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Research Paper

Thermal accumulation mechanism of asphalt pavement in permafrost regions of the Qinghai–Tibet Plateau

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HIGHLIGHTS

- Analyze the radiation and energy balance characteristic of asphalt pavement.
- Discuss the heat storage of subgrade from the heat transmission.
- Systems analyzed the thermal accumulation mechanism of asphalt pavement.

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ABSTRACT

This paper monitors and calculates the hydrothermal data in an "atmospheric–pavement structure–permafrost" system of an asphalt pavement from 2010 to 2014 and compares the data with that observed from an adjacent natural surface system. Asphalt pavements have small albedo and low transfer coefficients, showing an increase in shortwave absorption and a decrease in heat dissipation. In comparison with the natural ground, the asphalt pavement absorb an additional 17.07 MJ/m^2 of shortwave radiation and 10.97 MJ/m^2 of longwave radiation, while the monthly upward shortwave, latent heat, and sensible heat were less than 5.46, 19.7, and 30.5 MJ/m^2, respectively. According to the theory of energy balance, the heat absorption of an asphalt pavement was 8.56 times greater than that the natural surface, leading to the water–heat change in the subgrade. Given the horizontal and vertical movements of water in the subgrade, a high aquifer formed under pavement with depth of 10–30 cm and average volume moisture content of 22–26% with vapor–water phase transition. The increase of moisture in the subgrade promotes heat accumulation in the soil. As results, the average ground temperature increased by 0.32 °C/a in an asphalt pavement structure and could reach 0.8 °C/a near the permafrost table. Pavement properties, pavement-surface radiation and energy balance, and subgrade's water–heat accumulation generally constitute the thermal accumulation mechanism of asphalt pavement in cold regions.

1. Introduction

Asphalt pavements are widely used as the surface layer of paved roads in cold regions. Asphalt pavement surface with high absorptivity to solar radiation; the heat absorption of asphalt pavement also affects its base and sub-base, as well as the subgrade [1]. The intensity of heat absorption can increase to nearly 30% at the center of the subgrade [2], descending the artificial permafrost table gradually and thawing the ground ice in the subgrade. As a results, temperature increase and moisture change are different in pavement structure and subgrade [3,4]. Variations of water and heat in the subgrade have caused numerous permafrost engineering problems [5,6], such as pavement cracking, subgrade collapse, and roadbed deformation [7]. Thermal accumulation mechanism of the asphalt pavement is closely related to service performance of road engineering and the thermal stability of permafrost subgrade [8].

The increase in asphalt pavement temperature is closely related to its heat absorption. The shortwave radiation absorption at the surface of an asphalt pavement is between 0.85 and 0.95 [9–11], depending on the age and filler of the asphalt surface layer [12,13]. Sensible heat (H) and infrared radiation are considered primary heat sources [14]. Asphalt pavement affects the humidity and

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moisture transfer between air and soil, and the latent heat (λE) flux above asphalt pavement is smaller than that of natural surface [15]. In 1996, a pioneered observation of radiation and energy balance above an asphalt pavement on the Qinghai–Tibet Plateau (QTP), founded that the heat storage of asphalt pavement structure was two to four times of that under the adjacent natural surface [16]. However, data series covered few months only. Further research shows that the asphalt pavement not only absorbs a great amount of solar radiation but also negates both latent heat and sensible heat (H) discharge [17]. This pattern of heat absorption and heat dissipation increases the average annual temperature at the bottom of the asphalt pavement, which is slightly higher than that of the surface layer [18]. In addition, asphalt pavement affected water exchange between the roadbed and atmosphere [19] for the reason that warming permafrost in the subgrade releases unfrozen water, which has no way to go due to the sealing effect of the asphalt layer [20,21], and simultaneously shows a long-term thermal effect [22]. Therefore, the heat absorption mechanism of asphalt pavement should be analyzed considering the "atmosphere–pavement structure–permafrost" system.

This study conducted an in-situ observation of atmospheric, radiation, energy balance, and hydrothermal changes of an asphalt pavement in the Beiluhe permafrost region in the QTP. On the basis of the monitoring data, we explained the heat source of the asphalt pavement from radiation and energy balance. Then, we illustrated the hydrothermal changes in the pavement structure under the influence of meteorological factors, demonstrating the water–heat transfer and accumulation in permafrost subgrade. Finally, explained the thermal accumulation mechanism of the asphalt pavement in the atmosphere–pavement structure–permafrost system.

2. Data and method

2.1. Monitoring site

The in situ observation site (92.92°E and 34.82°N, latitude 4628–4633 m) is a predominantly continuous permafrost region in QTP. The mean annual air temperature changes from −3.58 °C to −2.79 °C, and annual rainfall in the region is 355 mm to 566 mm. The test subgrade is 13 m-width and 3.0 m-height. The asphalt surface layer is 0.09 m-thick, including a 0.04 m AC-13 fine grain-modified asphalt mixture and a 0.05 m AC-16-modified asphalt mixture laid below. The nearby weather station, at the Beiluhe permafrost station, (34.85°N and 92.93°E) was established in an open area without anthropocentric disturbance and with coarse grained soil covered [23].

2.2. Data measurements and calculation

Observation data is divided into three parts: meteorological elements, hydrothermal monitoring in the pavement structure (0–50 cm depth below ground), and subgrade. On the basis of the heat input–radiation–conduction in pavement structure and hydrothermal changes in the subgrade, we analyze the formation mechanism of asphalt pavement thermal effects. The data gathered were from September 2009 to December 2014.

2.2.1. Meteorological elements

Observations include precipitation, wind speed, air temperature and humidity, and air barometric pressure. They were tested using QMR102, 010C/034B, HMP45C, and CS100 probes, the resolutions of which were ±1%, 0.11 m/s, ±1%, ±1.5 mb, respectively (Table 1). Radiant flux includes downward shortwave radiation (DR), upward shortwave radiation (UR), upward longwave radiation (ULR), and downward longwave radiation (DLR). The downward heat flux heats up the earth surface, whereas upward heat flux escapes to the sky with some fraction being absorbed by the atmosphere. These radiant fluxes were tested using NR-01 with a resolution of 15 W/m^2. The instruments were placed three levels above asphalt pavement and two levels above natural surface (Fig. 1).

Table 1
Parameters of the experimental observation instruments.

Observation component	Instrument Model	Resolution	Manufacturer
Wind speed	010C/034B	0.11 m/s	Met One Company
Temperature, humidity	HMP45C	±1%	Vaisala Company
Barometric pressure	CS100	±1.5 mb	Setra Company
Radiation	NR-01	15 W m^{-2}	Campbell Company
Ground surface temperature	SI-111	±0.2 °C	Apogee Company
Ground temperature		±0.05 °C	SKLFSE
Water content	CS616	0.1% VMC	EKO Company
Soil heat flux	HFP01SC-10	±3%	Hukseflux Company
Precipitation	QMR102	±1%	Vaisala Company

Characteristics of radiation and energy balance analysis are shown in Eqs. (1) and (2). Energy transfer (H, λE, transfer coefficients) was calculated using the observed wind speed, barometric pressure, humidity and using the aerodynamic method [17]. Compared with the natural ground, asphalt pavement endothermic and thermal storage was elaborated.

$$Rn = (\mathrm{DLR} - \mathrm{ULR}) + (\mathrm{DR} - \mathrm{UR}) \quad (1)$$

$$Rn = H + \lambda E + G \quad (2)$$

where Rn (W/m^2) is the net radiation; DLR, ULR, DR, UR stand for downward longwave radiation, upward long-wave radiation, downward shortwave radiation, and upward shortwave radiation, respectively; H (W/m^2) is sensible heat flux; λE is the latent heat flux; and G (W/m^2) is the heat storage, expressed by soil heat flux at difference depth. Data were gathered from September 2012 to December 2014.

2.2.2. Hydrothermal characteristics in the pavement structure

The calculated depth at the surface is zero. The observations include water and temperature at 0, 5, 10, 15, 20, 30, and 50 cm depth; soil heat flux (G) at 5 cm and 15 cm depth under roadbed center; Middle position of roadbed center and the sunny road shoulder, and the sunny road shoulder position under asphalt pavement (Fig. 2). Surface temperature measurements were tested by SI-111 infrared probe with a resolution of ±0.2 °C, 50 cm above ground level. The ground temperature was tested by thermistor, made by the State Key Laboratory of Frozen Soil Engineering (SKLFSE) with a resolution of ±0.05 °C. Water was tested by CS616 probe with are solution of 0.1% VMC. Soil heat flux was tested by HFP01SC-10 probe with a resolution of ±3%. From the relationship among precipitation, water, and temperature in pavement structure, hydrothermal change process in pavement structure and its impact on the underlying permafrost were analyzed.

2.2.3. Hydrothermal process in permafrost subgrade

Water observation was located in roadbed center, the sunny road shoulder position, and middle position of roadbed center and the sunny road shoulder under asphalt pavement, whereas temperature observation was located under the roadbed center, the sunny road shoulder position, shady shoulder position, sunny and shady subgrade position. The observation depth ranged from 0.5 m to 4 m (Fig. 2). The freezing–thawing and hydrothermal processes were studied using water and temperature data. Ground