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The influence of heat flux on melting ice on concrete pavement with carbon fibre heating wire

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Abstract. In this paper, the method of melting ice with carbon fibre heating wire (CFHW) buried in concrete pavement is presented to avoid the adverse effects of snow-melting chemicals. The melting ice effect, pavement temperature and energy distribution are analysed. It is shown that, with the air temperature of -5℃ and 0.4 m/s wind speed, the time of melting 6.5 mm thick ice on pavement is 8.17 hours, 5.5 hours, 4.25 hours and 3.33 hours when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The pavement temperature can be divided into three stages at the depth of 0.5 cm, including temperature rising process, constant temperature process and rapid temperature increase process. The greater the heat flux, the less the time it takes to melt ice, the lower the total energy needed to melt ice. This work is important for choosing how much heat flux to melt ice.

1. Introduction

Ice on concrete pavement significantly impacts aircraft landing and vehicle running in winter because ice reduces the friction coefficient between the tire and the pavement surface. The traditional method of pavement ice removal with snow-melting chemicals or machine induces traffic delay and needs a large number of manpower, chemicals and machine, which is labor intensive and time-consuming. It is necessary to conduct timely and high-efficient removal of ice and avoid the adverse effects of snow-melting chemicals on concrete pavement. Some other pavement deicing methods have been researched, such as hydronic heating system [1-4], electrically conductive concrete [5-7] and CFHW [8-10]. The current research of melting ice mainly focuses on CFHW. Zhao et al. studied pavement and bridge deck deicing with CFHW [9, 10]. In different climatic conditions, the results showed that the method can meet the requirement of melting ice on bridge deck and pavement with different input energy. The heat flux is an important factor of melting ice effect. However, the influence of heat flux on melting ice on concrete pavement is less studied. Therefore, the method of melting ice with CFHW requires further study on the application of pavement. It needs a systematic study on the influence of heat flux on melting ice on concrete pavement.

2. Experiment

2.1. Materials

The raw materials include cement, fine aggregate, coarse aggregate, water and CFHW. The cement is Ordinary Portland Cement 42.5. The fine aggregate is natural sand with fineness modulus of 2.85. The

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mixed water is tap water. The heating material is 24k CFHW. The amount of cement is 325 kg/m^3. The ratio of water to cement is 0.42. The sand ratio is 0.29.

2.2. Experiment program

The size of concrete pavement is 60 cm×60 cm×30 cm. Except for the upper surface of pavement, the remaining five surfaces have 5 cm thick polystyrene boards for thermal insulation. As shown in figure 1, the 24k CFHW is located 5 cm below the pavement surface. The CFHW spacing is 10 cm. The concrete pavement is cured for 28 days in natural environment. The depths of six temperature sensors vertically embedded in pavement are 0.5 cm, 5 cm, 10 cm, 15 cm, 20 cm and 30 cm, respectively. The temperature sensors are located in the middle of CFHW. The freezer is used to simulate outdoor weather in winter. The average air temperature is -5℃ in the freezer. The relative humidity is 85%. The solar radiation intensity is 0 W/m^2. The wind speed is 0.4 m/s. Before test, the pavement is placed to constant temperature in the freezer, and 6 mm precipitation water is frozen into 6.5 mm thick ice on the pavement surface.

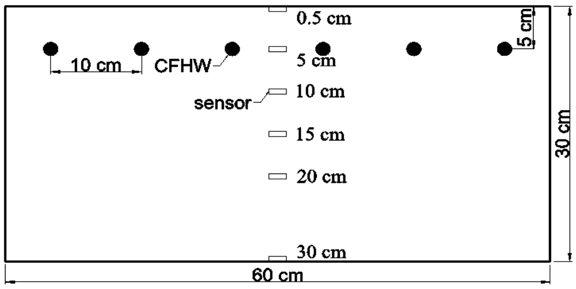


Figure 1. Temperature sensors layout scheme for pavement.

3. Results and discussion

In the experiment, the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively.

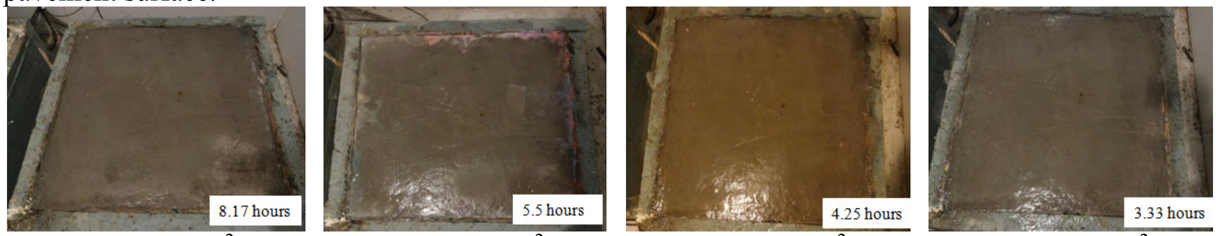
3.1. Melting ice and pavement temperature

The process of melting ice on concrete pavement is shown in figure 2 and figure 3. When the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, the initial melting time at the bottom of the ice is 2.83 hours, 1.67 hours, 1.33 hours and 1.17 hours, respectively. The total melting time of the ice is 8.17 hours, 5.5 hours, 4.25 hours and 3.33 hours, respectively.

(a) 300 W/m^2 (b) 400 W/m^2 (c) 500 W/m^2 (d) 600 W/m^2

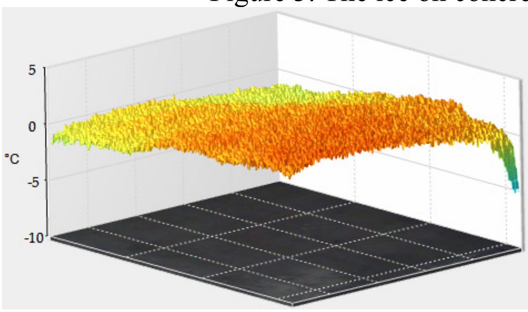
Figure 2. The ice on concrete pavement begins to melt.

The temperature of pavement surface is measured by using an infrared thermal imager at the end of melting ice. Figure 4 shows the temperature of pavement surface when all ice is melted. The temperature of pavement surface is from -1.8℃ to 2.3℃ at 8.17 hours when the heat flux is 300 W/m^2. The temperature of pavement surface is from -1.9℃ to 2.4℃ at 5.5 hours when the heat flux is 400 W/m^2. The temperature of pavement surface is from -2.2℃ to 2.5℃ at 4.25 hours when the heat flux is 500 W/m^2. The temperature of pavement surface is from -2.6℃ to 3.2℃ at 3.33 hours when the heat flux is 600 W/m^2. The average temperature of pavement surface is 0.5℃, 0.3℃, 0.2℃ and 0.1℃ when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The greater the heat flux, the greater the temperature difference of pavement surface, but the lower the average temperature of pavement surface.

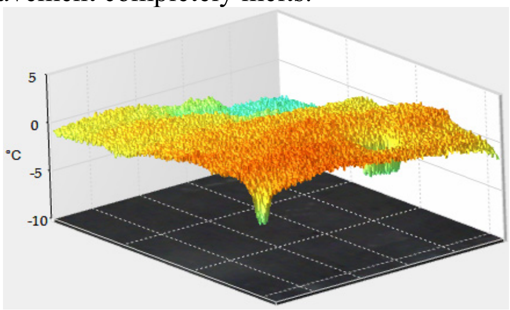


(a) 300 W/m^2 (b) 400 W/m^2 (c) 500 W/m^2 (d) 600 W/m^2

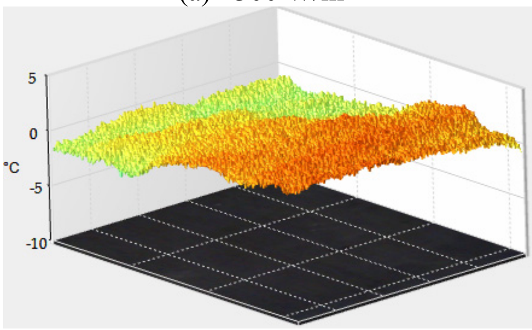
Figure 3. The ice on concrete pavement completely melts.



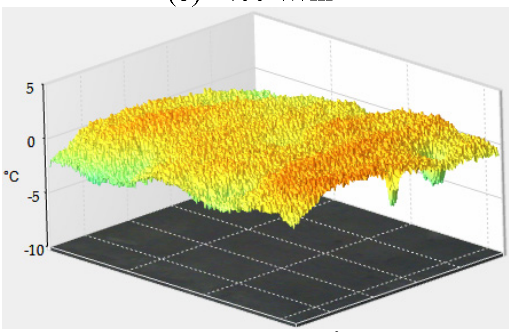
(a) 300 W/m^2



(b) 400 W/m^2



(c) 500 W/m^2



(d) 600 W/m^2

Figure 4. The temperature of pavement surface when all ice is melted

The relationship between the pavement temperature and time at different depths of concrete pavement is shown in figure 5. The pavement temperature is measured by using six temperature sensors. The pavement temperature increases with the heating time when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The greater the heat flux, the greater the pavement temperature at the same heating time. As shown in figure 5(a), the pavement temperature can be divided into three stages at the depth of 0.5 cm. The first stage is the temperature rising process. At the initial stage of the heating system operation, the upper region of the pavement is subjected to a heat flow from the bottom to the top, and the pavement temperature gradually increases. The pavement temperature is less than 0.5°C in the first stage. The second stage is the constant temperature process. With the continuous operation of the heating system, the pavement surface temperature reaches the melting point of the ice. Since the melting process of the ice is a phase change process, a large amount of latent heat is required to be consumed. Therefore, the temperature near the pavement surface remains substantially constant. The pavement temperature range is from 0.5℃ to 2℃ in the second stage. The third stage is the rapid temperature increase process. The pavement is directly in contact with the atmosphere after melting ice in the middle of the pavement. Under the action of the heating system, the pavement temperature rises rapidly until the ice on the edge of the pavement is completely melted. The temperature is more than 2°C in the third stage.

The pavement temperature is basically the same at initial time of heating. In the process of melting ice, the pavement temperature at the depth of 5 cm is shown in figure 5(b). The pavement temperature increases by 8.89℃, 9.37℃, 10.03℃ and 10.37℃ when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The pavement temperature at the depth of 15 cm is shown in figure 5(c). The pavement temperature increases by 6.66℃, 6.33℃, 6.30℃ and 6.19℃ when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The pavement temperature at the depth of 30 cm is shown in figure 5(d). The pavement temperature increases by 5.51℃, 3.99℃, 3.46℃ and 2.75℃ when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. As shown in figure 5(b) ~ (d), the temperature of pavement below the embedded CFHW increases with the heating time in the process of melting ice. As the depth of the pavement increases, the temperature tends to be consistent at the same location when the heat flux is from 300 W/m^2 to 600 W/m^2.

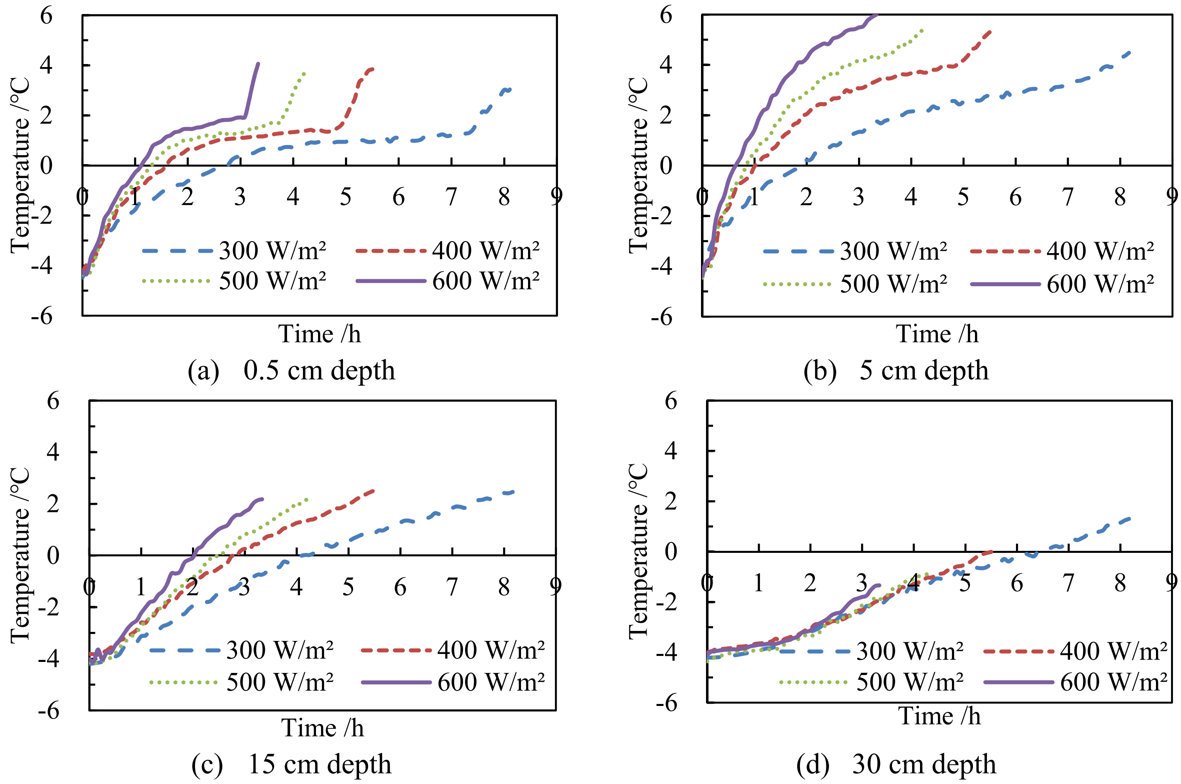


Figure 5. Pavement temperature variation with time.

3.2. Energy distribution

At the end of melting ice, the temperature increases along the depth of pavement is shown in figure 6 when the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, respectively. The temperature increase is the temperature difference of pavement between the beginning of heating and the end of melting ice. The temperature increase is basically the same when the depth is from 12 cm to 14 cm. The greater the heat flux, the greater the temperature increase of the pavement where the depth is less than 12cm. Conversely, the greater the heat flux, the lower the temperature increase of the pavement where the depth is more than 14 cm.

When the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, the temperature increase can be expressed by equations (1), (2), (3) and (4), respectively. The heat absorbed by concrete pavement can be expressed by equation (5). The per-meter-squared energy of ice can be expressed by equation (6).

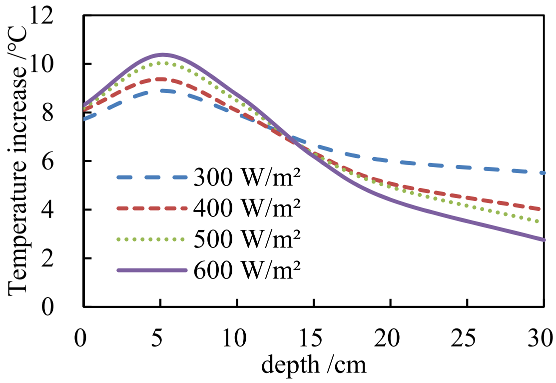


Figure 6. Temperature increases along the depth of pavement.

$$T(x_1) = -6\times10^{-5} x_1^4 + 4.3\times10^{-3} x_1^3 - 9.62\times10^{-2} x_1^2 + 6.157\times10^{-1} x_1 + 7.7198 \quad (1)$$

$$T(x_2) = -6\times10^{-5} x_2^4 + 4.5\times10^{-3} x_2^3 - 1.067\times10^{-1} x_2^2 + 6.782\times10^{-1} x_2 + 8.1126 \quad (2)$$

$$T(x_3) = -9\times10^{-5} x_3^4 + 6.4\times10^{-3} x_3^3 - 1.484\times10^{-1} x_3^2 + 9.613\times10^{-1} x_3 + 8.1896 \quad (3)$$

$$T(x_4) = -9\times10^{-5} x_4^4 + 6.5\times10^{-3} x_4^3 - 1.563\times10^{-1} x_4^2 + 1.0469 x_4 + 8.2986 \quad (4)$$

$$Q(x) = \int_0^{30} \frac{C\rho T(x)}{100} \mathrm{d}x \quad (5)$$

$$Q_i = C_i M_i \Delta T + M_i q_i \quad (6)$$

Where $Q(x)$ is the per-meter-squared energy increase of pavement, C is the heat capacity of pavement, ρ is the density of pavement, x is the depth of pavement, $T(x)$ is the temperature increase as a function of the depth of pavement, Q_i is the per-meter-squared energy of melting ice, C_i is the specific heat capacity of ice, M_i is the per-meter-squared weight of ice, ΔT is the temperature increase of ice, q_i is the latent heat of ice.

Table 1. Parameters of the concrete and ice.

Materials	Density (kg m^{-3})	Weight (kg m^{-2})	Specific heat capacity (J kg^{-1} K^{-1})	Latent heat (kJ kg^{-1})	Temperature increase of ice (K)
Concrete	2500	---	920	---	---
Ice	917	6	2100	333.5	5

Table 2. Energy and proportions of energy.

Heat flux (W m^{-2})	Energy increase of pavement (kJ m^{-2})	Energy of melting ice (kJ m^{-2})	Total input energy (kJ m^{-2})	Proportion of pavement energy (%)	Proportion of melting ice energy (%)
300	5.106×10^3	2.064×10^3	2.450×10^4	20.8	8.4
400	4.782×10^3	2.064×10^3	2.200×10^4	21.7	9.4
500	4.629×10^3	2.064×10^3	2.125×10^4	21.8	9.7
600	4.421×10^3	2.064×10^3	2.000×10^4	22.1	10.3

The parameters of concrete and ice are presented in table 1. The energy increase of pavement and energy of melting ice are calculated by equations (5) and (6), respectively. The energy increase of pavement, energy of melting ice and total input energy are presented in table 2. When the heat flux is from 300 W/m^2 to 600 W/m^2, the energy increase of pavement decreases from 5.106×10^3 kJ/m^2 to 4.421×10^3 kJ/m^2 at the end of melting ice. The total input energy decreases from 2.45×10^4 kJ/m^2 to 2×10^4 kJ/m^2. The proportion of pavement energy increases from 20.8% to 22.1%. The proportion of melting ice energy increases from 8.4% to 10.3%. The proportion of heat loss decreases from 70.8% to 67.6%. Therefore, only a small amount of energy is used for melting ice. Most of the energy is lost.

4. Summary

The method of melting ice with CFHW embedded in concrete pavement is effective when the heat flux is from 300 W/m^2 to 600 W/m^2. The average air temperature is -5℃. The wind speed is 0.4 m/s. When the heat flux is 300 W/m^2, 400 W/m^2, 500 W/m^2 and 600 W/m^2, the time of melting 6.5 mm thick ice on concrete pavement is 8.17 hours, 5.5 hours, 4.25 hours and 3.33 hours, respectively; at the end of melting ice, the average temperature of the pavement surface is 0.5℃, 0.3℃, 0.2℃ and 0.1℃, respectively. The greater the heat flux, the greater the temperature difference on the pavement surface at the end of melting ice. The pavement temperature at a depth of 0.5 cm can be divided into three stages, including temperature rising process, constant temperature process and rapid temperature increase process. As the depth of the pavement increases, the pavement temperature tends to be consistent at the same location. The greater the heat flux, the less the time it takes to melt ice, the lower the total energy needs to melt ice. When the heat flux is from 300 W/m^2 to 600 W/m^2, the proportion of pavement energy increases from 20.8% to 22.1%, and the proportion of melting ice energy increases from 8.4% to 10.3%. Improving the heat flux can effectively reduce the total energy consumption of melting ice. The heat flux is an important parameter affecting melting ice. It needs comprehensive consideration in the design of melting ice engineering.

Acknowledgments
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