An Experimental and Engineering Application of an Active Snow-Melting System for Highways Based on Heat-Pipe Technology

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Abstract. Major traffic accidents caused by snow cover and ice on pavements are responsible for large numbers of casualties and extensive property losses each year around the globe. A full-scale heat-pipe-based active snow-melting test system for outdoor asphalt roads was constructed to study and analyze its working performance on in-service asphalt highways. Based on long-term monitoring data, the active snow-melting system was analyzed to determine the temperature-field distribution pattern and relevant influencing factors as well as its performance on asphalt pavements. The research results show that: (1) the system exhibited excellent performance. Three natural snowfall events occurred on the full-scale test platform. In each event, the snow-melting system was able to effectively melt the snow. (2) Under long-term low-temperature conditions in winter, the active snow-melting system was able to increase the pavement temperature by approximately 10 °C. (3) In winter, the underground soil temperature decreased by approximately 4 °C as a result of heat extraction by the underground heat pipes and gradually recovered to its previous level as the outdoor ambient temperature gradually increased. This finding suggests that underground soil can provide heat to the snow-melting system for an extended period of time and continuously ensure its pavement snow-melting performance. The engineering application on the G18 Highway further demonstrates the effectiveness and reliability of active snow-melting systems based on heat-pipe technology.

Keywords: Ground soil heat, Heat pipe technology, Active snow melting, Highway
1. Introduction
Snow cover on highway pavements is a major factor leading to traffic accidents. In winter, ice and snow directly reduce the adhesion coefficient between tires and pavements by 60–75%. As a result, vehicles encounter dangerous situations (e.g., skidding and increased braking distances) [1]. Statistics show that major traffic accidents caused by snow cover and ice on pavements are responsible for large numbers of casualties and extensive property losses each year around the globe[2]. How to effectively melt snow and de-ice is therefore an important issue to ensure driving safety on pavements in winter [3]. Additionally, with the popularization and construction of intelligent highway networks, conventional snow-removal practices (e.g., clearing ice and snow and spreading snow-melting agents) no longer meet the requirements of constructing an intelligent highway network due to their excessive reliance on manual labor and their detrimental effects on road structure. Therefore, there is an urgent need to conduct experimental studies with new energy sources and materials to melt snow on active roads. This is of great importance to ensuring the achievement of highway operation goals (i.e., unobstructed, intelligent, and safe operation) in winter[4, 5].

Regarding research on active-pavement snow-melting technology, numerous researchers have extensively studied and applied active-pavement ice- and snow-melting technology for energy conversion-type pavements. In the 1990s[6], the United States and Japan conducted several geothermal-energy-based pavement snow and ice-melting demonstration projects in which heat-exchange fluids (e.g., groundwater) were used to exchange energy with pavements[9]. However, fluid-heating-based ice- and snow-melting systems have relatively strict requirements for later-stage manual operation and maintenance. Heat pipe technology has since been developed and used in applications [8]. A heat pipe can transfer heat rapidly between objects through phase changes in the internal working medium. Owing to their excellent heat transfer performance, small heat losses, exceptionally high environmental adaptability and enduring sustainability, heat pipes have been extensively and deeply applied in a number of fields, including energy, chemicals, and prevention and control of frozen soil[10]. Heat-pipe-based heat-transfer technology offers the transportation industry a new active snow and ice-melting technology that requires no later-stage maintenance[11].

In summary, in regard to melting pavement snow by heating based on heat pipe technology, researchers in China and elsewhere are currently focusing on studying new heat-transfer media, combinations of heat sources, and temperature-increase patterns on rigid concrete pavements[12]. By comparison, there is a lack of systematic research on pavement snow-melting performance and temperature variation patterns on asphalt road structures treated with heat pipe technology. In view of this, in this study, based on the heat-transfer characteristics of heat-pipe systems and asphalt highway structures, a full-scale heat-pipe-based highway snow and ice-melting test platform was constructed. The focus was to examine the heat-transfer and snow- and ice-melting performance of heat pipes in asphalt road structures as well as relevant temperature variation patterns. This study offers beneficial guidance on the use of heat-pipe systems to equip highways with automatic snow-melting capacity.

2. Test system design
15 ℃. Low-temperature snowfall weather is relatively frequent in this area in winter, providing an opportunity for conducting a relatively large number of experimental observations. The snow-melting pl The outdoor asphalt pavement snow-melting test system was located in Mouping, Yantai. The temperature in the isothermal ground layer in this area is the same as the local annual mean temperature (approximately at form was installed as a 60 m-long, full-scale, single-lane asphalt pavement. The platform consisted of various sections with differing parameters, including spacing between embedded heat pipes and asphalt surface thickness, for comparative analysis purposes. During the test, the temperature fields and snow-melting performance in various asphalt pavement sections were monitored to analyze the effects of two key parameters on snow-melting performance, namely, spacing between heat pipes at the heat dissipation end and the embedding depth of heat pipes.
To analyze the heat-transfer process in the condensation section of a heat pipe inside the asphalt pavement, temperature sensors were placed at the top and bottom interfaces of the middle surface layer of the pavement. Additionally, two asphalt layer thicknesses (10 and 18 cm) were used on the test platform. Temperature sensors were placed 1, 6, and 13 m below the surface along the heat-pipe depth direction to detect the temperature variation in the ground at various depths.

The test monitoring platform included a real-time video monitoring system and a small meteorological station for environmental monitoring. The long-distance video surveillance system was able to monitor snow-melting conditions on the test platform in real time and capture image information. The snow-free area ratio on the test platform was subsequently analyzed by image analysis. On this basis, the snow-melting rate was further comparatively analyzed. The small meteorological station monitored and acquired data for the environmental parameters (e.g., temperature, humidity, and wind speed) of the test platform.

3. Test results and analysis

The test platform operated normally since its construction on December 20, 2018. The temperature-measurement system monitored the temperature field in the road in real time in the presence of heat pipes under low-temperature snowfall and high-temperature summer heat conditions. The wireless temperature measurement modules acquired temperature data once every hour. The long-distance video platform monitored the road conditions continuously 24 hours a day. The acquired temperature data were primarily relied on to analyze and discuss the process by which the heat-pipe system melted snow on the asphalt pavement, the dynamic variation of the pavement temperature field during low-temperature snowfall periods, and the sustainability of snow-melting performance of the heat-pipe system.

3.1. Analysis of the process by which the heat pipes melted snow on the asphalt pavement

A moderate snowfall occurred on the outdoor snow-melting test platform in Mouping, Yantai, February 14-15, 2019. Figure 1 shows the variation of the outdoor ambient temperature. After long-period low-temperature weather, the snowfall process began at 22:00 on February 14, 2019 and lasted for 8 h. By 03:00 on February 15, a 3.3 cm-thick snow cover had formed on the heat-pipe-free pavement section. Snow-cover thicknesses on non-test sections were measured multiple times. On this basis, the average snow cover thickness was found to be 5.3 cm. Figure 2 shows the snowfall conditions and the variation of the snow-cover on the pavement recorded by video cameras. Additionally, the snow-cover thickness measurement rods set up on the test platform were used to record the snow-cover thicknesses at various pavement sections. Figure 3 shows the measurements.

| Table 1. Structural parameters and schemes of the test platform |
|---------------------------------------------------------------|
| **Section No.** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Length/m** | 5 | 5 | 5 | 10 | 5 | 5 | 5 | 5 |
| **Covered pipe spacing/m** | 0.3 | 0.4 | 0.45 | 0.3 | 0.4 | 0.45 | Blank section | Single-pipe section |
| **Asphalt surface layer/m** | 0.1 | 0.18 | 0.18 | 0.18 |
| **Water-stable macadam base/m** | 0.4 |
| **Number of embedded pipes** | 18 | 13 | 11 | 33 | 13 | 11 | 0 | 1 |
Figure 1. Variation of the outdoor ambient temperature at the location of the test platform

Figure 2. Snow-melting process on the test platform

Figure 3. Measurements of snow-cover thicknesses on the test pavement during the snowfall event

It can be observed from variation of the outdoor ambient temperature (Figure 1) that the asphalt pavement on the test platform experienced long-term, low-temperature cycling before the snowfall event was below 0 ℃. Snow would therefore accumulate in the form of dry snow on the pavement. The heat-pipe-free pavement section basically would be unable to provide the latent heat needed to melt snow, and the snow cover on this section could be melted only by the energy from solar radiation the following day. Before the snowfall event, the temperature of the asphalt surface remained above 0 ℃, thanks to the preheating action of the heat pipes. Snow that fell on the pavement thus melted immediately. Simultaneously, snow already started accumulating on the heat-pipe-free section. In comparison, the ultimate cumulative snow-cover thickness on the heat-pipe-free section reached 5.3 cm. After the snowfall event ended, the snow on the heat pipe-free section began to gradually melt under solar radiation.

3.2. Temperature variation in the ground in which the heat pipes were embedded

A heat-pipe system is a medium that facilitates energy exchange between an isothermal ground layer and a low-temperature pavement. Extensive research on ground temperatures at various depths has found that the temperature of an isothermal layer varies insignificantly within a certain depth range and that the temperature of an isothermal layer is basically consistent with the local annual mean temperature. Based on the equations and the long-term statistical temperature data acquired on the test
platform, the relationship between soil temperature and depth on the test platform in winter was calculated as shown in Figure 4. Based on the temperature–depth relationship, in winter, the soil temperature gradually increases with depth in a range of 0–6 m and remains basically constant at depths beyond 9 m. Fluctuations of the outdoor ambient temperature basically affect the soil temperature within a depth range of 0–6 m. Additionally, a 0 °C frost line appears 1–2 m below the pavement surface. On this basis, the heat-absorption ends of the heat pipes were placed at depths more than 13 m below the surface during the embedding process. Additionally, an insulating layer was added to the outer wall of the section of each heat pipe within a depth range of 0–1.5 m below the surface.

There are two key factors that determine whether a heat-pipe system can operate steadily and reliably over an extended period of time, namely, the transfer of energy from the isothermal layer by the heat-pipe system and the replenishment of the isothermal layer with energy by the heat-pipe system. Figure 12 shows the long-term temperature variation in the ground in the normal and heat-pipe-embedded sections on the test platform at various depths. As demonstrated by the temperature monitoring data in Figure 5, the temperature in the isothermal ground layer in the blank section fluctuated to a relatively small extent as the outdoor ambient temperature increased. During low-temperature periods, the ground temperature in the blank control section basically remained relatively cold, specifically, a lowest value of 14.7 °C under winter low-temperature conditions and the highest value of 16.1 °C in summer high-temperature conditions.

![Figure 4. Relationship between soil temperature and ground depth in Yantai](image)

**Figure 4.** Relationship between soil temperature and ground depth in Yantai

**Figure 5.** Comparative analysis of long-term temperature variation at various ground depths

Compared to the blank section, there was a notable decrease in the temperature of the isothermal ground layer in the heat-pipe-embedded section under winter low-temperature conditions. The data demonstrate that energy transfer by the heat pipes could reduce the temperature in the isothermal ground layer to 12.5 °C (a 2.2 °C decrease). As the surrounding ground replenished the isothermal ground layer with heat, the temperature of the isothermal ground layer in the heat pipe-embedded section was able to remain at approximately 13 °C.

On December 28, 2018, moderate snow (6–8 cm) fell at the test section. Additionally, the maximum daily temperature was only -4 °C. On-site infrared (IR) imaging of the pavement temperature showed that the temperature of the heat-pipe-embedded pavement section remained basically at approximately 0 °C, whereas the temperature of the ordinary pavement was as low as
approximately -9 °C. Evidently, the heat pipes significantly increased the pavement temperature. Additionally, as demonstrated in the right panel of Figure 14, there was basically no snow cover on the heat pipe-embedded pavement section, whereas there was no indication that the snow cover on the ordinary lane would melt, due to the relatively low temperature.

![Figure. 6. Snow-melting effects of the heat-pipe system on the test section of the G18 Highway](image)

4. Conclusions
Based on the research and application of active-highway snow-melting technology for snowfall periods in winter, the following conclusions were drawn:

1) The test platform results and the application of heat pipes in melting snow on the in-service highway demonstrate that the heat-pipe system is able to effectively heat asphalt pavements, reduce the extent of snow accumulation and icing on asphalt pavements, and accelerate the melting of snow cover during low-temperature periods in winter. This suggests that heat pipe technology can effectively realize active snow melting on asphalt highway pavements.

2) The heat-pipe system was able to continuously transfer heat to each structural layer of the asphalt pavement over an extended period of time under low-temperature weather conditions. The temperature field data demonstrate that the heat-pipe system was able to maintain the pavement temperature at approximately 0 - 6 °C when the outdoor ambient temperature remained at 0 - -9 °C over an extended period of time.

3) When embedded in in-service highways, heat pipes are able to realize active-pavement snow melting in winter and effectively shorten the time needed to melt snow cover. Heat-pipe-based active snow melting systems on special sections of highways can reduce the number of traffic accidents caused by late removal of pavement snow cover.

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