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Analysis on Thermal Insulation Measures of Highway Tunnel in Seasonal Frozen Soil Region

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Abstract: The highway tunnel in seasonal frozen soil area is experiencing continuous freezing and thawing due to the change of temperature. The phenomenon of frost heave and thaw settlement is frequent, and there are huge potential safety hazards. The prevention and control of frost damage in seasonal frozen tunnel is an important topic in highway engineering research. Thermal insulation method is one of the most widely used frost prevention methods in tunnel construction in cold regions. For highway tunnels in seasonal frozen area, the insulation layer is mainly laid at the tunnel entrance to achieve the effect of repairing frost damage. Taking Zhamutai high-speed tunnel project as an example, combined with field monitoring data, the rationality of thickness and length of insulation layer and its insulation effect are evaluated. The results show that: compared with the initial surrounding rock temperature field without insulation layer, after the insulation layer is laid, the tunnel temperature is generally maintained at about-5 ℃, and the tunnel basically eliminates the risk of frost damage; comparing the insulation layers of three different insulation materials, the overall temperature field trend of tunnel surrounding rock is consistent, and the anti-freezing insulation effect is ideal.

1. Introduction

With the continuous development of China's transportation industry, infrastructure such as railways, highways and tunnels is extending to cold regions. However, the phenomenon of frost damage caused by low temperature conditions in cold regions is very common, causing serious damage to tunnel structures and major hidden dangers to traffic operations. A systematic study on the prevention and control of freezing damage in tunnels in cold regions has been carried out at home and abroad. The former Soviet Union adopted comprehensive waterproof and drainage measures (waterproof layer, drainage pipe in lining, drainage ditch) to prevent freezing and prevent frost damage [1] ; norway adopted the measures of adding waterproof and antifreeze shed to prevent freezing damage [2] ; the United States uses thermal insulation drainage system to prevent frost damage [3] ; in Japan, heat insulation method and heating method are used to solve the problem of tunnel freezing damage [4] ; in the early days of China, waterproof and drainage structures were used to prevent frost damage. In recent years, the technology of adding tunnel insulation layer has been actively explored [5]. A large number of engineering practice shows that the frost damage of tunnel is mainly drainage and antifreeze problems. For example, cold-proof drainage tunnel, central deep buried ditch, thermal insulation ditch, antifreeze insulation layer and other measures are adopted[6-11].However, for highway tunnels in seasonally frozen areas, the lining structure of the tunnel will undergo large deformation cracking or even damage under the action of groundwater frost heave, which has become the most serious problem affecting the safety of tunnel construction and operation. Once the frost damage occurs in the tunnel, it is not only difficult to repair, but also the cost is very huge. Some tunnels are even completely scrapped. For example, the lining of Tianshan No.2 Tunnel in China is almost scrapped due to cracking, seepage and hanging ice. At present, for the highway tunnel in the seasonal frozen area, the tunnel insulation is mainly carried out by laying the insulation layer at the entrance of the tunnel. By laying the insulation material, the tunnel lining and the surrounding rock are treated with anti-freezing and heat preservation to avoid the freezing of groundwater in the surrounding rock, so as to achieve the effect of regulating freezing damage. However, due to the complexity of soil surrounding rock and the diversity of influencing factors, theoretical calculation and experience often cannot accurately evaluate the temperature change of soil, and the thermal insulation measures taken may not be reasonable. At this time, it is necessary to further evaluate whether the anti-freezing measures taken by the tunnel are effective and reasonable.

2. Analysis on Antifreezing Insulation Measures of Highway Tunnel

2.1. Overview of Tunnel Anti-Freezing Insulation Measures

The source of tunnel freezing damage mainly comes from the repeated freezing and thawing of water in the lining structure and rock strata. Temperature, water and surrounding rock conditions are the three basic factors of freezing damage in tunnel in cold region, and the comprehensive anti-freezing measures mainly control these three basic factors. The comprehensive anti-freezing measures of tunnel in cold region mainly include heat preservation technology and drainage technology, which complement each other and are indispensable. Therefore, the prevention and control of freezing damage in tunnel are mainly two problems: drainage prevention and freezing prevention. Engineering practice and theoretical analysis show that if the underground water in the surrounding rock of the back of the lining can be removed, the frost damage of the tunnel will be greatly reduced or even eliminated. In the process of groundwater discharge in the tunnel, the heat of groundwater will gradually lose. If the temperature is too low, there will be freezing phenomenon, resulting in poor drainage system, resulting in increased water pressure on the back of the tunnel lining, resulting in lining leakage and frost heave damage. Therefore, in the process of tunnel frost prevention and control, ' waterproof is the foundation, drainage is the core, and heat preservation is the key ', the three must be organically combined.

About thermal insulation technology, the current domestic tunnel antifreeze insulation technology principle can be divided into two categories, namely thermal insulation technology and heating antifreeze technology. Comprehensive anti-freezing effect and cost, the current domestic use is more common thermal insulation fortification technology. Heating anti-freezing technology is feasible to prevent freezing damage in local severe freezing sites and short tunnels with short freezing time, but it may not achieve the expected results for long tunnels or tunnels with long freezing time. Most of the technical measures have the disadvantages of large energy consumption, high operating costs, and difficult maintenance of equipment and facilities, which limit and restrict the application of this technology.

From the study of the temperature field distribution law of the tunnel in the cold region, it can be seen that the temperature difference between the tunnel entrance section and the tunnel is large. Due to the dual influence of the temperature in the tunnel and the surface temperature of the mountain at the top of the tunnel, the tunnel entrance section will accelerate the melting and freezing, and the freezing damage is more serious. Therefore, the frost protection of the tunnel portal section needs special treatment.

2.2. Construction Method of Tunnel Insulation Layer

Thermal insulation refers to the lining surface or between the primary support and the secondary lining insulation material, using thermal insulation materials to minimize the heat released in the surrounding rock or the invasion of external heat, in order to maintain the surrounding rock behind the tunnel lining to maintain the original frozen or melted state, no freeze-thaw cycle. The insulation layer of some tunnels in China is set on the inner side of the secondary lining, and fiberboard and foam board are used as insulation materials. In order to ensure the appearance, fire prevention and moisture resistance of the tunnel lining, fiber reinforced board and fiber reinforced silicate cover board are laid on the surface of the insulation material.

The insulation layer has good thermal insulation effect, convenient construction and good economy. It is the most commonly used thermal insulation measure in China. There are three main laying methods of insulation layer: surface spraying method, surface laying method and intermediate laying method. The function and purpose of setting insulation layer in different permafrost strata are different:

(1) For tunnels in permafrost regions, it is required to prevent the frozen soil in the surrounding rock from melting in the warm season, maintain the original frozen state of the surrounding rock, and avoid thermal collapse of the surrounding rock. In this case, the insulation layer can reduce the heat exchange between the hot air in the tunnel and the permafrost in the surrounding rock, which is commonly known as ' cold insulation '.

(2) For tunnels in seasonal frozen soil areas, it is required that in the cold season, the insulation layer can hinder the exchange of cold air in the tunnel and the air in the surrounding rock, maintain the original wood frozen state of the surrounding rock, prevent the water behind the tunnel or in the surrounding rock from generating freeze-thaw cycles, and avoid the lining structure from being subjected to additional load of frost heaving pressure. This situation is set insulation layer, which is set up for the purpose of commonly known as ' warm '.

2.3. Selection of Construction Methods

In the actual project, the construction method should be selected according to the actual situation of the tunnel from the aspects of thermal insulation effect, project cost, fire prevention, waterproof, maintenance and durability. From the effect of a large number of engineering practice, the effect of the intermediate laying method is the best, and the required thickness of the antifreeze insulation layer is also thinner under the same conditions. The surface spraying method is second, and the surface laying method is poor. Because the surface laying method is fixed by keel, the steel keel has the problem of cold bridge heat transfer, which affects the heat preservation effect. From the engineering cost, the surface spraying method is the highest, the surface laying method is the second, and the middle laying method is the lowest. However, the construction process of the intermediate laying method is cumbersome, the operation is difficult and the efficiency is low.

From the perspective of fire prevention, the surface spraying method and the surface laying method need to spray the tunnel fire prevention materials. There are fire hazards during operation, but there is no fire hazard during construction. However, after the intermediate laying method is completed, the subsequent construction work is easy to ignite the insulation material, and the fire hazard is greater. From the perspective of waterproof, the surface spraying method and the surface laying method are constructed after the tunnel lining is completed. As long as the tunnel waterproof quality is good, there is no waterproof problem. The intermediate laying method has two waterproof boards to ensure waterproof safety, and there is no waterproof problem.

From the durability of tunnel structure, because the durability of the antifreeze insulation layer material is generally good, we only consider the durability of the tunnel structure. The secondary lining of the intermediate laying method is directly exposed to the low temperature environment. Under the repeated drastic changes of temperature, it will inevitably damage the structure and affect the durability of the overall structure. The surface spraying method and the surface laying method avoid the direct exposure of the tunnel secondary lining to the environment, which is beneficial to the service life of the tunnel structure.

Combined with the above analysis, we compare the advantages and disadvantages of middle laying method, surface laying method and surface spraying method, summarized in Table 1.

Table 1: Comparison of construction methods of antifreeze insulation layer

Construction technology	Performances contrast						
	Insulation effect	Engineering cost	Fire resistance construction	Fire resistance operation	waterproof	maintenance	durability
Surface spraying method	Better	High	Worse	Good	Good	Easy	Good
Surface laying method	Worse	Higher	Good	Better	Good	Hard	Better
Intermediate laying method	good	Low	Good	Better	Good	Hard	Worse

3. Thermal Insulation Materials

3.1. Classification of Thermal Insulation Materials

Thermal insulation materials are generally materials or material composites that guide the thermal coefficient to be less than or equal to 0.2 and have significant resistance to heat exchange. The usual insulation material is a light, loose, porous, low thermal conductivity material. Thermal insulation materials have been widely used in industrial and civil buildings, industrial equipment and pipeline engineering. In addition to the thermal conductivity of the material, the water absorption, combustion performance, strength and other indicators of the material should also be considered when choosing the tunnel insulation layer and drainage pipe. The most commonly used thermal insulation materials for tunnel insulation layer are phenolic foam and rigid polyurethane foam.

3.2. Calculation of Insulation Thickness

The calculation methods of tunnel insulation layer thickness mainly include equivalent thickness method, meteorological analysis method and finite element calculation method. The equivalent thickness method is the most widely used, the calculation method is as follows.

Firstly, the maximum freezing depth of surrounding rock is calculated according to Formula (1).

$$\frac{\delta_0}{\lambda_0} = \frac{d}{\lambda_2} \tag{1}$$

Where: δ_0- Maximum freezing depth in meteorological data , m;

λ_0- Thermal conductivity of loose rock (soil) covering the surface, W/(m·degree);

d- Maximum frozen depth of surrounding rock after conversion, m;

λ_2- Thermal conductivity of tunnel surrounding rock, W/(m degree).

The thickness of the surface insulation layer is calculated according to Formula (2) :

$$\frac{1}{2\pi\lambda_2}\ln\frac{r+d}{r}=\frac{1}{2\pi\lambda_1}\ln\frac{r+\delta}{r} \tag{2}$$

where : λ_1:Thermal conductivity of insulation layer, W/(m degree);

r:Tunnel equivalent radius, m;

δ:Calculation thickness of insulation layer, m.

The above parameters are given directly by the tunnel design data. And by consulting the relevant norms and related literature, combined with the previous research data. In the calculation, the thermal insulation layers of polyurethane and phenolic resin are considered respectively, and the thermal conductivity is the maximum value required by the relevant material specifications. The thermal conductivity of polyurethane is 0.024 W / (m K), and the thermal conductivity of phenolic resin is 0.032 W / (m K).

3.3. Length Calculation of Insulation Layer

Usually, the Heichuan Xifan formula method is used to calculate the length of the antifreeze insulation layer, as shown in Formula (3).

$$L=154.7(-t)^{0.604} \tag{3}$$

Where:*t*:Monthly mean temperature of coldest month at hole,degree;

L:Distance from possible freezing damage location in tunnel to tunnel entrance,m.

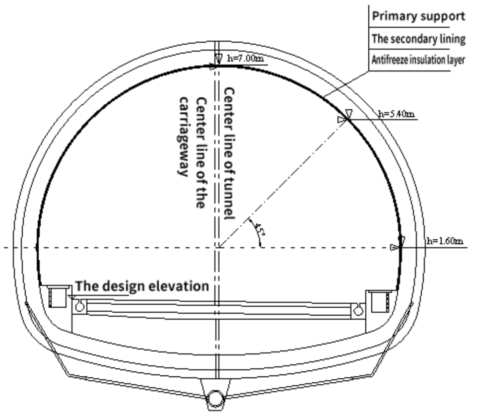
4. Comparative Analysis of Tunnel Insulation Effect

4.1. On-Site Monitoring of Insulation Effect

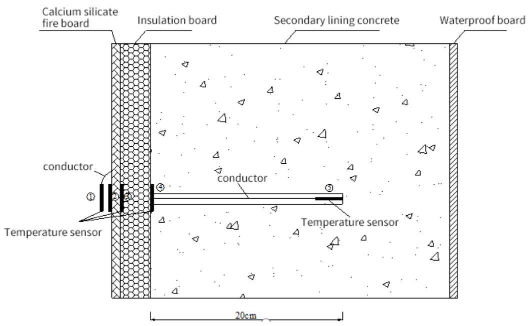
Taking a tunnel of Heda Expressway as an example, the left line of the tunnel is 2970 m long and the right line is 2510 m long. Insulation layer length is set to : import end length 450m, export end length 830m, insulation layer thickness is set to : polyurethane foam 7cm, phenolic foam 9cm, laying as shown in Figure 1. In view of the rationality of the thickness and length of the insulation layer of the Zhamutai high-speed tunnel and its thermal insulation effect, the project team set up temperature sensors at various positions of the tunnel for real-time data collection and subsequent analysis.

Figure 1: Insulation board laying

The temperature of the tunnel is measured, and 16 monitoring sections are set along the longitudinal length of the tunnel. A total of 3 monitoring points are set in the section, as shown in Figure 2 (a), which are the side walls, 1.60 m away from the road surface ; 45 hance, 5.40 m from road surface ; tunnel vault. In the section where the anti-freezing insulation layer is laid, five temperature sensors are arranged at each measuring point, and the specific position is shown in Figure 2 (b).



(a) Hole position map



(b) Component specific layout diagram

Figure 2: Layout of temperature sensor inside tunnel structure

4.2. Tunnel Monitoring Data

The daily temperature data of each position of the tunnel from January 2017 to September 2018 were continuously collected by the equipment, and the insulation effect was analyzed according to the average value of the monitoring data of each position of the tunnel in the coldest month. 1,2,3,4,5represent air, fire board surface, insulation board surface, lining surface and 20cm away from the lining surface respectively. Due to the large amount of measured data, the temperature is taken as the average temperature of the month. The average temperature field data of the coldest month at each monitoring position are shown in Table 2. The arrangement of measuring points is shown in Figure 3.

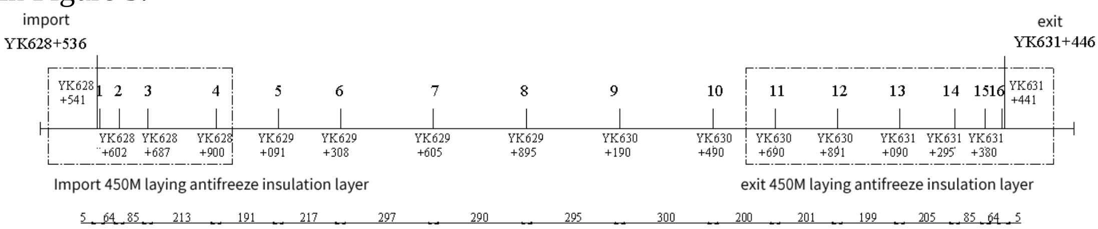


Figure 3: Layout of longitudinal monitoring section of tunnel

Table 2: The average temperature field data of the coldest month in each section of Zhamutai tunnel

	K630+190	K630+490	K630+690	K630+891	K631+090	K631+295	K631+380	K631+441
Sidewall 1	-4.786	-7.710	-8.760	-8.987	-9.299	-9.927	-8.462	-8.059
Sidewall 2	-	-	-8.642	-7.883	-8.487	-9.496	-9.016	-5.594
Sidewall 3	-	-	-8.054	-7.575	-7.359	-8.983	-8.739	-5.406
Sidewall 4	-5.247	-7.244	-0.341	-0.714	-1.137	-3.282	-2.617	-2.647
Sidewall 5	-4.604	-5.805	0.176	0.098	.077	-2.205	-1.697	-1.932
Hance 1	-5.083	-7.564	-8.801	-8.301	-9.060	-9.402	-8.270	-10.595
Hance 2	-	-	-8.715	-7.311	-8.411	-9.350	-8.919	-6.703
Hance 3	-	-	-5.859	-7.524	-7.359	-8.726	-8.718	-6.791
Hance 4	-7.146	-7.486	0.725	0.043	-0.504	-2.838	-2.154	-2.256
Hance 5	-4.587	-6.311	1.414	0.859	-0.786	-2.334	-1.701	-1.829
arch roof 1	-4.794	-7.277	-8.205	-7.802	-8.487	-8.410	-8.543	-9.237
arch roof 2	-	-	-7.888	-7.791	-7.598	-8.239	-8.915	-6.809
arch roof 3	-	-	-7.769	-7.147	-6.718	-7.351	-8.304	-6634
arch roof 4	-3.277	-7.080	0.446	0.633	0.709	-1.180	-1.492	-5.474
arch roof 5	-3.863	-6.177	0.454	1.496	1.769	-0.445	0.085	-4.748

From the above temperature field data, it can be seen that the temperature of the tunnel section without insulation layer does not change much, and is lower than 0 degree.From the K630 + 891 observation point, the temperature of the tunnel section with insulation layer is obviously improved on the lining surface and 20 cm away from the lining surface, basically maintained at about 0 degree.In theory, it can effectively alleviate the freezing damage of the tunnel entrance and exit and ensure the safety of driving.

4.3. Variation Rule of Monitoring Data of Each Section

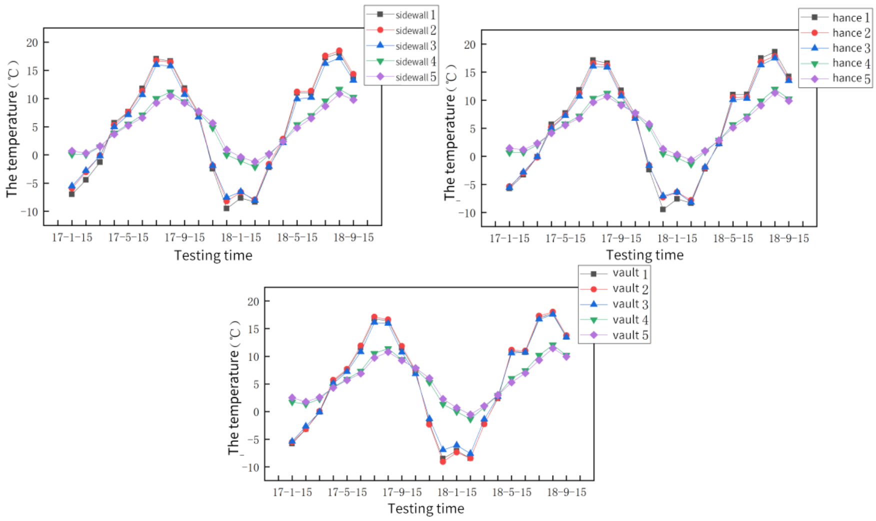


Figure 4: Temperature monitoring data of side wall, arch waist and vault of K628 + 900 section

Due to the large number of monitoring points and data, in order to clearly show the change of tunnel temperature monitoring data and analyze the change law of temperature field, this section selects two monitoring points of the insulation layer at the inlet and outlet, and one monitoring point in the middle without insulation layer for data analysis. Each monitoring point temperature data selection time is 14 : 00, the measured part of the tunnel is divided into the above side wall, 45 °arch waist and tunnel vault three positions, 1, 2, 3, 4, 5 respectively, said the air, fire board surface, insulation board surface, lining surface and from the lining surface 20cm and so on five have strong reference temperature.

(1)Laying insulation layer section entrance end

The annual temperature monitoring data of each part of K628 + 900 section are shown in Figure 4:

Based on the data of the entrance end of the tunnel, the following conclusions can be drawn by analyzing the temperature monitoring data of the coldest month :

1) When the tunnel entrance end is in the coldest month, the lowest temperature of the air, the surface of the fire board and the surface of the insulation board represented by 1,2 and 3 respectively is below-10 degree. With the deepening of the tunnel, the temperature gradually rises, but it is always lower than-5 °;

2) Under the action of insulation layer, the temperature of the lining surface and 20 cm away from the lining surface represented by 4 and 5 respectively is greatly higher than that in the tunnel, and the monitoring temperature is slightly lower than 0 °. With the deepening of the tunnel, the temperature rises to above 0 degree, and the frost heave risk basically disappears.

3) According to the measured temperature, the coldest month at the entrance of the tunnel temperature is low, the need to lay the insulation layer, and the insulation effect is expected after laying.

(2) The middle section without insulation layer

The K629 + 605 section is the middle section of the tunnel, which is to lay the insulation layer. Therefore, only the annual temperature monitoring data of air, lining surface and 20 cm away from the lining surface represented by 1,4 and 5 respectively, as shown in Figure 5:

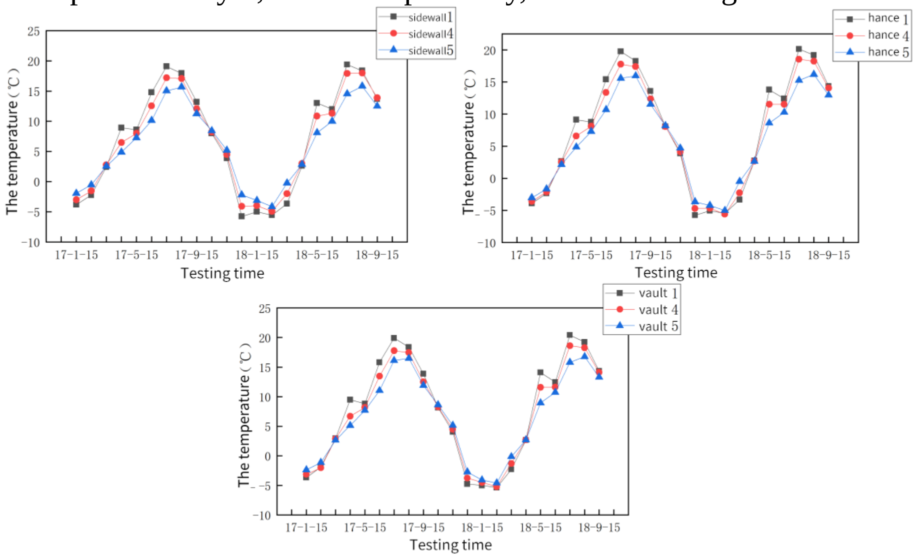


Figure 5: Temperature monitoring data of side wall, arch waist and vault of K629 + 605 section

From the above monitoring data changes can be seen :

1) With the deepening of the tunnel, the temperature in the tunnel gradually increased, due to the thermal insulation effect provided by the thermal insulation layer at the entrance, the temperature of the middle section of the tunnel was significantly higher than the initial surrounding rock temperature field simulated above.

2) The average temperature of each part of the middle section of the tunnel is basically above -5 degree in the coldest month, which proves that the thermal insulation measures are effective, and the risk of frost heave is basically eliminated throughout the tunnel.

3) Laying insulation layer outlet end

The temperature monitoring data of the coldest month at the exit end of the tunnel are analyzed. The temperature field distribution is similar to the temperature field distribution at the entrance end. Due to the influence of air flow and external temperature, the average minimum temperature of the air at the exit end of the tunnel is below-10 degree in the coldest month, which proves that it is necessary to take thermal insulation measures. Under the action of thermal insulation layer, the temperature of lining surface and 20cm away from the lining surface is much higher than that in the tunnel, the temperature basically meets the requirements of the specification, and the frost heave risk basically disappears, indicating that the anti-freezing effect of thermal insulation layer is expected.

The annual temperature monitoring data of K631 + 380 sections at the exit of the tunnel are shown in Figure 6 respectively:

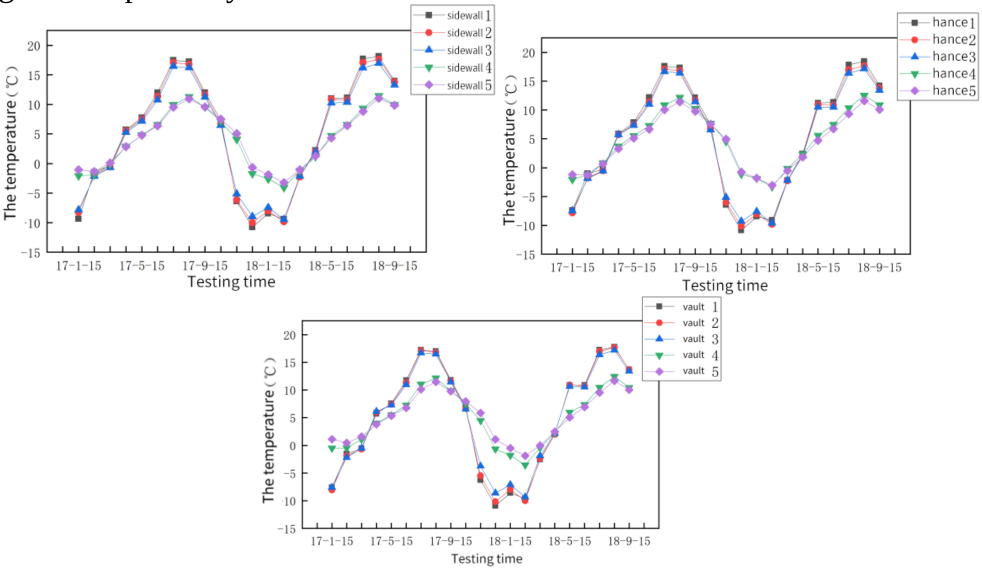


Figure 6: Temperature monitoring data of side wall, arch waist and vault of K631 + 380 section

4.4. Monitoring Data after Insulation at Each Ambient Temperature

In order to analyze the thermal insulation effect more specifically, the temperature changes at 20 cm after the tunnel lining at -5 degree, -10 degree, -15 degree and -20 degree are compared, as shown in Figure 7.

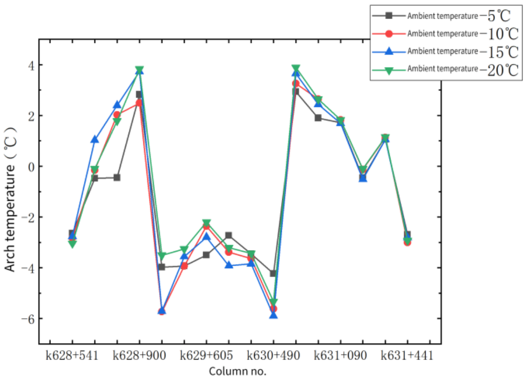


Figure 7: Changes of temperature field at 20 cm behind tunnel lining under different ambient temperatures

According to the analysis of the temperature field of the initial tunnel surrounding rock, the temperature of the entrance and exit sections at both ends of the tunnel is easy to fluctuate with the external environment, which is not conducive to the stable operation of the tunnel. It can be seen from the above data that the temperature at 20 cm after the lining of the tunnel entrance and exit section with insulation layer is obviously improved, and the minimum temperature is about-3 ℃, which meets the anti-freezing requirements. The temperature of the middle section without insulation layer is slightly lower, and the minimum temperature is about-5 ℃, which basically meets the anti-freezing requirements, indicating that the length of insulation layer is reasonable. With the change of ambient temperature, the change trend of temperature field at 20cm behind the lining of each section is basically the same, and there is no significant difference in temperature, which shows that the effect of insulation layer is obvious. After laying the insulation layer, the temperature conduction change process after the tunnel lining is slower, and it is less affected by the temperature fluctuation of the external environment, which is more conducive to the stable operation of the tunnel.

5. Conclusion

(1) Compared with the initial temperature field of surrounding rock without insulation layer, after the insulation layer is laid, the minimum temperature of surrounding rock in the tunnel entrance section where frost heave is most likely to occur is about -5 degree, which is increased by about 10 degree, indicating that the insulation layer plays a role in anti-freezing and heat preservation. Due to the increase of the minimum temperature at the entrance of the tunnel, the temperature of the middle section of the tunnel without insulation layer also increases, which is generally maintained at about -5 degree. The tunnel basically eliminates the risk of freezing damage, indicating that the length of the insulation layer is reasonable.

(2) Compared with the insulation layer using different insulation materials, the temperature field data at the vault of the tunnel section that is most prone to freezing damage is mainly analyzed. The overall temperature field trend of the tunnel surrounding rock of the three heat preservation schemes is consistent, indicating that the heat preservation schemes using three materials have ideal anti-freezing and heat preservation effects.

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