer, the better insulation layer laying method was surface method. It also shows that the closer the insulation layer is to the interface between the surrounding rock and the ambient air, the better its insulation effect.

1. INTRODUCTION

With the development of the western region and the "One Belt And One Road" initiative, the number of construction of tunnels and Bridges in high altitude, high latitude and cold regions is increasing. However, freezing injury is very common in tunnels built in cold areas with harsh natural conditions \cite{1-6}. Therefore, it is very important to study the mechanism of tunnel freezing damage and the technology of cold protection and insulation under severe cold conditions.

Domestic and foreign scholars have used a variety of methods to study this problem in depth. Based on the solid heat transfer theory, Wu Chunyong et al. \cite{7-9} established a shallow tunnel heat transfer mathematical model considering the combined effect of surface and river temperature in the tunnel, and analyzed the influence of the tunnel depth, the temperature in the tunnel and the thickness of the insulation layer on the temperature field of the tunnel. law. Wang Xiuling et al. \cite{10-11} researched that the passive
insulation measures of laying an insulation layer could not completely eliminate frost damage, and proposed a design method for tunnel insulation and anti-freezing using geothermal heat, and proposed a new development direction for tunnel insulation in cold areas. Zheng Bo[12] proposed that when determining the length of the insulation layer of the tunnel in the cold zone, the annual average temperature change and the attenuation of the temperature amplitude in the tunnel should be considered. This view provides an idea for the design of calculation conditions when performing finite element calculations; Xia Caichu et al.[13~14] optimized the design of the lining structure of Baimang Xueshan No. 1 Tunnel, reducing the laying length of the insulation layer by 3810 m, thereby effectively reducing the cost of laying the insulation layer and speeding up the construction. The analytical solution of the tunnel temperature field derived by Zhang Guozhu et al.[15] combined with the specific conditions of the Zhihaidai tunnel to calculate the temperature change in the Zhihaidai tunnel along the longitudinal tunnel, which provides method support for calculating the annual average temperature and the annual temperature vibration variation curve in the tunnel; Which can further determine the appropriate position of the end of the insulation layer, which provides method support for calculating the annual average temperature and the annual temperature vibration change curve in the tunnel. The research results can provide theoretical basis for thermal insulation and anti-freezing of tunnels in cold areas, and can also provide reference for similar projects.

2. THERMAL INSULATION ENGINEERING MEASURES

Heat preservation and heat insulation measures belong to passive heat preservation mode; Since the heat exchange coefficient between surrounding rock, lining and cold air is very large, the flow of cold air will take a lot of heat away after the tunnel is through. The heat insulation layer can effectively prevent the heat transfer between surrounding rock, lining and cold air. Heat preservation and heat insulation layer has the advantages of two aspects: one, in the permafrost region, in the summer heat preservation and heat insulation layer can prevent heat flow behind the tunnel lining, the permafrost surrounding the tunnel not melt, can reduce the influence of the freeze-thaw cycle, prevent freezing and thawing cycle prompted a hole behind the lining, to reduce the possibility of water frost heave; Ii. In the area with seasonal frozen soil, the thermal insulation layer can prevent the heat loss of tunnel lining and surrounding rock in cold winter, prevent the surrounding rock from freezing and reduce the impact of frost heave. The main methods of heat preservation and insulation are as follows

2.1. Laying thermal insulation materials

According to the principle of heat transfer, if the thermal conductivity between substances becomes infinitely small, there is no heat transfer between them. Thermal insulation measures are the application of this principle. The current conventional method is to use materials with very low thermal conductivity, such as: polyurethane foam, polyphenolic foam, polystyrene, dry-process aluminum silicate fiber, etc. These materials are characterized by low thermal conductivity, not easy to burn, low water absorption, easy processing, small processing thickness, etc., which are very suitable for use in tunnels.

2.2. Install cold-proof and heat-preserving doors

For tunnels in cold regions, the convection of cold air is the main way to cause heat loss in the tunnel. Install cold-proof and heat-preserving doors at the entrance and exit of the tunnel, which can prevent and
slow down the convection of cold air, prevent a considerable part of the cold air from intruding into the tunnel during the cold winter, increase the average temperature of the air in the tunnel in winter, and limit the freezing of the surrounding rock in the tunnel season. The depth of the circle prevents freezing of the tunnel ditch. However, the cold-proof insulation door needs to be opened repeatedly during operation, which is greatly affected by seasonal traffic. Generally, it is only suitable for remote areas where vehicles in winter are much smaller than in summer, and traffic control is required to enable vehicles to pass through in a certain period of time. Therefore, the usability of the method is greatly restricted.

2.3. **Adopt air curtain technology**

In order to achieve good thermal insulation effect, comprehensive thermal insulation measures should be taken for tunnels in cold areas. Air curtain technology is one of the auxiliary thermal insulation measures in tunnel, which is similar to the cold insulation door at tunnel entrance. Since the air is a poor conductor of heat, the use of the air curtain at the tunnel opening in cold season can also reduce the exchange of heat energy inside the tunnel and cold energy outside, so as to maintain a high temperature inside the tunnel. Keeping relatively high temperature in the tunnel in the permafrost area in winter is of great significance to relieve the frost heaving of the tunnel and ensure the smooth flow of the tunnel drainage system, and is also beneficial to the prevention and control of wind and snow blowing in the tunnel opening. Compared with the cold insulation door and air curtain, its biggest advantage is not to affect the driving, keep the traffic smooth, can reduce the possibility of traffic accidents, simple management, maintenance.

3. **LABORATORY TEST FOR INSULATION EFFECT OF THERMAL INSULATION LAYER**

3.1. **Indoor test plan for thermal insulation effect of thermal insulation layer**

3.1.1. **Test equipment and materials**

3.1.1.1. **High and low temperature test chamber**

This test uses the HLT system high and low temperature test box to simulate the operating environment of the tunnel. The system can be used to assess and determine the adaptability of electrical, electronics, automotive electrical appliances, materials and other products to storage and use under high and low temperature environmental conditions. Its main performance parameters are:

1. Temperature range: -40°C-130°C; Humidity range: 10%-98%RH
2. Temperature fluctuation: ±0.5°C (no load)
3. Temperature deviation: ≤±2°C
4. Average rate of temperature rise and fall: 0.7°C~1.0°C/min (no load)
5. Time setting range: 0~9999 hours.

![Figure 1 High and low temperature test chamber](image-url)
3.1.1.2. **Flick insulation board**
Flick thermal insulation material is a kind of polymer composite material which is made from Flick as the main raw material, mixed with a variety of inorganic fillers, and cured by foaming. It has the characteristics of non-combustibility, low thermal conductivity, good heat insulation effect, no Freon, wide temperature adaptation range, anti-aging, and convenient construction. It overcomes the flammability of traditional foam insulation materials (such as extruded polystyrene, polyurethane), The shortcomings of more smoke and deformation when exposed to heat, while retaining the characteristics of light weight and convenient construction of traditional foam insulation materials. Known as the "King of Insulation Materials". Flick exterior wall insulation materials have low thermal conductivity, generally not greater than 0.035 W/(m·K) at room temperature.

![Figure 2 Insulation material](image1)

3.1.1.3. **Moisture proof sticker**
In this experiment, self-adhesive aluminum foil moisture-proof stickers were used to change the moisture-proof performance of the insulation layer, and the influence of the moisture-proof layer of the insulation layer on the insulation performance was studied.

![Figure 3 Self-adhesive aluminum foil moisture-proof sticker](image2)

3.1.1.4. **Temperature Sensor**
In this experiment, a temperature sensor was embedded on the surface of the insulation layer and the simulated lining to collect the temperature on the back of the insulation layer in real time, and the temperature and humidity acquisition module Modbus RTU RS485 was used to realize automatic data collection.

![Figure 3 Self-adhesive aluminum foil moisture-proof sticker](image3)
3.1.2. Integrated design of test system
According to the environment of the tunnel, the test system mainly includes environmental simulation devices (simulating environmental temperature and humidity), cold-proof and thermal insulation material simulation, secondary lining material simulation, surrounding rock material simulation, stable heat source simulation device in the formation, temperature measuring element and data acquisition device composition.

3.1.3. Test condition setting

| Test conditions | Ambient temperature | Humidity environment |
|-----------------|---------------------|---------------------|
| 1               | -30°C               | 5%                  |
| 2               | -20°C               |                      |
| 3               | -10°C               | 5%                  |
| 4               | -5°C                |                      |

3.2. Analysis of test results
The law of temperature change with time behind the insulation layer under different working conditions is extracted, and the comparative analysis is as follows:
a. The temperature behind the insulation layer changes with time (-30°C)

b. The temperature behind the insulation layer changes with time (-20°C)

c. The temperature behind the insulation layer changes with time (-10°C)
d. The temperature behind the insulation layer changes with time (-5°C)

Figure 6 The test results

It can be seen from Figure 7 that the airtightness and moisture-proof performance of the tunnel cold-proof insulation layer have a greater impact on the cold-proof and heat-preservation effect. Its insulation performance is in the order of seamless insulation layer > slit insulation layer > water purification insulation layer, and sealant is passed after slitting. After sealing, the thermal insulation effect of the thermal insulation layer can basically restore its original thermal insulation performance. It can be known from the experiment that when the tunnel insulation layer is well sealed, it can basically ensure that the temperature behind the tunnel insulation layer is positive to achieve the effect of cold protection and insulation. Therefore, during the construction of the insulation layer, sealant should be used for the joint position of the insulation layer To process. At the same time, it can be seen from the test results that when the thermal insulation layer is immersed in water, its thermal insulation performance decreases rapidly, and the temperature behind the thermal insulation layer decreases rapidly with time, and the temperature drops rapidly to below zero. There is no trend of convergence, and the cold resistance and thermal insulation performance is lost. The cold-proof and thermal insulation layer of the tunnel in the district shall adopt certain measures of moisture-proof and anti-soaking performance.

4. NUMERICAL SIMULATION

4.1. Model establishment

The temperature of surrounding rock at the entrance of the tunnel is greatly affected by environmental temperature. The surrounding rock at the entrance of the cave is now analyzed. The ZK20+480 section 100m away from the entrance of the tunnel is selected, and the buried depth of the tunnel is 35m. The size of the established model is shown in Figure 7. The material parameters of C30 concrete are used for the initial support and secondary lining of the entrance section. The surrounding rock adopts the thermodynamic parameters of granite. The tunnel entrance is located in a seasonally frozen soil area. From the upper and lower limits of the frozen soil and the geothermal gradient, it can be roughly assumed that the temperature load at the upper boundary is 9°C and the lower boundary is 12°C. The same temperature load is applied in the tunnel-5°C (the average monthly temperature is lower than the average temperature of the month at 0°C). The thermal conductivity of polyurethane used in the numerical simulation is 0.027W/(m·°C), and other material properties refer to Table 2. In order to ensure that the thickness of the insulation layer remains unchanged, when the insulation layer is a single layer, 0.05m is used. The layer is 0.025m. The model size and grid are shown in Figure 7. The laying methods mainly include four types: no insulation layer, insulation layer between the second lining and the primary branch.
(referred to as the intermediate method), and insulation layer on the surface of the second lining (referred to as the surface method), simultaneously set an insulation layer on the surface of the second lining and between the second lining and the primary support (referred to as the double layer method).

![Figure 7 Finite element meshing diagram](image)

**TABLE 2** THERMAL PARAMETERS OF SURROUNDING ROCK

| Material                      | Frost heave rate | Thermal conductivity $\lambda$ (W·m⁻¹·K⁻¹) | Specific heat capacity $C$ (J·kg⁻¹·K⁻¹) |
|-------------------------------|------------------|---------------------------------------------|----------------------------------------|
| C30 concrete                  | —                | 1.510                                       | 840                                    |
| Frozen surrounding rock (IV)  | —                | 1.901                                       | 970                                    |
| Unfrozen surrounding rock (IV)| Max:5%           | 1.124                                       | 1164                                   |
| Polyurethane foam             | —                | 0.027                                       | —                                      |

4.2. Analysis of calculation results

![Image](image)

a. Temperature cloud map of surrounding rock without thermal insulation layer
b. Temperature cloud map of surrounding rock during intermediate method

c. Temperature cloud map of surrounding rock in surface method

d. Temperature cloud map of surrounding rock in double-layer method

Figure 8 Temperature cloud
Figure 9 Radial temperature change curve of surrounding rock with different insulation layer laying methods

The cloud diagram of the surrounding rock temperature field under various insulation layer laying methods is plotted in Figure 8. Ten nodes are selected along the radial direction at the tunnel vault. The distances from the nodes to the outer surface of the tunnel lining are: 0m, 0.5m, 1.0m, 1.5m, 2.0m, 2.5m, 3.0m, 4.0m, 5.0m and 6.0m. The curves of surrounding rock temperature with radial distance under various insulation layer laying methods are plotted in Figure 9.

Analyzing the temperature change curve of surrounding rock under different insulation layer laying methods can get the following laws:

- Comparing the temperature change curves of surrounding rock with and without insulation layer, it can be seen that at the same depth of surrounding rock, the temperature of surrounding rock with insulation layer is significantly higher than that without insulation layer. It shows that the insulation layer can prevent the surrounding rock from dissipating heat and maintain the temperature of the surrounding rock.

- Comparing the temperature change curves of surrounding rock with and without insulation layer, it can be seen that at the depth of 5m and 6m of surrounding rock, the temperature of surrounding rock is -1.05°C and -1.57°C without insulation layer, and the temperature of surrounding rock with insulation layer (outer layer method) is 0.241°C and 0.745°C. It shows that the insulation layer can reduce the negative temperature range of the surrounding rock.
Figure 10 Radial temperature increase curve of surrounding rock with different insulation layer laying methods

The curves of the increase of surrounding rock temperature (and the temperature of surrounding rock without insulation layer) with radial distance under various insulation layer laying methods are plotted in Figure 10.

Analyzing the temperature increase curve of surrounding rock under different insulation layer laying methods, the following laws can be obtained:

- From the three temperature increase change curves in Figure 10, it can be seen that as the depth of the surrounding rock increases, the temperature increase becomes smaller and smaller. It shows that as the depth of the surrounding rock increases, the influence of the insulation layer on the temperature of the surrounding rock becomes less and less.

- Comparing the three temperature increase curves, it can be seen that at the same surrounding rock depth, the surface method has the largest temperature increase (1.71℃ at 0m, 1.64℃ at 0.5m, 1.60℃ at 1.0m, 1.54℃ at 1.5m, and 1.51 at 2.0m, 1.47℃ at 3.0m, 1.41℃ at 4m, 1.36℃ at 5.0m, 1.29℃ at 6.0m), the double-layer method has the largest increase in surrounding rock temperature (1.63℃ at 0m, 1.56℃ at 0.5m, 1.53℃ at 1.0m, 1.47℃ at 1.5m, 1.44℃ at 2.0m, 1.40℃ at 2.5m, 1.35℃ at 3.0m, 1.29℃ at 4m, 1.23℃ at 5.0m and 1.16℃ at 6.0m), The surrounding rock temperature increase of the intermediate method is second (1.55℃ at 0m, 1.48℃ at 0.5m, 1.45℃ at 1.0m, 1.39℃ at 1.5m, 1.36℃ at 2.0m, 1.32℃ at 2.5m, 1.27℃ at 3.0m, 1.22℃ at 4m, 1.16℃ at 5.0m and 1.1℃ at 6.0m). It shows that under the same insulation layer thickness, the surface method has the best insulation effect; the closer the insulation layer is to the interface between the surrounding rock and the ambient air, the better the insulation effect.

5. CONCLUSION

- Through laboratory tests, the insulation performance, effect and influencing factors of the insulation layer are analyzed. In order to ensure the insulation effect of the tunnel in the cold region, it is suggested to adopt certain measures or materials to improve the sealing and dryness of the insulation layer.

- Through numerical simulation, the insulation effect of different insulation layer laying methods (intermediate method, double layer method and surface method) is compared and analyzed, and the better insulation layer laying method is surface method under the same thickness of insulation layer. It also shows that the closer the insulation layer is to the interface between surrounding rock and ambient air, the better the insulation effect will be. The surface method is used to lay the insulation layer in Wu nv Peak tunnel, which shows the rationality of setting the insulation layer in this tunnel.
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