INTRODUCTION

The stability and service performance of asphalt pavement are affected by the state of the heat and water present in subpavement soil layers.\textsuperscript{1,2} The primary road engineering problems encountered in cold regions are closely related to water and heat changes in subpavement soil layers and include pavement cracking, uneven deformation, and muddy

Hydrothermal accumulation under asphalt pavement in cold regions

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Abstract

Water and heat changes are the main problems that plague the stability and service performance of roadbeds in cold regions. Though hydrothermal transfer and accumulation directly affect roadbed properties, these processes remain poorly understood as monitoring data are often collected over short time periods and large spacing in depth. This research compares water and temperature data collected from 2012 to 2015 to elucidate the physical mechanisms of hydrothermal accumulation under both asphalt pavement and original pavement. These thermal and physical mechanisms include differences in the freezing process (FP) and the thawing process (TP), water transport, condensation, and hydrothermal accumulation. For instance, when compared to the underlying layer, the thawing of the surface layer of asphalt pavement was delayed by 35 days because of differences in hydrothermal properties. During TP, liquid water content changes from 3.31\%-13.2\% to 15\%-37.67\%, and the unfrozen water content of the soil layers under the asphalt pavement was approximately 6.85\%-12.34\% higher than that of the soil layers under the original pavement. A layer with high water content and heat formed under the surface layer of asphalt pavement and provided the appropriate conditions for vapor transport and condensation. Soil layers thawed early in the preceding year, and this hydrothermal accumulation occurred on an annual basis. The annual minimum monthly average temperature was thus found to be increasing at the rate of 0.34°C/y. As water content also accounts for heat accumulation and was found to be more sensitive to change than temperature, the results of this study can provide theoretical and technical data useful for highway construction and design in permafrost regions.

KEYWORDS

asphalt pavement, hydrothermal accumulation, liquid–vapor water transport, thawing and freezing process
roadbeds. In permafrost regions, water in subpavement soil layers undergoes annual dynamic freezing process (FP) and a thawing process (TP; e.g., movement and distribution). The thermal dynamics of embankments in permafrost region have been well studied, and it is clear that water and heat changes are inseparable. However, the lack of information on the hydrothermal accumulation process limits our understanding of the finer points of engineering problems present in permafrost regions.

Several permafrost engineering problems are caused by hydrothermal accumulation and redistribution. Embankment materials and soil in cold regions undergo FP–TP, which aggravates damage to pavement. Early works related to the changes in subpavement soil water focused on the effects of permafrost temperature on roadbeds. Numerous findings on heat absorption and temperature variation in asphalt pavement have been obtained and demonstrate that asphalt pavement experiences thermal accumulation. Changes in water and temperature have also been shown to be coupled. The formation of thawing corridors in the bottoms of roadbeds was first observed in the 1980s, and the role of water in heat accumulation was first noticed in cold regions. The subsurface hydrothermal condition is a critical factor that affects the strength and deformation of embankments. Water moves vertically and horizontally throughout roadbeds, and water accumulation under surface layer has been attributed to the heat–water exchange between the atmosphere and permafrost. The equilibrium of water content of soil samples collected from the shallow sections of roadbeds was 5%. In fact, it was much higher than the optimal water content.

When water accumulation occurs in subpavement due to the transfer of vapor water, considerable frost-heave damage is inflicted on the pavement, which acts as a “pot cover” that prevents evaporation and promotes hydrothermal accumulation. Shear stress concentrates as a result of the variations in soil thermal–physical properties across seasons and across space, and some studies have even demonstrated that during TP, the volumetric water content in the cushion layer of a given roadbed may exceed 30% and may reach 57%.

In this work, the soil hydrothermal changes from multiple FP–TP cycles under asphalt pavement and an original pavement were analyzed by applying in situ monitoring data. Second, the internal connection between water and thermal regimes at different times and soil depths was clarified. Finally, the hydrothermal accumulation effects are considered in terms of thermal physical properties, hydrothermal transfer, and yearly changes. This work will provide future references for the maintenance and design of roads in cold regions.

### 2 DATA AND METHODS

#### 2.1 Site description

The study’s test data come from mechanism test sections (original pavement sites) and highway test sections (asphalt pavement sites). Two sections were built in 2004 and 2009, respectively. The road shows an approximately north–south trend and has a width of 12 m and a subgrade height of 2.7 m. The asphalt pavement site is located at 34.82°N,
92.93°E at an elevation of 4633 m (Figure 1). The asphalt pavement is composed of surface and base layers. The thickness of the surface layer is 9 cm, that of the AC-13 layer is 4 cm, and that of the AC-16 modified asphalt concrete is 5 cm. The base layer is cement-stabilized sand with a thickness of 20 cm (Figure 1B). A water-impermeable tack coat is located at the depth of 10 cm. The original pavement is located at 34.82°N, 92.92°E at an elevation of 4639 m. Its surface is covered with coarse-grained soil (Figure 1C).

Meteorological data were retrieved from the Beiluhe Meteorological Station near the test sections, located in a continuous permafrost region on the Qinghai–Tibet Plateau, at an altitude of approximately 4628-4633 m. In the study area, the annual freeze period ranges from 6 months to 7 months; the mean annual ground temperature (MAGT) is in the range of −0.3 to −1.1°C; and the active layer thickness ranges from 1.9 to 3.5 m. The mean average air temperature ranges from −2.7 to −3.6 °C, and the annual precipitation ranges from 1.9 to 3.5 m. The mean air humidity is between 50% and 60% (Table 1).

2.2 Data measurements

Meteorological data measurements included air temperature, precipitation, and humidity. Hydrothermal data measurements in the roadbed included ground temperature, volumetric water content, and soil heat flux (G). The ground temperature and water of the original pavement were monitored under the roadbed center at soil depths of 0-80 cm at a spacing of 10-20 cm. G was monitored at subpavement depths of 5 and 15 cm (Figure 2). The ground temperatures of soil layers under the roadbed center, sunny road shoulder, and shady road shoulder of the asphalt pavement were observed at the depths of 0-4 m at a spacing of 5-50 cm. The water content of soil layers under the asphalt pavement was observed at the depths of 0-4 m at a spacing of 5-50 cm (Figure 2). Information on the test instruments is shown in Table 2.

Data were collected and stored using the Campbell CR3000 data logger collector produced by the Campbell Company. The machine automatically generated sets of average values every 30 minutes. Data were corrected prior to the analysis. In this work, continuous monitoring data obtained by this device from 2012 to 2015 were utilized.

### TABLE 1 Meteorological conditions of the Beiluhe area

| Year | Annual rainfall (mm) | Humidity (%) | MAAT (°C) |
|------|---------------------|--------------|-----------|
|      |                     |              | 2 m       | 10 m      |
| 2012 | 456.41              | 59.6         | −2.91     | —         |
| 2013 | 566.83              | 51.77        | −3.28     | −3.26     |
| 2014 | 612.93              | 53.23        | −3.46     | −3.51     |
| 2015 | 598.84              | 50.63        | −3.14     | −3.17     |

3 RESULT

3.1 Changes in ground temperature

The FP–TP that occurs over the course of a year can be divided into four stages: TP, complete TP (CTP), FP, and complete FP (CFP). Changes in ground temperature under the asphalt pavement during the different stages are presented in Figure 3A. From these data, it can be seen that the 5 cm soil layer began to thaw March 19. The thaw time of the ground surface lagged behind that of the 5 cm soil layer by about 35 days. The 10 cm soil layer began to thaw on March 25 and completely thawed on April 2. The 20 cm soil layer thawed on April 8, and the 30 cm soil layer can be seen to have thawed 3 days earlier than 3 days than 20 cm layer. The 50 and 80 cm soil layers thawed on April 11 and 26, respectively. The ground surface temperature exceeded 0°C on April 25. The ground temperatures reached the highest annual value with an average of 14.79°C in the middle of July. The temperatures of the 10 cm soil layer fell in the range of 12.77-20.45°C and were higher than those of the pavement surface. The ground temperature increased in soil layers above the depth of 45 cm. The ground surface temperature was lower than 0°C on September 30 at surface layer. The 5, 10, 20, and 50 cm soil layers began to freeze on October 28, November 1, October 30, and November 16, respectively. Freeze depth reached 80 cm on November 26, and the thaw period ranged from 214 to 223 days above 80 cm depth.

Surface layers under the original pavement began to thaw on April 26. The 15, 30, and 50 cm soil layers thawed on April 29, May 4, and 5, respectively. Thaw depth reached 80 cm on May 25. During TP, the ground temperature under the asphalt pavement was higher than that under the original pavement at the same depth and had the average value of 3.38°C. The surface layer began to freeze on September 21. The 5, 15, 30, and 50 cm soil layers began to freeze on October 19, 20, 28, and 31, respectively. The freeze depth reached 80 cm on November 5, and the thaw period ranged from 174 to 179 days.

The TP and FP parameters of the soil under the asphalt pavement were different from those of the soil underlying the original pavement (Figure 3B). These parameters included time, depth, and temperature change. The thawing time of the soil under the asphalt pavement was approximately 24-28 days earlier than that of the soil under the original pavement, and the soil layers at depths of 5-10 cm thawed first. The freezing time of the soil under the asphalt pavement was 9-20 days later than that of the soil under the original pavement, and its FP was also prolonged. Freezing time and thawing time, as well as the extent of ground temperature warming, varied at different soil depths. These differences directly affected the transport direction and flux of water vapor in the soil.
3.2 | Changes in water content

The liquid water content under surface layer exhibited different characteristics during the FP and the TP and at increasing temperatures (Figure 4). The liquid water content of the 10 cm depth layer was initially increased by 3.31% during the TP. The soil layer under this layer froze rapidly. Thus, liquid water could not migrate in a vertical direction. Similarly, the liquid water content of the 20 and 30 cm layers was increased by 13.19% and 3.99%, respectively. However, the ground temperature of the 20 cm layer was lower than that of the 30 cm layer. The vertical migration of liquid water was limited within a certain period, and the ground surface temperature was lower than the subsurface temperature for approximately 1 month. The movement of liquid water to the cold area (pavement direction) was hindered by the tack coat.
During this process, the change shown by the liquid water content was closely related to soil thawing and liquid water migration.

The ground temperature of the shallow soil layers (10-60 cm depth range) increased during the CTP. The ground temperatures of these layers were lower than those of the overlying and underlying layers. This fact could be attributed to the high liquid water content and the slow incremental increase in the ground temperature of the shallow soil layers. The liquid water content of the 10-30 cm soil layers increased because liquid water in the 10-20 cm layers moved downward while the water content of the 20-30 cm soil layers moved upward. The liquid water content of these layers reached 37.67% at 20 cm depth layer. Liquid water in the deep soil layers (>30 cm depth) migrated downward, changing the liquid water content in these layers from 14.4% to 26.6%. The distribution of liquid water in the 30 cm soil layer was divided into two parts. Liquid water transport, migration rate, and flux decreased as ground temperature decreased in August.21,22 The road surface layer froze first and liquid water migrated to the pavement during the FP. The freeze time of the 10 cm soil layer was similar to that of the 20 cm soil layer. Thus, liquid water would be frozen in situ in the 20 cm soil layer. Generally, liquid water distribution in shallow layers exhibited a spindle-like profile. The liquid water content above 30 cm depth remained between 12.7% and 15.7%, even as the ground temperature decreased.

The soil in the original pavement thawed beginning with the surface layers and progressing to the deep layers, and its liquid water content increased from 7.65% to 12.31% during the TP. Liquid water migrated through the profile in a single downward direction. The liquid water content in the tested soil profile was 9%-18% during the CTP. The water content of the 30 cm soil layer was 9.87%-11.46%. Liquid–vapor flux density decreased as a result of the narrowed ground temperature gradient. Liquid water migrated from the bottom to the top of the soil profile during the FP. The freezing time of the soil layers at depths above 30 cm under the original pavement was shorter than that of the soil layers under the asphalt pavement. Freezing time, however, did not vary between soil layers. The liquid water content was maintained at 3.36%-5.85%.

### 3.3 Changes in the ground temperature gradient and liquid water content

Annual variations in the ground temperature gradient and the liquid water content are shown in Figure 5. The change in liquid water content is related to the variation in the ground temperature gradient of the overlying and underlying soil layers, with the size of the temperature gradient reflecting the intensity of liquid water transfer and the direction of the increment in liquid water content. A layer with high liquid water content existed below the asphalt pavement and the original pavement in the CTP. The center of this layer was distributed between the 15 and 30 cm soil layers. This work focused mainly on the temperature gradient above and below this layer with high water content.

In the 10-20 cm soil layer under the asphalt pavement (Figure 4), the ground temperature gradient was oriented upward and had a range of 0.088-0.18°C/cm, whereas
liquid water moved downward under the effect of the ground temperature gradient. In the 20-30 cm soil layer, the ground temperature gradient was oriented downward and had a range of −0.088 to −0.307°C/cm, whereas liquid water moved upward. Liquid water content over 1 day increased from January to June and ranged from 0% to 0.34%. Later, it decreased from June to December and ranged from 0.04% to 0.25%. Liquid water content changed drastically during the FP and the TP. At the same time, it was correlated with the temperature gradient of the 20-30 cm soil layers (Figure 5).

The ground temperature gradient in the soil layers under the original pavement exhibited a downward orientation during the cold season and an upward orientation during the warm season. The ground temperature gradient in the 5-15 cm soil layers fell in the range of −0.05 to −0.06°C/cm. The ground temperature gradient in the 15-30 cm soil layers varied between −0.07 and −0.08°C/cm. Liquid water content alternately increased and decreased during the CTP. The change in water content and temperature gradient in the 15-30 cm soil layers showed no significant correlation.

An increase in liquid water content demonstrated a negative correlation with the temperature gradient during other stages. Therefore, the increase in liquid water content cannot be attributed to liquid water migration. Instead, the increase in the water content of the soil layers under the original pavement is attributed to precipitation, while the water content of the soil layers under asphalt pavement was unaffected by precipitation. The reason for the increase in the liquid water content of soil layers under the asphalt pavement is an area requiring further study.

4 | DISCUSSION

4.1 | Thermal properties and thawing–freezing processes

In addition to the heat absorption of the asphalt pavement, the difference between asphalt pavement material and the soil layer is another important factor to consider in terms of thermal properties. Thermal conductivity is a thermal property indicator that can be directly tested. The thermal
conductivity coefficient ($\lambda$) of AC-16 is 1.10-1.5 W/m·°C in the frozen state and was 0.8 and 1.5 W/m·°C in the thawed state. The $\lambda$ of AC-13 is close to AC-16 in terms of material composition. However, the water content of the AC-16 layer is 1.3~6.2% smaller than that of the AC-13 layer, so the $\lambda$ of AC-13 is greater than that of AC-16. The equivalent $\lambda$ of cement-stabilized sand was 0.7 W/m·°C at low-temperature states. In the thawed state, the $\lambda$ increases with an increase in liquid water content, when coarse particulate material is larger than fine particulate material. The $\lambda$ of silty clay is 1.67-2.15 W/m·°C in the frozen state and 0.73-1.09 W/m·°C in the thawed state. The relationship of $\lambda$ with the asphalt pavement structure and the soil layer changes over a year.

According to the heat conduction theory, when the $G$ and the transfer depth (distance) are constant, the $\lambda$ is inversely proportional to the amount of temperature change that occurs within a given depth range, meaning that the $G$ decreases with an increase in depth. During TP, the ice in pore phase to liquid water, which absorbs a large amount of heat, and the $\lambda$ will be abrupt, and under these circumstances, the thawing time is extended. According to the observed data, the thawing date of the asphalt pavement (AC-13 layer) above 5 cm depth was approximately 35 days later than that of the underlying structure. AC-16 layer and base layer (10~15 depth layer) thawed before the AC-13 layer. The small $\lambda$ and liquid water content in AC-16 layer and its water-impermeable tack coat contributed to the 10 cm depth's higher ground temperature and advanced thawing when compared to that of the 5 cm. Meanwhile, cement-stabilized sand has a larger $\lambda$ and liquid water content than AC-16. When soil in the 5~15 cm depth range thawed in advance, the 20 cm depth layer was still in frozen state. When the ground temperature rises to 2.19°C at the 10 cm depth, the cement-stabilized sand begins to thaw. Below 30 cm, the liquid water content in the soil's pores is reduced with depth, and the $\lambda$ can also be seen to decrease. The change range in ground temperature below 30 cm depth was higher than that of the cement-stabilized sand under the same heat flux. The ground temperature increment of 30 cm layer was larger than that of the asphalt pavement. We observed that the 30 cm depth soil layer thawed 3 days earlier than the asphalt pavement structure. In general, the highest temperature of the asphalt pavement structure appeared in this layer.

The asphalt pavement limits water–heat conduction from the soil to the atmosphere. As heat absorption through the asphalt pavement increases, liquid water accumulates in the soil layer under the pavement during the CTP. The heat absorbed through the asphalt pavement in June, July, and August accounted for 51.1% of the total heat absorbed for the year and was 1.94 times the heat absorbed by the original pavement. The liquid water content at the depth of 30 cm under asphalt pavement increased by 19.6%-35.7% and was 2.11-2.73 times that value at the same depth under the original pavement. Both the $\lambda$ of the soil and its heat capacity increased as its liquid water content increased. The change in ground temperature was found to decrease with an increase in thermal properties ($\lambda$ and heat capacity), and the temperature difference in fixed different depths decreases. The ground temperature at the depth of 30 cm under the asphalt pavement was 1.01°C higher than that at the depths of 20 and 50 cm, and was 5.58 times the value of that under the original pavement at the same depth. This temperature structure (warm-cold-warm) provided a cold front for vapor water condensation and liquid water migration, during the FP and the CFP. The liquid water content of layers above the depth of 30 cm under the asphalt pavement was larger than that of layers under the original pavement. When the water changes to ice in the soil pores, the $\lambda$ will also increase. In comparison, the change in $\lambda$ of asphalt materials is minimal between thaw and freeze state, and the temperature change in the asphalt material was found to be more than that of soil. The freezing time of the surface layer of asphalt pavement was earlier than that of the underlying soil by 11~28 days. The temperature difference between the top and the bottom of the surface layer was small, and sometimes equal. To some extent, the small $\lambda$ and small temperature difference in the asphalt material may limit the release of heat, and also extend the freezing process of the subgrade soil, resulting in lots of heat and water stored in the subpavement layer. The liquid water content under the asphalt pavement was higher than that of the original pavement by 6.85%-12.34% in the subsurface layer. The freezing time of the asphalt pavement was longer than that of the original pavement. Water plays an important role in the prolongation of the FP and the truncation of the FP. All of these phenomena provide conditions for the advance of the thawing time in the following year. Water affects the FP, TP, and heat accumulation process of the subgrade by changing the thermal properties of the medium.

### 4.2 Liquid water migration and vapor condensation

Liquid and vapor water transport is the main mechanism of water movement in permafrost roadbeds and is dominated during thawing. Therefore, this work mainly focused on liquid water and water vapor transport. Vapor water transport in the soil layer under the asphalt pavement was drastically different from that in the soil layer under the original pavement. In the roadbed, liquid water migrates to cold sections, whereas vapor migrates to warm sections.

The ground temperature from the shallow to deep layers under the original pavement was in a “warm–cold–warm” state. Liquid water in soil layers at the depths of 10-30 cm accumulated at the depth of 20 cm. Liquid water in soil layers below the depth of 30 cm moved to the permafrost table under the actions of gravity and the temperature gradient.
(Figure 6), while the direction of vapor transport is upward. Vapor transport may exceed liquid transport, and pore pressure can reach hundreds of kilo-Pascals. Under these conditions, water will transit from the vapor state to the liquid state at any temperature condition as long as a cold temperature interface exists. The ground temperature at the depth of 20 cm was lower than that at the depth of 30 cm (Figure 7). The 20 cm soil layer provided a cold interface wherein vapors condensed rapidly. Other factors also affected the changes in water transfer in the shallow layer. Precipitation directly decreased ground temperatures at layers above the depth of 20 cm under the asphalt pavement and at layers above the depth of 30 cm under the original pavement. The cooling rate during the day was greater than that during the night under the same precipitation conditions. The maximum cooling degree could reach 7.06°C within a short duration. The temperature of the surface layer was lower than that of the underlying soil layers during cooling. These temperature structures and conditions were favorable for vapor condensation.

Vapor water condensation cannot be directly observed because it occurs on the mesoscale and can only be judged on the basis of liquid water content. As shown in Figure 7, the liquid water contents at the 20 and 30 cm depth showed significant increases between 1:00-5:00, 5:30-9:00, and 21:00-23:30 by 6.6%-8.1%, 6.4%-8.7%, and 5.7%-9.8%, respectively. In addition, the liquid water at the depth of 30 cm increased by 0.35% per hour, whereas that at the depth of 20 cm decreased at the rate of -0.13% per hour. The ground temperature from 1:00 to 5:00 at the depth of 30 cm was 1.29°C and 1.47°C higher than that at the depths of 20 and 50 cm, respectively. Vapor water was transported to soil layers at the depths of 20 and 30 cm under the effect of the temperature gradient. The liquid water content at the depth of 30 cm was only 9.18%-16.1%, and a large amount of vapor was transported through pores because of soil unsaturation. Vapor water first condensed at the depth of 20 cm and then condensed during transport. Thus, the increase in the liquid water content at the depth of 20 cm was greater than that at the depth of 30 cm. During this process, the ground temperature at the depths of 20-30 cm decreased continuously, the ground temperature gradient declined, and the cold front moved downward. In this case, both the quantity transported and the migration distance of the vapor water would decrease. The liquid water content at the depth of 30 cm decreased at 3:00, and the decrement in liquid water content lagged behind that in ground temperature by approximately 30 minutes. Liquid water
content at the depth of 20 cm also began to decrease after 30 minutes. Comparing the time between vapor water condensation and liquid water change revealed that the change in liquid water content at the depth of 20 cm was strongly correlated with liquid water migration. From 5:30 to 9:00, the ground temperature at the depth of 50 cm was higher than that at the depths of 20 and 30 cm and liquid water migrated to the cold section. Comparing the changes in liquid water content during the periods of 1:00 to 5:00 and 5:30 to 9:00 indicated that the amount of water vapor condensation may be comparable to the amount of liquid water migration under certain conditions. After 9:00, the ground temperature at the depth of 20 cm increased, and the increment in the liquid water at the depth of 30 cm was greater than the decrement of liquid water at the depth of 20 cm. Thus, the change in liquid water content at the depth of 30 cm occurred along with a certain degree of vapor water condensation, and liquid–vapor water convection also occurred. The ground temperature profile provided conditions for vapor water transport but lacked the cold front necessary for vapor water condensation. On the other hand, the decrement in ground temperature at the depth of 30 cm after 21:00 provided the appropriate temperature conditions for vapor water condensation and the liquid water content at the depth of 20–30 cm drastically increased.

The increase in liquid water content at the 30 and 10 cm depths between 0:30 and 3:30 can mainly be attributed to vapor water condensation (Figure 8). The ground temperature profile at the depths of 10 and 50 cm was in a “warm–cold–warm–cold” state that provided segmented transportation and condensation of vapor water. The ground temperature gradient between the 10 and 20 cm depths was slightly narrower than that between the 30 and 50 cm depths. Therefore, the increment in liquid water content was small. The ground temperature at the depth of 30 cm later decreased. The increment in the liquid water content at the depth of 30 cm from 6:00 to 21:00 can be attributed to the combination of liquid water migration and vapor water condensation. The increment in liquid water content after 21:00 is attributed to vapor water condensation. In addition, the liquid water content at the depth of 20 cm changed within the range of 33.7%–38.3% (the mass water content was close to 44%–46%). When the soil volumetric water content was >30% and was larger than the plastic limit of the general cohesive soil. Given that free-flowing water encapsulated loosely bound water, condensed water vapor would take the form of a large liquid film. Liquid water moved downward under action of gravity.36 Soil pores do not provide sufficient space for the further condensation of vapor water. Vapor water condensation requires certain water and pore conditions in addition to certain temperatures and pressures, and mainly occurs at night. High water content was not conducive for water vapor condensation in the soil layer.

Water exhibits horizontal movement in addition to condensation and movement under gravity. A comparison of Figure 9C, D reveals that the liquid water content increased under the shoulder and moved to the central and deep sections of the roadbed during the TP (depth > 3 m). Liquid water migrated to the cold section. In August, the liquid water content of the soil layers under pavement was 9.75%–21.44% and was 9.05%–18.30% for those under the embankment center. The ground temperature under the center of roadbed was higher than the ground temperature at the shoulder at similar depths. The direction of water movement was perpendicular to the water contour line and to the center of the roadbed.8 However, heat accumulation occurred below the depth of 3 m at the center of the roadbed and displayed a disk-shaped isotherm (Figure 9C). Water content under the shoulder was higher than that under the central section of the roadbed. The direction of the increment in water content was inconsistent with the direction of liquid water migration. At this time, the change in the amount of water was affected by other factors, such as precipitation and temperature. Therefore, different levels of water transport exist at various depths in the roadbed as verified through laboratory tests.4 Water accumulation can thus be concluded to constitute an important aspect of heat accumulation.

4.3 Annual accumulation of water and heat in the subpavement layer

The emergence of a high water content layer within the subpavement layer (at the depth of 15–20 cm) was a common phenomenon. Annual changes were also considered. As shown in Figure 10A, the annual average water content of the soil layers under the asphalt pavement decreased from 26.7% to 23.4%. The minimum water content increased from 12.9% to 13.6%, and the maximum water content decreased from 39.3% to 31.6%. The temperature in December increased from −12.5 to −11.14°C with the rate of 0.34°C/y. As shown in Figure 10B, the annual average liquid water content of the soil layers under the original pavement changed from 9.9% to 10.4%. The minimum change in water content ranged from 5.5% to 5.9%, and the maximum change in water content...
ranged from 16.6% to 14.4%. The water contents of the sub-pavement layer and the ground temperature increased during the cold season. The liquid water content under the original pavement decreased with the temperature increase. The heat accumulation was limited to a certain extent. Water can also account for heat accumulation and was more sensitive than temperature.

As shown in Figure 11, the heat absorption time of the asphalt pavement was approximately 3 months longer than that of the original pavement. The monthly heat release and absorption of the soil layers under the asphalt pavement were 0.27-0.55-fold and 0.97-2.12-fold higher than those of the soil layers under the original pavement, respectively. Intensive heat absorption during the summer and limited heat release during the winter accounted for hydrothermal accumulation in the subpavement layer during the cold season. The accumulation of unfrozen water contents during winter promoted early thawing during the following year. The effects of soil properties on water migration and flux warrant further study.

**FIGURE 9** Direction of water transport in the roadbed

**FIGURE 10** Characteristics of the annual variation in the liquid water content and ground temperature in the roadbed
5 | SUMMARY

The in situ testing of hydrothermal regimes revealed that hydrothermal accumulation under asphalt pavement in cold regions can be attributed to (a) differences in thermal properties between the pavement and soil, (b) liquid water migration and vapor water condensation, and (c) annual variations in hydrothermal states. Compared with the surface layer, the thawing of the 20 cm soil layer under asphalt pavement was delayed by 35 days, whereas that of the 30 cm soil layer was delayed by 19 days owing to the fact that the λ of the asphalt was lower than that of the soil. When the soil was thawed in situ, the downward migration of water was restricted under the effect of the temperature gradient. The soil profile was a “cold–warm–cold” state during the TP because asphalt material exhibited stronger thermal conductivity and lower permeability than the soil. The heat was consumed during the increase in ground temperature. The high potential energy of the shallow layer under the asphalt pavement can be attributed to heat absorption. The retention of liquid water at the subpavement layer (10-30 cm depth) was accompanied by the condensation of vapor water, while water moved to deeper soil layers under the effect of gravity. The asphalt froze earlier than the soil, and a large amount of heat was stored in the roadbed. During freezing, the liquid water content of soil layers under the asphalt pavement was approximately 6.85%-12.34% higher than that of the soil layers under the original pavement. Water conditions in winter advanced thawing, as well as the increment in water content in the following year, resulting in an increase in water content and ground temperature during the cold season. Hydrothermal accumulation shows long-term effects.

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