Cold Regions Science and Technology 103 (2014) 57–62

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Automatically melting snow on airport cement concrete pavement with carbon fiber grille

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ARTICLE INFO

Article history:
Received 29 July 2013
Accepted 23 March 2014
Available online 31 March 2014

Keywords:
Melting snow
Airport cement concrete pavement
Carbon fiber grille
Temperature distribution
Energy distribution
Three-dimensional infrared ray temperature

ABSTRACT

In this paper, the method of melting snow with carbon fiber grille buried in airport pavement is presented to avoid the adverse effects of snow-melting chemicals on the structure, function, environment and safety. The outdoor snow-melting experiment of airport cement concrete pavement is conducted when the snow is heavy and the air temperature is from −3 °C to −1 °C. Electrical power is supplied to the airport pavement through the use of carbon fiber grille. It is shown that, with an input power of 350 W/m^2, the temperature of pavement surface can achieve an increment of 4.63 °C and the 2.7 cm thick snow can be melted within 2 h, which is just for melting snow at this condition. After the heating stopped, the residual heat can melt snow on the pavement in real time when the temperature of pavement surface is kept above 0 °C. The temperature and energy distribution along the depth of pavement are analyzed at different times. The findings indicate that the method of melting snow on airport pavement with carbon fiber grille is feasible in the snowy weather condition.

1. Introduction

Snow, ice and slush on airport cement concrete pavement significantly impact aircraft landing, taxiing and takeoff safety in winter because snow, ice and slush reduce the friction coefficient between the tire and the surface of airport pavement, which not only hinders the transportation of people and goods but also threatens people's lives and properties (Zhao et al., 2010). The traditional method of pavement snow removal with snow-melting chemicals or machine induces flight delay and needs a large number of manpower, chemicals and machine, which is labor intensive and time-consuming. The use of snow-melting chemicals also leads to some adverse effects on the structure, function and environment (Wang et al., 2006): damage to concrete pavement (e.g., steer bar corrosion and surface scaling), corrosion of drainage system and destruction of the soil ecological environment (Kayama et al., 2003; Thunqvist, 2004).

It is necessary to conduct timely and high-efficient removal of snow and avoid the adverse effects of snow-melting chemicals on airport pavement. Some other pavement snow-melting methods have been researched, such as infrared heat lamps (Zenewitz, 1977), electric heating cables (Henderson, 1963), electrically conductive concrete (Tuan and Yehia, 2004; Xie and Beaudoin, 1995; Zhang et al., 2011), hydronic heating system (Lee et al., 1984; Liu and Spitler, 2004a, 2004b; Liu et al., 2006a, 2006b; Miró, 2012) and carbon fiber heating wires (Zhao et al., 2010, 2011).

The current research of melting snow mainly focuses on electrically conductive concrete. To attain high electrical conductivity, concrete must contain a certain amount of electrically conductive components, such as steel shaving, steel fibers, graphite product, carbon fibers and nickel particle (Hou et al., 2002; Tuan, 2004, 2008; Tuan and Yehia, 2004; Xie and Beaudoin, 1995; Yehia and Tuan, 1998, 1999; Yehia et al., 2000; Zhang et al., 2011). However, the research and application of electrically conductive concrete mainly focus on bridge deck and highway pavement, which can't meet the requirements of airport pavement. In addition, the electric resistivity of the conductive concrete varies with time, which is inconvenient for the control.

Some studies have demonstrated the experimental tests, design and numerical simulations for snow-melting using hydronic heating system (Liu and Spitler, 2004a, 2004b; Liu et al., 2006a, 2006b). The use of embedding hydronic heating system in airport pavement has been limited to relatively small surface area comprising aircraft parking slots and has not been applied to larger area such as runway. This study has identified three international airports in Scandinavia that use heating sections of outdoor pavement: Oslo-Gardermoen, Stockholm-Arlanda and Helsinki-Vantaa (Miró, 2012). In all three cases, the heat is applied to the pavement by means of hydronic system connected to the district heating system. Although the hydronic heating system is capable of melting snow on airport pavement to some extent, its construction is complex and the snow-melting performance is delayed to heat the circulating liquid.

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http://dx.doi.org/10.1016/j.coldregions.2014.03.008
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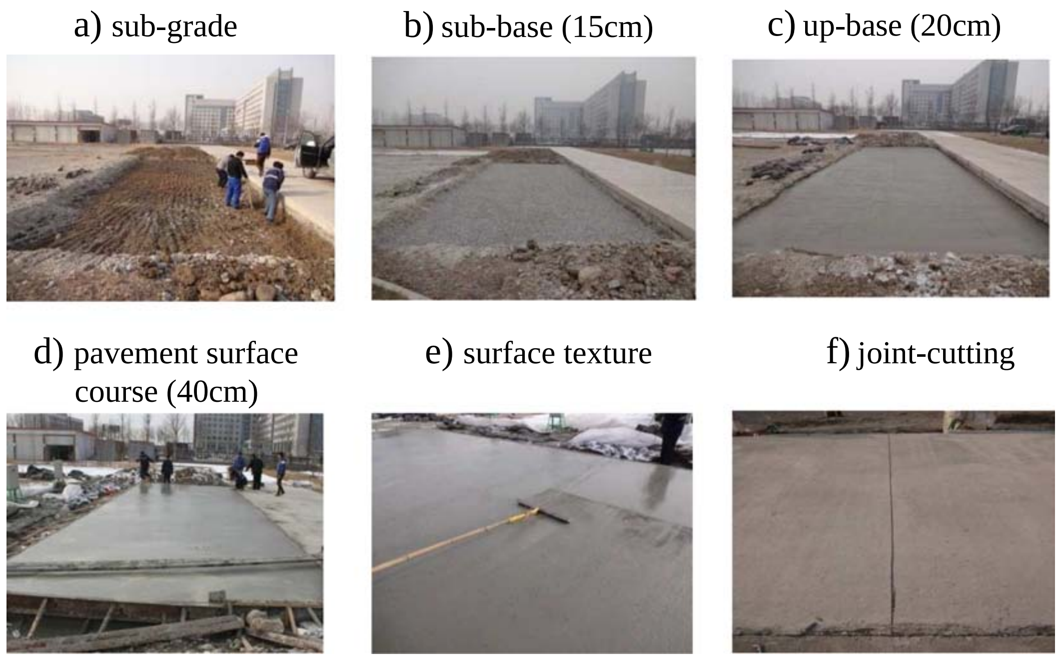

Fig. 1. Airport cement concrete pavement construction.

In recent years, Zhao et al. (2010, 2011) conducted a systematic study on bridge deck and pavement snow-melting by embedding carbon fiber heating wires in concrete. In different climatic conditions, the results showed that the method can meet the requirement of bridge deck and pavement snow-melting with different input powers. However, the snow-melting method with carbon fiber heating wires requires further study on the application of airport pavement. The selection of snow-melting method and technologies depends highly on the geographic, economical, environmental and safe factors of practical projects. Therefore, melting snow on airport cement concrete pavement with carbon fiber grille is proposed.

This paper studies the method of melting snow on airport pavement in which carbon fiber grille is buried. Carbon fiber grille is made of steel mesh and carbon fiber heating wires which have high tensile strength and good electric-thermal properties. In addition, steel mesh can reinforce the airport pavement. In the case of input power, the temperature of airport pavement surface maintains above the freezing temperature in order to prevent snow accumulation. Finally, the full-scale snow-melting experiments are performed in outdoor environment.

2. Experiment

2.1. Airport pavement design and construction

The design and construction of airport cement concrete pavement was conducted according to specifications for Cement Concrete Pavement Design for Civil Airports and technical specifications for Construction of Cement Concrete Pavement for Airfield Area of Civil Airports. The airport pavement was cast by using commercial concrete whose flexural strength is more than 5.75 MPa at an age of 28 days. Fig. 1 has shown that the structural layer combination includes sub-grade, sub-base, up-base and cement concrete pavement surface course. The surface texture and joint-cutting are also shown in Fig. 1. The size of each pavement is 4.6 m × 4.6 m × 0.4 m. The resistance thermometer sensors were placed along the concrete pavement depth at 0 m, 0.5 m, 0.1 m, 0.2 m, 0.3 m and 0.4 m, respectively. The carbon fiber grille was located 5 cm below the pavement surface. The carbon fiber grille was made of steel mesh and 48 k carbon fiber heating wires that were a given spacing at 10 cm.

2.2. Experimental equipment

The required experimental equipment mainly includes AC voltage regulator, resistance thermometer sensor, field data acquisition, data adapter and infrared thermal imager. The measurement range of the resistance thermometer sensor is −50–153 °C; the accuracy of the resistance thermometer sensor is 0.1 °C. The field data acquisition was used to collect temperature signal, which was connected to the data adapter. The temperature data obtained by monitoring system could automatically store in the computer system.

3. Results and discussion

The heating requirement for snow-melting depends on rate of snowfall, air temperature, wind velocity and relative humidity. The snow-melting system must first melt the snow and then evaporate the resulting water film. The rate of snowfall determines the heat required to warm the snow to 0 °C and to melt it. The evaporation rate

Table 1
Climatic data, input power, snow-melting time and power consumption.

Precipitation (mm)	Wind scale	Air temperature (°C)	Heat flux (W/m^2)	Snow melting time (h)	Power consumption (kWh/m^2)	Pavement surface temperature before heating (°C)	Pavement surface temperature after heating (°C)	Date
2.06	1–2	−1.8–−1.2	350	2.0	0.70	−1.2	3.4	3 Feb.
1.10	1	−3.8–−3.4	300	1.5	0.45	−1.0	2.3	20 Jan.
1.00	2–3	−2.5–−1.0	250	2.0	0.50	−2.1	2.6	1 Feb.
0.40	1	−3.5–−3.1	200	1.75	0.35	−0.6	2.9	30 Jan.

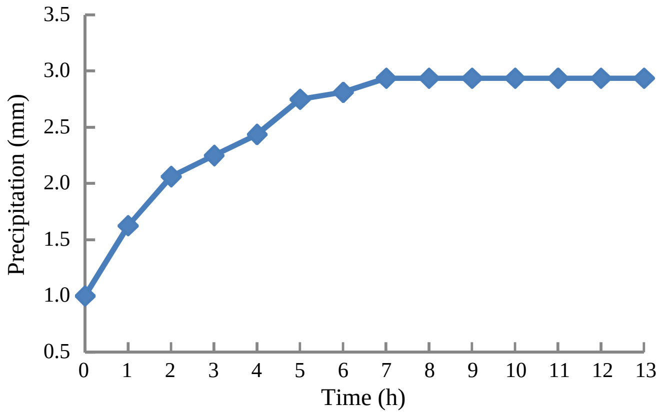

Fig. 2. Relationship between precipitation and time.

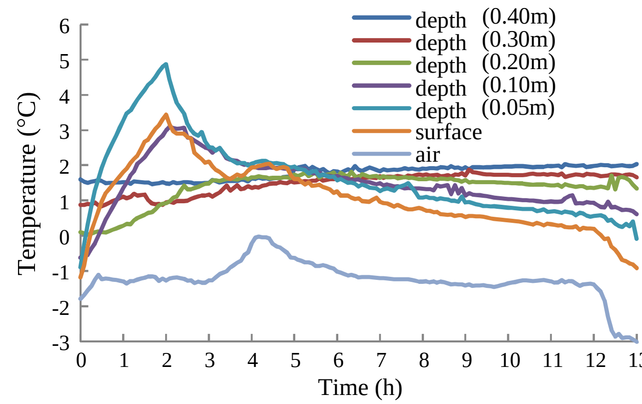

Fig. 4. Temperature variation with time.

of the melted snow from the pavement is affected by the wind speed and by the difference in vapor pressure between the air and the melted snow (ASHRAE Handbook, 1995).

3.1. Melting snow

The relevant information about the snow-melting experiment is given in Table 1. The heat flux was designed according to actual weather condition and ASHRAE handbook. In these experiments, no radiation occurred because of weather condition.

The snowfall time was from 7:00 to 16:00 on 3rd February 2013 in Beijing. The snow-melting experiment about airport cement concrete pavement was tested from 9:00 to 22:00. The heating time was from 9:00 to 11:00. The relative humidity was 80%–92%. It can be seen in Fig. 2 that the total precipitation of snow is from 1.0 mm to 2.9 mm when the test time is in 7 h, and then the snow stops. Fig. 3 shows that the wind velocity varies between 0.8 m/s and 1.8 m/s. The heat flux of airport pavement is 350 W/m^2 according to the actual input power, the area of pavement and the heating time.

Fig. 4 shows that the average temperatures of air and different pavement depths are measured against time. The airport pavement was heated for 2 h, and then the electric power was turned off because the accumulated snow was completely melted. In this experiment, the air temperature was between −3 °C and −1 °C in outdoor environment. The snow began melting when the average temperature on pavement surface rose above freezing temperature in 0.25 h. The average temperature is the average value of temperature measurement at different locations but at the same depth. The average temperature of pavement surface rose by 4.63 °C in 2 h. The average temperatures at the depths of 0.05 m, 0.10 m and 0.20 m rose by 5.76 °C, 3.63 °C and 0.82 °C in 2 h, respectively. The average temperatures at the depths of 0.30 m and 0.40 m almost had no change in 2 h. It is found that the influence of heating on the temperature in pavement becomes small when the location is away from the grille. The average temperatures of pavement surface and at the depths of 0.05 m and 0.10 m decreased significantly when the heating stopped. The average temperatures at the depths of 0.20 m, 0.30 m and 0.40 m changed a little when the heating stopped. The snow could be melted in real time when the test time was from 2 h to 7 h. Although the snow was falling and the electric power was turned off, the pavement realized the goal of snow free when the test time was from 2 h to 7 h.

Fig. 5 shows the temperature distributions along the depth of pavement at initial time, 2 h and 12 h. It can be seen that, by increasing the depth of pavement, the temperature increases by 6.94 °C/m and 4.83 °C/m at initial time and 12 h, respectively. The peak temperature location of pavement is at the depth of 0.05 m in 2 h. The temperature of pavement surface decreases to 0 °C in 12 h.

The snow-melting process of airport pavement is shown in Fig. 6. As shown in Fig. 6, the 2.7 cm thick snow whose precipitation is 2.06 mm can be completely melted in 2 h. In this paper, the criterion for evaluating the snow-melting performance is snow free area ratio, which is the ratio of the snow free surface area to the total surface area. The snow free area ratios are 0, 0.05, 0.7 and 1.0 at initial time, 1 h, 1.5 h and 2 h, respectively. Nine sensors are installed on the pavement surface for monitoring the temperature distributions as shown in Fig. 7. Fig. 8 shows the temperature on pavement surface. It can be seen in Fig. 8 that the maximum temperature difference on pavement surface is 0.5 °C, 2.0 °C and 0.4 °C at initial time, 2 h and 12 h, respectively. It can meet the uniform temperature requirement of melting snow when the maximum temperature difference on pavement surface is 2 °C.

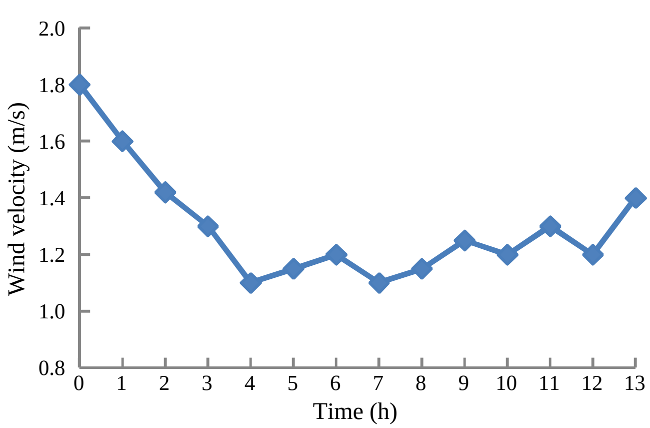

Fig. 3. Relationship between wind velocity and time.

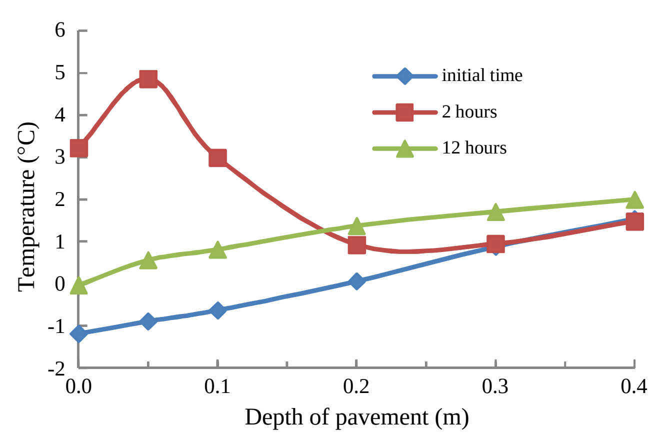

Fig. 5. Temperature distribution along the depth of pavement.

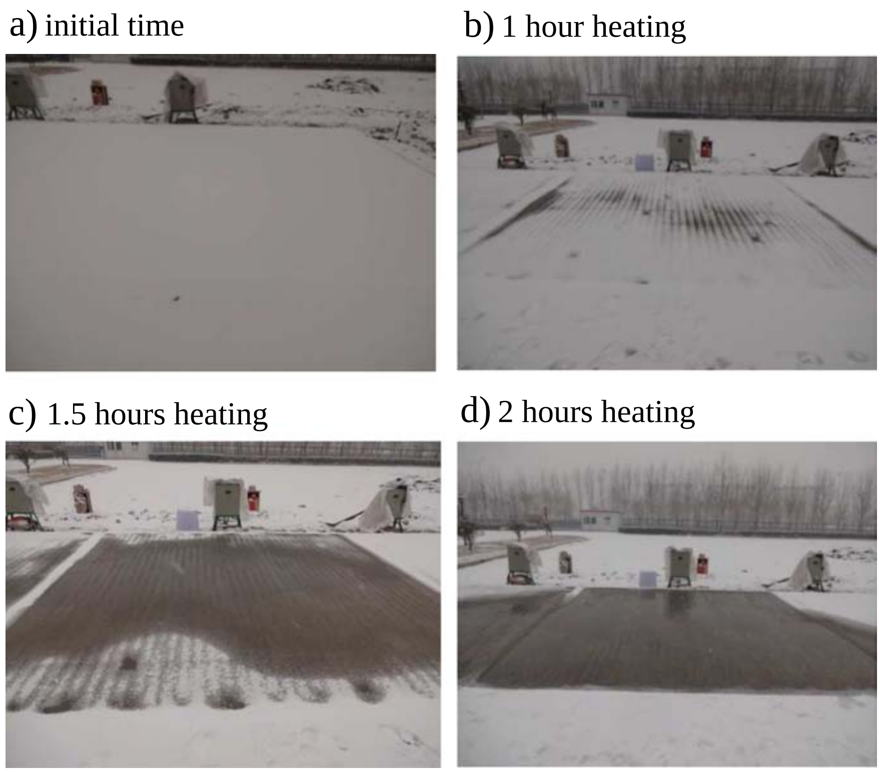

Fig. 6. Melting snow on airport cement concrete pavement.

Fig. 9 shows the three-dimensional infrared ray (3D-IR) temperature of airport pavement. The 3D-IR temperature is obtained from the surface of pavement and snow. The 3D-IR temperature is from −7.4 °C to −4.7 °C at initial time, and the average temperature is −5.9 °C. The proportion of temperature that is between −7 °C and −5 °C accounts for 99%. The 3D-IR temperature is from −5.3 °C to 1.3 °C at 2 h, and the average temperature is −1.6 °C; the proportion of temperature that is between −3 °C and 0 °C accounts for 95%. These indicate that the snow on pavement surface has been melted when its temperature reaches the freezing temperature. The maximum 3D-IR temperature difference is large relatively because of the uneven surface of snow and the different distance between the pavement and the infrared thermal imager.

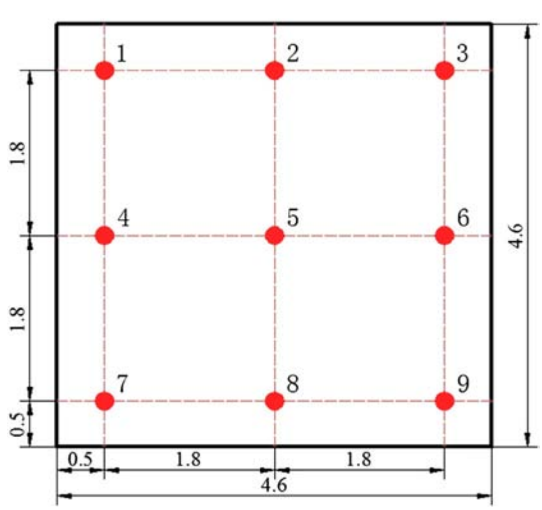

Fig. 7. Sensor locations on airport pavement surface.

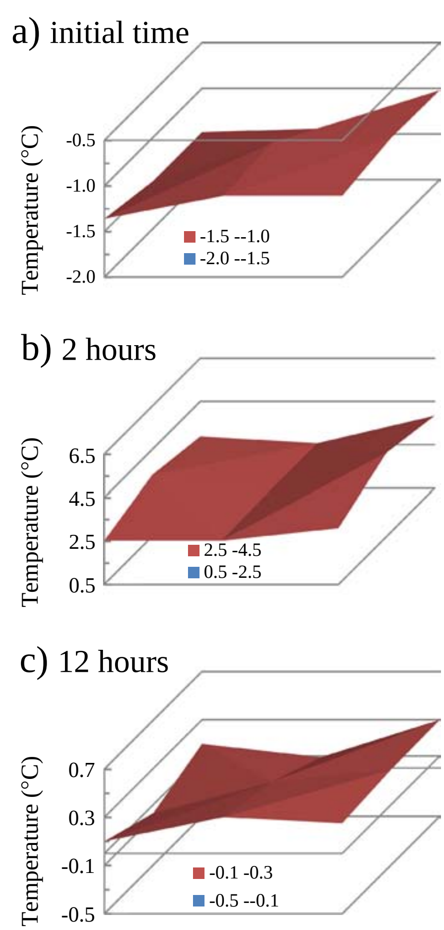

Fig. 8. Temperature on airport pavement surface.

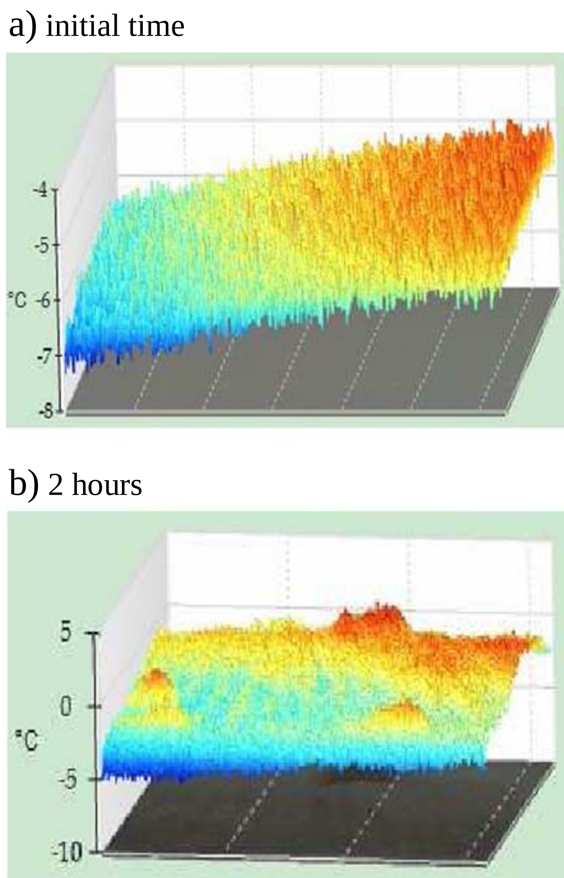

Fig. 9. 3D-IR temperature of airport pavement.

3.2. Energy distribution of airport pavement

Compared with the initial time, Fig. 10 shows the temperature increase along the depth of pavement at 2 h and 12 h. The thermal properties of airport cement concrete pavement and fresh snow are presented in Table 2. The parameters of snow on airport pavement are listed in Table 3.

The heat absorbed by airport pavement can be expressed as

$$Q_c = \int_0^{0.4} C_c \rho_c T(x) dx \tag{1}$$

where Q_c is the per-meter-squared power increase of pavement, C_c is the heat capacity of pavement, ρ_c is the density of pavement, and $T(x)$

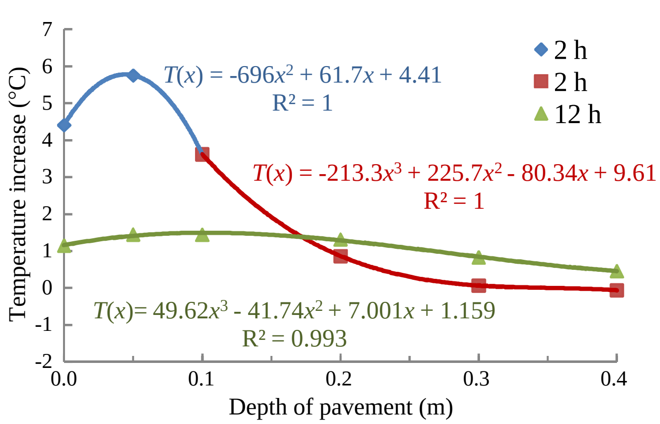

Fig. 10. Temperature increase along the depth of pavement.

Table 2
Thermal properties of concrete and snow.

Materials	Density ($kg \cdot m^{-3}$)	Heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Latent heat ($kJ \cdot kg^{-1}$)
Concrete	2500	920	–
Fresh snow	100	2090	333.5

is the temperature increase as a function of the depth of pavement when the time is certain.

The power of snow-melting can be expressed as

$$Q_s = C_s M_s \Delta T + q_s M_s \tag{2}$$

where Q_s is the per-meter-squared power of snow-melting, C_s is the heat capacity of snow, ΔT is the temperature increase of snow-melting, q_s is the latent heat of snow, and M_s is the per-meter-squared snow weight.

The proportions of pavement power and snow-melting power can be expressed by Eqs. (3) and (4), respectively:

$$\eta_c = \frac{Q_c}{Q} \tag{3}$$

$$\eta_s = \frac{Q_s}{Q} \tag{4}$$

where η_c is the proportion of pavement power, η_s is the proportion of snow-melting power, and Q is the total power.

The proportions of per-meter-square pavement power and snow-melting power are presented in Table 4. At the heating stage of 2 h, the proportions of pavement power and snow-melting power are 68.7% and 27.9%, respectively; the total heat loss is 3.4% in 2 h. The proportions of pavement power and snow-melting power are 40.9% and 12.2% when the time period is 2–12 h, respectively. Therefore, the proportions of snow-melting power and total heat loss are 40.1% and 19.0% in 12 h. It can be seen in Table 4 that the main heat is used to melt snow and heat airport pavement.

4. Conclusions

Melting snow on airport pavement with carbon fiber grille was researched in this paper. The design and construction of airport pavement is reasonable, which the carbon fiber grille is located 5 cm below the pavement surface and the interval of heating wires is 10 cm. From the limited experiments, a snow-melting input power of 200–350 W/m^2 is required according to the snowy weather condition in Beijing. The validity of the proposed method of snow-melting with carbon fiber grille has been verified with the results of field full-scale experiments.

In the process of snow-melting, most of the energy is used to melt snow and heat airport pavement, the system inherently creates a non-linear temperature gradient within the pavement. Whether the temperature stresses are large enough to induce a thermal expansion which widens existing cracks in the pavement and accelerates corrosion of the reinforcing mesh is still a question that needs to be researched. The further researches include: the influence of the carbon fiber grille on the function of the structure and the bond between the reinforcing

Table 3
Parameters of snow on airport pavement.

Time period (h)	Precipitation (mm)	Per-meter-squared snow weight (kg/m^2)	Temperature increase (°C)
0–2	2.06	2.06	4.3
2–12	0.88	0.88	4.3

Table 4
Proportions of power.

Time period (h)	Power increase of pavement (kJ/m^2)	Power of snow melting (kJ/m^2)	Total power (kJ/m^2)	Proportion of pavement power (%)	Proportion of snow melting power (%)
0–2	1.73×10^3	7.04×10^2	2.52×10^3	68.7	27.9
2–12	1.03×10^3	3.06×10^2	2.52×10^3	40.9	12.2

steel and the concrete; the field experiments of snow free all the time; the influence of the electromagnetic field on the aircraft navigation; and the application in practical engineering.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (Grant No. 51208018), Science and Technology Project of CAAC (MHRD201225) and Beijing Nova Program (Z121110002512090).

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