Engineering Test Research of XPS Insulation Structure Applied in High Speed Railway of Seasonal Frozen Soil Roadbed

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Abstract
Dynamic performance and thermal properties of insulation materials are the key parameters during the insulation application for high-speed railway subgrade. This paper conducted field tests and field monitoring for the materials, especially for thermal performance, elastic deformation, and accumulated deformation of insulation materials. Experiment results show that mechanical properties of full section insulation layer structure is stable, which satisfies the requirements of the high speed railway.

Keywords: High-speed railway, Insulation materials, Dynamic test, Field monitoring

1 Introduction

A reasonable anti-frost structure is the key to prevent frost heave in the high-speed railway subgrade. At present, the anti-frost structure in the severe cold region of China is designed based on frost resistant filler combined with waterproof and drainage principles (Ye et al., 2007). The anti-frost filler will be used to fill the subgrade in the range of frozen depth, and waterproof sealing measures will be used in the subgrade surface. Qi et al. (2013) verified the rationality of the anti-frost structure design. Zhao et al. (2011) explained
the anti-frost treatment measures of the Passenger Dedicated Line subgrade in a seasonal frozen soil region. Wang et al. (2014) integrated and analyzed the monitoring results of high-speed railway subgrade frost heave; then summarized the reasons causing the frost heave. Yan et al. (2015) proposed the required thermal insulation material and its thickness to eliminate frost injury, and then formed the construction technology process of the thermal insulation board. Moreover, Sheng et al. (2003), Su and Gao (2003), Wen et al. (2005, 2006), Lv et al. (2007), Su et al. (2007), Liu (2010), Xin (2012), Wang and Liu (2014) have also researched the insulation layer material. From the current situation of frost heave research, some positive effects have been obtained. However, due to the unknown frost heave mechanism of weak frost heave filler and lack of construction quality control, the surface sealing measures became ineffective in some sections. Therefore, limited frost heave has occurred in these sections, which affects track irregularity.

Installing insulation material under the high-speed railway subgrade to prevent frost heave is an effective and economic technical measure; this method has been successfully applied in some existing ballasted railways. The thermal insulation performance of this approach has been verified, but at present has not been introduced into the design of anti-frost structures for high-speed railway subgrades with ballast-less track. This paper systemically describes the elastic and accumulated deformation behavior of insulation material under different train loads by using in-situ structure dynamic load testing, also monitor the temperature field and displacement field. This information could provide a test reference for the design of anti-frost structure using insulation material for high-speed railway subgrades in severely cold regions.

2 Performance of the Insulation

Common XPS thermal insulation board was used as test material in the thermal performance test. Table 1 shows test results. As presented in Table 1, heat resistance was greater than 0.89 (m².K)/W and thermal conductivity coefficient was less than 0.028W/(m.K) when the temperature was between 10°C and 25°C. This indicates that the XPS is an excellent heat insulating material; the compressive strength could achieve 150 kPa, satisfying the control requirements of high-speed railway subgrade.

<table>
<thead>
<tr>
<th>No.</th>
<th>Test item</th>
<th>Standard requirement</th>
<th>Test result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compressive strength</td>
<td>≥150 kPa</td>
<td>304 kPa</td>
</tr>
<tr>
<td>2</td>
<td>Moisture absorption. soak 96 h (volume fraction)</td>
<td>≤1.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>3</td>
<td>Moisture permeability factor (23°C±1°C, RH50%±5%)</td>
<td>≤3.5 ng/(m.s.Pa)</td>
<td>1.9 ng/(m.s.Pa)</td>
</tr>
<tr>
<td></td>
<td>Thermal resistance (thickness 25 mm. average temperature 10°C)</td>
<td>≥0.89 (m².K)/W</td>
<td>0.896 (m².K)/W</td>
</tr>
<tr>
<td>4</td>
<td>Thermal resistance (thickness 25 mm. average temperature 25°C)</td>
<td>≥0.83 (m².K)/W</td>
<td>0.890 (m².K)/W</td>
</tr>
<tr>
<td>5</td>
<td>Thermal conductivity coefficient (average temperature 10°C)</td>
<td>≤0.028 W/(m.K)</td>
<td>0.0269 W/(m.K)</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity coefficient (average temperature 25°C)</td>
<td>≤0.030 W/(m.K)</td>
<td>0.0290 W/(m.K)</td>
</tr>
<tr>
<td>7</td>
<td>Density</td>
<td>--</td>
<td>36.71 kg/m³</td>
</tr>
</tbody>
</table>

Table 1 Thermal performance test results of XPS thermal insulation board
3 The In-situ Insulation Effect

Proving Ground located in K139 + 680 of Harbin-Dalian high-speed rail where monthly average minimum temperature is about \(-10^\circ C\) around and ground frost depth is about 1.2~1.5m. 0.55m Graded gravel was used in subgrade surface, 1.4m AB Group soil was used in lower, and they composed the surface layer. Particle size distribution can be seen in fig.1.

![Figure 1: Filler grading curve](image)

Both tests of partial thermal insulation method and whole section thermal insulation method have been made and studied respectively. This aims to compare the maximum frozen depth and the influences to each subgrade cross-section of these two insulation methods under the same condition. The characteristics of temperature field using two different insulation methods can be obtained, by monitoring the temperature of these two subgrade cross-sections. Finally the thermal insulation effect of these two methods can be evaluated.

A 15m long subgrade has been selected using partial thermal insulation method. Figure 2 shows the installation methods of both insulation board and components, and a 15m long subgrade has been selected using whole section thermal insulation method. Figure 3 shows the installation methods of both insulation board and components.

![Figure 2: The test scheme of partial thermal insulation of off-line test section](image)
Figure 3: The test scheme of whole section thermal insulation of off-line test section

Figure 4, figure 5, figure 6 and figure 7 show the monitoring data of frost heave after two frost heave periods (2013-2014 and 2014-2015).

Figure 4: The time travel curve of frost heave of partial thermal insulation test section

Figure 5: The time travel curve of frost heave of whole section thermal insulation test section
Figure 6: The isothermal diagram of subgrade temperature field of partial thermal insulation (2015.02.10)

Figure 7: The isothermal diagram of subgrade temperature field of whole section thermal insulation (2015.02.10)

Figure 4, figure 5, figure 6 and figure 7 show that, in the two frost heave periods, the maximum frost heave (10mm) occurred at the center of both left and right track plate in partial section situation. But in whole section situation, the displacement of each monitoring point was less than 2mm. The isotherm maps in figure 6 shows that, the maximum frozen depth located under the base plate, the partial thermal insulation method cannot eliminate the frost heave effectively. Figure 7 shows that, the insulation board can effectively isolate the heat exchange between subgrade and atmosphere. This is mainly due to the base plate can only suspend the effect of heat exchange, but cannot isolate the heat exchange process. As temperatures continue to reduce, the cold air can infiltrate into the place under base plate (subgrade without insulation board installation) and cause frost heave. But installation the insulation board using whole section thermal insulation method can effectively prevent the infiltration of cold air, only small part of cold air can infiltrate into the subgrade from both sides due to the heat transmission effect. Therefore, the whole section thermal insulation method has a better effect on thermal insulation property.

4 The In-situ Dynamic Test of Insulation Structure

The test site was located in the DK140 subgrade test section of the Harbin-Dalian high-speed railway. The thickness of the subgrade surface layer was 0.7 m and it was filled with graded crushed stone mixed with 5% cement. The bottom layer of the subgrade was filled with anti-frost-resistant filler 2.3m in thickness. 0.1m-thick XPS insulation board was used between the subgrade surface layer and the bottom layer. The earth pressure boxes, accelerometers, and settlement plates were pre-buried to test for stress, deformation, and other parameters, as presented in figure 8.

The SBZ30 dynamic-loading test machine provided the dynamic loading, as presented in figure 9. The test machine was installed on the line through a vibration pedestal formed with cast-in-place reinforced concrete and by adjusting the frequency and vibration phase of the eccentric block. Dynamic load tests under
different test stress levels should first be made to test the elastic deformation and cumulative deformation of the insulation material. The maximum applied dynamic stress level during testing is about 2.5 times greater than that produced by a high-speed railway train. After determining the general deformation behavior, the long-term dynamic vibration test with load level of 5–10 kPa was performed to further study the durability and the power performance of the thermal insulation material. From the initial value of static measurement and the observed values of each static measurement, the settlement beyond and underneath the insulation board relative to the settlement base rod can be calculated. Then, the accumulative deformation of insulation board can be developed from the former relatively settled values. The applied frequency was controlled at about 14 Hz. The data collection was performed while the test was conducting.

![Figure 8: Subgrade structure in the test section](image1)

![Figure 9: SBZ30 dynamic loading test machine](image2)

From the test results of elastic deformation under different dynamic stress levels, a correlation curve could be developed as presented in figure 10. The test curve shows that there is a linear relationship between elastic deformation and the dynamic stress level of an insulation layer, indicating that the insulation layer is still within the range of elastic deformation. It can be seen that the dynamic deformation of the insulation layer was within 0.08 mm under the range of dynamic stress level of high-speed railway train and therefore of little influence with respect to track irregularity.
Figure 10  Range of insulation board elastic deformation of high-speed railway train

Figure 11  Accumulative deformation of insulation layer under long-term dynamic load

Figure 11 shows the cumulative deformation test curve after applied ten million occurrences of dynamic load. It can be seen that there is a developing trend of accumulative deformation with relatively slow rate of development in the loading process. Under the real dynamic loading of a high-speed railway, the accumulative deformation of the insulation layer tends to be stable. The accumulated deformation of the insulation layer was 0.06 mm after applying ten million occurrences of dynamic load (equivalent to an actual dynamic load interval of 15 years). The accumulated deformation value was within the range of elastic deformation, which had only a small influence on the irregularity of a high-speed railway line.

5  Conclusions

After performing the in-situ dynamic load test and in-suit monitor on XPS thermal insulation material, the following conclusions can be drawn:

1) The in-situ dynamic load test indicated that there was a linear relationship between elastic deformation and the dynamic stress level of the insulation layer. Under dynamic loading of a high-speed railway, the dynamic deformation of the insulation layer was within 0.08 mm. After applying ten million occurrences of dynamic load, the accumulated deformation of the insulation layer was less than 0.06 mm. Subgrade structures using XPS insulation board therefore do not influence the irregularity of high-speed railway lines.

2) The in-situ insulation test shows that the using of thermal insulation measures on shoulders and the space between lines can reduce the frozen depth and frost heave of thermal insulation part. However, this method was not effective for the frost heave under the track structure, cannot prevent the frost heave effectively. The whole section thermal insulation method can significantly reduce the frozen depth and frost heave under the track structure, with a better anti-frost heave effect compared with the partial thermal insulation method.

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