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Research Article

Influencing Factors of Snow Melting and Deicing on Carbon Fiber Embedded in Bridge Decks

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To study the general law of the influence of embedded carbon fiber heating wires on the melting of snow and ice on bridge decks and to solve the problem of icing on large bridges in winter, relevant model tests were carried out. In this experiment, a carbon fiber heating wire was used as the heat source to make a large-scale asphalt concrete bridge deck model with a built-in carbon fiber heating wire. The effect of different heating powers, ambient temperatures, snow and ice thicknesses, and wind levels on the melting of snow and ice on bridge decks was studied. The snow-melting and ice-melting tests performed at different heating powers show that as the heating power increases within a certain range, the time required for the snow and ice layers to melt and the power consumption decrease. Under certain conditions, to ensure the rapid melting of snow and ice layers on the surface of road bridges, a heating power of 400 W/m^2 is selected. At this time, the heating effect is the best, and this method is economical and practical. The snow-melting and ice-melting tests performed at different ambient temperatures and with different thicknesses of the snow and ice layers show that as the ambient temperature decreases or the thickness of the ice layer increases within a certain range while keeping the other factors constant, the time required for the snow to melt and the power consumption increase, and the power consumption is relatively large. The snow-melting test performed at different wind levels shows that with the increase in the wind level within a certain range while keeping the other factors constant, the uniformity of the overall temperature distribution on the surface of the specimen worsens, the snow-melting time increases, and the temperature rises. The rate of temperature increase decreases. Therefore, in actual engineering applications, when the wind speed is too high, the methods of manually or mechanically removing snow can increase the snow removal rate on bridge decks. Under different conditions, choosing the right heating power can effectively improve the efficiency of melting snow and ice on bridge decks. The research results of this paper provide a theoretical reference for the actual construction of bridge decks in the future.

1. Introduction

As the elevated part of a bridge is suspended in the air, cold wind blows on the bridge from all directions, which causes the heat of the bridge body to be lost in all directions [1], making bridge decks prone to icing in winter and causing accidents. According to statistics, approximately 40,000 people die in traffic accidents caused by bridge icing every year in China [2]. It is particularly important to solve the problem of icing on bridge pavement.

At present, the methods of melting snow and ice on bridge decks are mainly divided into two categories: passive deicing methods and active deicing methods. Passive deicing methods mainly include artificial methods, mechanical methods, and deicing agent methods. The manual method [3] cannot be applied in a large area due to the high labor cost and low removal efficiency. The mechanical method will cause a certain degree of damage to the bridge deck due to its high gravity, and due to the subsequent maintenance cost being high, it cannot be widely used [4]. In addition, the use of snow-melting agents causes irreversible damage to the environment, buildings, and vegetation, so it is not vigorously promoted for use [5]. On the other hand, the active deicing method mainly includes the thermal melting method, and the electric heating method in the thermal melting method uses a heating cable as a heating element.

The method involves heat exchange between the surface and ice and snow [6–8]. Compared with the passive deicing method, the heating cable heating system has the advantages of no pollution, convenient construction, and remote control, so it has been widely studied. Yanfeng Li [9] et al. studied the selection of carbon fiber heating wires, the depth of burial, and the spacing of heating wires. They studied road surface changes through carbon fiber melting of snow and ice combined with finite element analysis. The results showed that the external climatic conditions (especially temperature) are the main factors of the snow-melting effect of heating cables. Hongming Zhao [10] et al. studied the influence of different spacings of heating wires on the surface temperature characteristics of concrete slabs through finite element modeling and studied the relationship between the input power and temperature rise of concrete slabs through indoor temperature rise experiments on concrete slabs. The results showed that under certain conditions that used a carbon fiber heating plate surface, the average temperature was above 0°C, and the temperature distribution met the requirements of uniform snow and ice melting. Bu Yin [11] et al. analyzed the heat dissipation of a carbon fiber heating bridge deck and studied the utilization and loss mechanism of the heat generated by carbon fiber heating wire. The results showed that convective heat transfer and latent heat affect the heat dissipation of carbon fiber heating bridge decks. In this method, temperature has the greatest effect on melting snow and ice on carbon fiber-heated bridge decks, followed by wind speed, and ice thickness has the least effect. Bai Bing [12] et al. developed a theoretical model describing their cotransport. The results showed that temperature and Darcy velocity have a negligible effect on the transport of individual HMs and that the recovery ratio of Cd2+ is higher than that of Pb2+. And it established a coupled thermo-hydro-mechanical mechanism in view of the soil particle rearrangement for saturated/unsaturated soils under the framework of granular thermodynamics. The deduced generalized phase stresses differ from the classical effective principle based on linear elastic porous media and can automatically consider the impact of the stress path, temperature path, and soil structure [13].

Iftekar Gull [14] et al. investigated the effect of mechanical depolymerization of carbon fibers in a mixture of methylcellulose and sodium dodecylbenzene sulfonate water on the dispersion of carbon fibers in self-compacting concrete (SCC) as a way to improve the properties of concrete. Sherif A. Yehia [15] et al. performed a thermoelectric-coupled finite element analysis to study the Joule heating of a conductive concrete overlay [16–18]. Quantao Liu [19] et al. concluded that induction heating can improve the self-healing rate of asphalt mastic and porous asphalt concrete. This method has the advantages of a wide range of material sources and simple preparation [20,21]. The current disadvantage is that the mechanical and electrical properties of the researched conductive concrete cannot be well balanced, and its high price makes its use difficult in a wide range of applications. Abubakar Gambo Mohammed [22] et al. investigated a novel resistance heating method for deicing and snow melting. Three different forms of carbon fiber were embedded in concrete samples, and their heating properties were tested. To simulate the condition of concrete exposed to low temperature, an environmental chamber was used to study the effect of various parameters such as thermal power density, ambient temperature, heating plate installation depth, concrete humidity, and carbon fiber form on temperature variation. The test results show that the carbon fiber electric heating method can effectively remove the icing and snow problems of the road. Yong Lai [23,24] et al. proposed a method for snow melting with carbon fiber grilles buried in airport sidewalks. At −3°C to −1°C, power is supplied to the airport sidewalk by using carbon fiber grille. The results show that when the input power is 350 W/m^2, the maximum road surface temperature can reach 4.63 °C, and the 2.7 cm-thick snow can be melted within 2 h.

Li et al. [25] takes the airpot pavement as the background to explore the law of temperature rise. Li et al. [26] conducted an experimental study on the efect of melting snow and ice on the bridge deck with carbon fiber heating wires. Analysis shows that carbon fiber is a new high-performance fiber-reinforced material, and its performance is excellent, with high strength, high modulus, high-temperature resistance, friction resistance, fatigue and creep resistance, and many other excellent properties, so it can provide a viable solution for melting snow and ice on bridge decks. Therefore, in this paper, we choose a 24 K carbon fiber heating line as the heat source and make a large asphalt concrete bridge deck model with a built-in carbon fiber heating line to study the effects of different heating powers, ambient temperatures, snow and ice thicknesses, and wind levels on the melting of snow and ice on the bridge deck to provide a reference for future applications in melting snow and ice on actual bridges.

2. Materials and Methods

2.1. Model. This test mainly explores the rate of temperature increase of a bridge deck and the melting of snow and ice, so the stress and load-bearing capacity of the specimens are not considered. The asphalt concrete specimens are shown in Tables 1–3 for each surface layer type.

The test specimens are 50 cm long, 50 cm wide, and 30 cm high. From top to bottom, they are a 4 cm thick AC-13 upper layer, 6 cm thick AC-20 lower layer, and 20 cm thick cement concrete pavement. The carbon fiber heating wire is pre-embedded inside the specimen and is distributed in a "U" shape 11 cm from the surface of the model. And the Keysight temperature recorder is used to read the surface temperature of the sample. To reduce heat loss, a 3 cm thick XPS board is pasted on the bottom and four sides of the mold for thermal insulation. The three-dimensional model of the asphalt concrete specimen is shown in Figure 1, and the cross-sectional view is shown in Figure 2. The Keysight temperature recorder is shown in Figure 3.

2.2. Experiment Material. As a new type of high-performance fiber material for reinforcement, carbon fiber has excellent performance and properties, such as high strength,

Table 1: C30 concrete mix ratio (kg).

Material	Water	Cement	Gravel	Pebble	Admixture
Quality	8.75	23.05	25.6	62.6	0

Table 2: AC-20 asphalt concrete mix ratio (kg).

Particle size (mm)	15~20	10~15	5~10	3~5	0~3
Quality	24	22	21	4	26

Table 3: AC-13 asphalt concrete mix ratio (kg).

Particle size (mm)	10~15	5~10	0~3
Quality	60	8	13

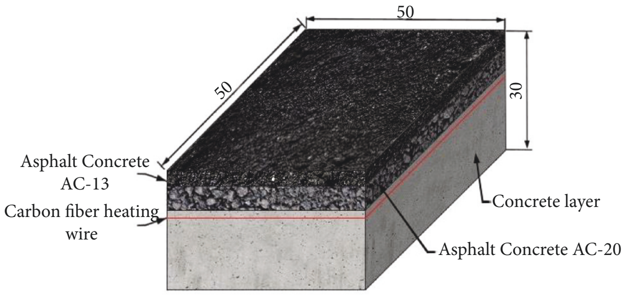

Figure 1: Three-dimensional model of an asphalt concrete specimen (cm).

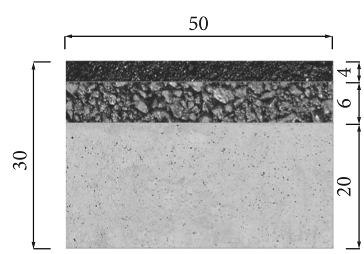

Figure 2: Cross-sectional view of an asphalt concrete specimen (cm).

high modulus, high-temperature resistance, friction resistance, fatigue and creep resistance, and many other excellent properties. The experiment uses 24K carbon fiber heating wire products, each of which has a total length of 12 m and is evenly arranged in the model in a "U" shape, and the adjacent spacing is 10 cm. The total length embedded in the specimen is 5 m, and the length exposed to the air is 7 m. The resistance of the heating wire is 17 Ω/m, the maximum voltage in the laboratory is 220 V, and the maximum heating power applied to the model is 400 W/m^2. Similarly, when the voltages are 180 V and 200 V, the corresponding heating powers are 260 W/m^2 and 320 W/m^2. The layout of the carbon fiber heating wire is shown in Figure 4.

2.3. Test Conditions. The test is mainly divided into two parts: the snow-melting test and the ice-melting test. In the snow-melting test and deicing test, snow and ice are spread

Figure 3: Keysight temperature recorder.

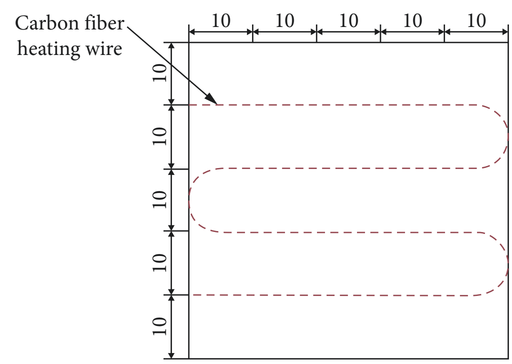

Figure 4: Layout of the heating wire (unit: cm).

on the surface of the test specimen in advance, and then, the power is turned on to heat the model when the thickness of the ice and snow required by the working condition is reached to carry out the test. The general rules of the influence of different heating powers, ambient temperatures, snow and ice thicknesses, and wind powers on the melting of snow and ice on bridge decks are studied. The four working conditions of the snow-melting test are shown in Table 4, and the two working conditions of the deicing test are shown in Table 5.

3. Results and Discussion

3.1. Research on the Influencing Factors of the Snow-Melting Test

3.1.1. Heating Power. The set working conditions are an initial ambient temperature of −3°C, Class 0 wind, and a snow thickness of 2 cm, and the effects of three different heating powers of 260 W/m^2, 320 W/m^2, and 400 W/m^2 on the time required for snow melting and power consumption influence are explored. The surface temperature change curve of the specimen at different powers is shown in Figure 5.

Figure 5 shows that when the heating power is 400 W/m^2 and the heating time is 0.49 h, the surface temperature of the test specimen can reach 0°C; at this time, the snow starts to melt. When it is heated for 1.83 h, the surface snow melts completely. At this time, the temperature is 4.43°C, and the total power consumption is 0.73 kW h/m^2. When the heating powers are 320 W/m^2 and 260 W/m^2, the surface temperature can reach 0°C after the heating time exceeds 1.01 h and

Table 4: Snow-melting test conditions.

Group class	Heating power (W/m^2)	Environmental temperature (°C)	Wind rating	Snow thickness (cm)
A	260 320 400	−3	0	2
B	400	−3 −6 −9	0	4
C	400	−3	0	2 4 6
D	400	−3	0 1 2	4

Table 5: Deicing test conditions.

Group class	Heating power (W/m^2)	Environmental temperature (°C)	Wind rating	Ice thickness (mm)
A	260 320 400	−3	0	5
B	400	−3	0	5 10 15

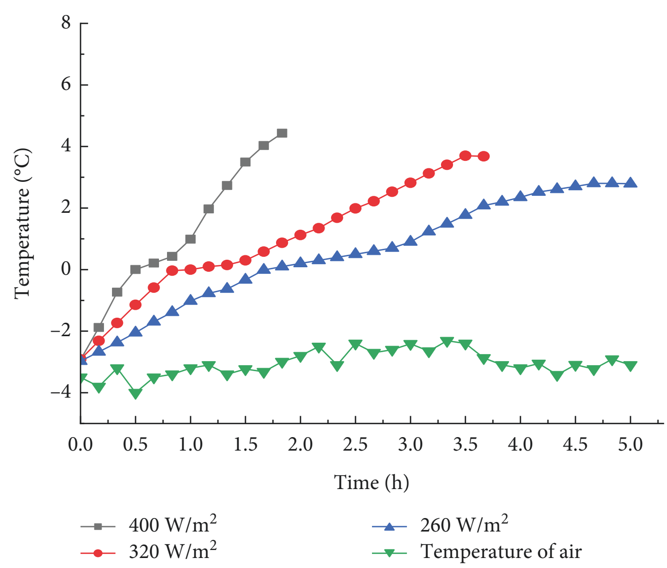

Figure 5: Curve of the surface temperature change of the test specimen under different powers.

2.03 h, respectively. The snow began to melt at this time. When heating for 3.67 h and 5.0 h, the surface snow can be melted. At this time, the temperatures are 3.68 °C and 2.79 °C, and the total power consumptions are 1.17 kW h/m^2 and 1.3 kW h/m^2, respectively.

In the snow-melting tests at the three powers, when the heating power is changed from 260 W/m^2 to 320 W/m^2, the time for complete snow melting is shortened by 1.33 h, and the power consumption is approximately 10% less than that in the case of 260 W/m^2. When the heating power is changed from 260 W/m^2 to 400 W/m^2, the time to completely melt the snow is reduced by 3.17 h, and the power consumption is reduced by 43.8% compared with that of the case of 260 W/m^2.

The rates of the surface temperature increase of the specimen at different powers are shown in Table 6. Comparing the rates of temperature increase under the three working conditions within 0~1.83 h shows that at 260 W/m^2, when the surface temperature of the test specimen increases from −2.972°C to −0.100°C, the rate of temperature increase is 1.760 °C/h. At 320 W/m^2, when the surface temperature of the specimen increases from −2.913°C to 0.872°C, the rate of temperature increase is 2.143 °C/h. At 400 W/m^2, the surface

Table 6: Rates of the surface temperature increase of the test specimen at different powers.

Heating power (W/m^2)	Initial ambient temperature (°C)	Average temperature when heating for 1.83 h (°C)	Rate of temperature increase (°C/h)
260	−2.972	0.100	1.679
320	−2.913	0.872	2.068
400	−2.931	4.432	4.023

temperature of the specimen increases from −2.931°C to 4.432°C, and the rate of temperature increase is 4.023 °C/h.

In summary, at heating powers of 260 W/m^2 and 320 W/m^2, the rate of temperature increase is close and far less than the rate of temperature increase at 400 W/m^2. Combining the snow-melting time and power consumption analyses at different powers shows that under the conditions of an initial ambient temperature of −3°C, a wind level of 0, and a snow thickness of 2 cm, to ensure that the snow on the road bridge surface melts quickly without inconveniencing travel, a heating power of 400 W/m^2 is selected to heat the road surface. At this time, the heating effect is the best, and it is economical and practical.

3.1.2. Environmental Temperature. The set working conditions are a heating power of 400 W/m^2, Class 0 wind, and a snow thickness of 4 cm, and the influence of three different ambient temperatures of −3°C, −6°C, and −9°C on the time required for snow melting and power consumption are explored. The surface temperature change curve of the test specimens is shown in Figure 6.

Figure 6 shows that when the ambient temperature is −3°C and the heating time is 1.27 h, the surface temperature of the test specimen can reach 0°C; at this time, the snow starts to melt. When heated for 2.93 h, the surface snow melts completely. At this time, the temperature is 4.89°C, and the total power consumption is 1.17 kW h/m^2. When the ambient temperatures are −6°C and −9°C and the heating times exceed 2.13 h and 3.15 h, respectively, the surface temperature reaches above 0°C, and the snow begins to melt at this time. When heating for 4.27 h and 5.33 h, the surface snow melts completely. At this time, the temperatures are 4.68 °C and 4.93 °C, respectively, and the total power consumptions are 1.71 kW h/m^2 and 2.13 kW h/m^2, respectively.

In the snow-melting tests at three different initial ambient temperatures, when the initial ambient temperature changes from −3°C to −6°C, the time to completely melt the snow will increase by 1.34 h, and the power consumption will increase by approximately 46.1% compared with that of the case of −3°C. When the initial ambient temperature changes from −3°C to −9°C, the time to completely melt the snow will increase by 2.40 h, and the power consumption will increase by 82.1% compared with that of the case of −3°C.

The rate of temperature increase of the specimen surface at different initial ambient temperatures is shown in Table 7. Comparing the rates of temperature increase under the three working conditions within 0~2.93 h shows that at an initial ambient temperature of −3°C, when the surface temperature of the test specimen increases from −3.130°C to 4.891°C, the rate of temperature increase is 2.738 °C/h. At an initial

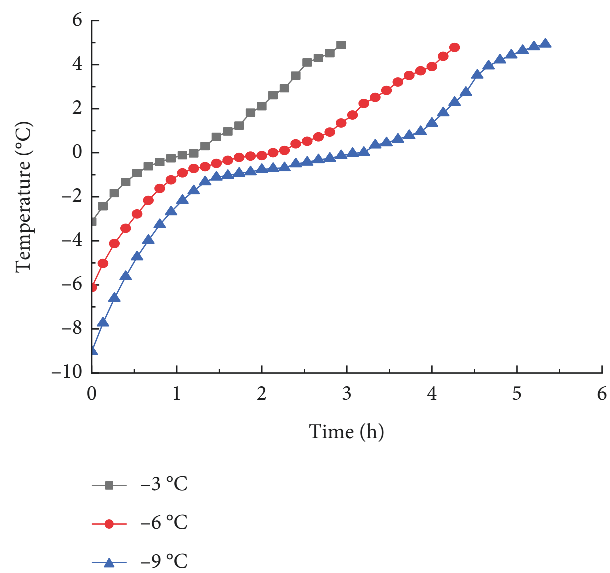

Figure 6: Temperature change curve of the surface of the test specimen at different ambient temperatures.

ambient temperature of −6°C, when the surface temperature of the specimen increases from −6.121°C to 1.352°C, the rate of temperature increase is 2.551 °C/h. At an initial ambient temperature of −9°C, the surface temperature of the specimen increases from −9.023°C to −0.136°C, and the rate of temperature increase is 3.126 °C/h.

In summary, at initial ambient temperatures of −3°C and −6°C, the rates of temperature increase are close to and less than the rate of temperature increase under the −9°C operating condition. Combining the snow-melting time and power consumption analyses at different initial ambient temperatures shows that as the initial ambient temperature decreases within a certain range while keeping the other factors constant, the time required for snow melting and the power consumption increase and the loss increases.

3.1.3. Snow Thickness. The working conditions are a heating power of 400 W/m^2, Class 0 wind, and an ambient temperature of −3°C, and the effects of three different snow thicknesses of 2 cm, 4 cm, and 6 cm on the time required for snow melting and power consumption are explored. The curve of the surface temperature of the test specimens with different snow thicknesses is shown in Figure 7.

Figure 7 shows that when the thickness of the snow cover is 2 cm, the surface temperature of the test specimen reaches 0°C when heated for 0.49 h, and the snow starts to melt. When heated for 1.87 h, the surface snow melts completely. The hourly temperature is 4.432°C, and the total power

Table 7: Rates of the temperature increase of the specimen surface at different initial ambient temperatures.

Heating power (W/m^2)	Initial ambient temperature (°C)	Average temperature when heating for 2.93 h (°C)	Rate of temperature increase (°C/h)
	−3.130	4.891	2.738
400	−6.121	1.352	2.551
	−9.023	-0.136	3.126

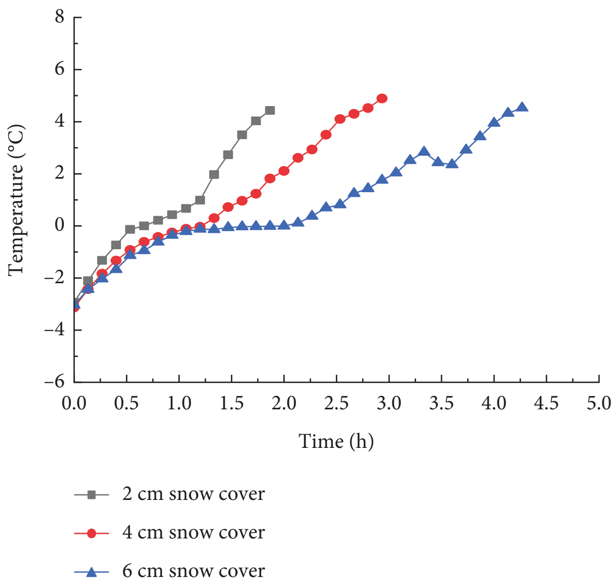

Figure 7: Curves of surface temperature changes of specimens with different snow thicknesses.

consumption is 0.73 kW h/m^2. When the snow thicknesses are 4 cm and 6 cm, the heating time exceeds 1.27 h. After 2.01 h, the surface temperature reaches above 0°C. Now, the snow begins to melt. When heating for 2.93 h and 4.27 h, the surface snow melts. At this time, the temperatures are 4.891 °C and 4.531 °C, and the total power consumptions are 0.17 kW h/m^2 and 1.71 kW h/m^2, respectively.

In the snow-melting tests with three different snow thicknesses, when the snow thickness is increased from 2 cm to 4 cm, the time for complete snow-melting increases by 1.06 h, and the power consumption increases by approximately 60.3% compared with that of the case where the snow thickness is 2 cm. When the snow thickness is increased from 2 cm to 6 cm, the time to completely melt the snow increases by 2.40 h, and the power consumption increases by 134.2% compared with that of the case where the snow thickness is 2 cm.

The rates of surface temperature increase of the test specimen with different snow thicknesses are shown in Table 8. Comparing the rates of temperature increase under the three working conditions within 0~1.87 h shows that when the snow thickness is 2 cm, the surface temperature of the test specimen changes from −2.931°C to 4.432°C, and the rate of temperature increase is 3.937 °C/h. When the snow thickness is 4 cm and the surface temperature of the specimen increases from −3.131°C to 1.821°C, the rate of temperature increase is 2.648 °C/h. When the snow thickness is 6 cm, the surface temperature of the specimen increases from −3.031°C to −0.015°C, and the rate of temperature increase is 1.629 °C/h.

In summary, under certain conditions, as the thickness of the snow increases, the rate of temperature increase decreases. The analyses of snow-melting time and power consumption with different snow thicknesses show that other factors remain unchanged in specific actual projects. With the increase in snow thickness within a certain range, the time required to melt snow and the power consumption increase, and the power consumption is relatively large.

3.1.4. Wind Rating. The set working conditions are a heating power of 400 W/m^2, an ambient temperature of −3°C, and a snow thickness of 4 cm to explore three wind levels: class 0 (0 m/s), class 1 (1.35 m/s), and class 2 (2.74 m/s). The impact of different wind levels on the time required for snow melting and power consumption is investigated. The surface temperature change curve of the specimen is shown in Figure 8.

Figure 8 shows that when the wind power level is class 0 and the surface temperature of the specimen reaches 0°C when heated for 1.27 h, the snow begins to melt. When heated for 2.93 h, the surface snow is completely melted. The hourly temperature is 4.891°C, and the total power consumption is 1.17 kW h/m^2. When the wind power levels are level 1 and level 2, the surface temperature reaches above 0°C after the heating times exceed 1.49 h and 1.93 h, respectively, and the snow begins to melt. When heating for 3.47 h and 5.20 h, the surface snow melts. At this time, the temperatures are 4.502 °C and 4.835 °C and the total power consumptions are 1.39 kW h/m^2 and 2.08 kW h/m^2, respectively.

In the snow-melting test with three different wind levels, when the wind level changes from level 0 to level 1, the time to completely melt the snow increases by 0.54 h, and the power consumption increases by approximately 18.8% compared with that of the case where the wind level is level 0. When the level is changed from level 0 to level 2, the time to completely melt the snow will increase by 0.91 h, and the power consumption will increase by 77.8% compared with that of the case where the wind level is level 0.

The rate of temperature increase of the specimen surface at different wind levels is shown in Table 9. Comparing the rate of temperature increase under the three working conditions within 0~2.93 h shows that in the working condition with a wind power rating of 0, when the surface temperature of the specimen increases from −3.131°C to 4.891°C, the rate of temperature increase is 2.738 °C/h. In the working condition with a wind power level of 1, when the surface temperature of the test specimen increases from −3.021°C to 3.684°C, the rate of temperature increase is 2.288 °C/h. In the working condition with a wind power level of 2,

Table 8: Rates of the temperature increase of the specimen surface with different snow thicknesses.

Snow thickness (cm)	Initial ambient temperature (°C)	Average temperature when heating for 1.87 h (°C)	Rates of temperature increase (°C/h)
2	−2.931	4.432	3.937
4	−3.131	1.821	2.648
6	−3.031	−0.015	1.629

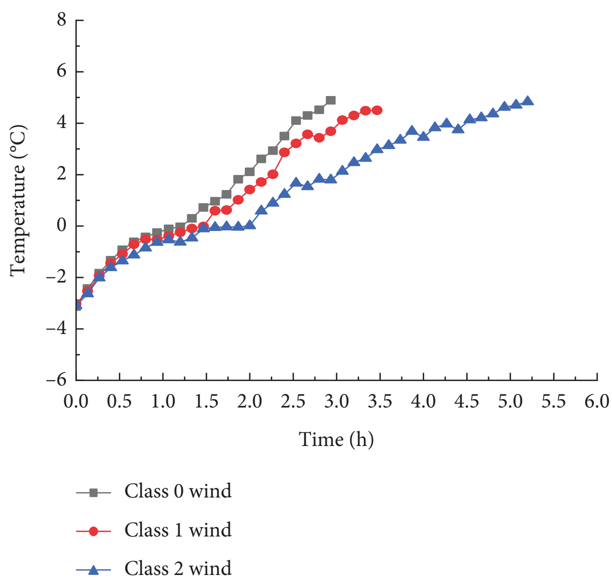

Figure 8: Curve of the surface temperature of the specimen with different wind levels.

when the surface temperature of the specimen increases from −3.094°C to 1.798°C, the rate of temperature increase is 1.670 °C/h.

In summary, when keeping the other factors constant, as the wind level increases within a certain range, the uniformity of the overall temperature distribution on the surface of the specimen worsens, and the snow-melting time increases. In addition, the rate of temperature increase decreases. Therefore, when the wind speed is too high in actual engineering applications, the methods of manually or mechanically removing snow increase the rate of snow removal from bridge decks.

3.2. Research on Influencing Factors of the Deicing Test

3.2.1. Heating Power. The research method in this section is the same as the snow-melting process. Working conditions are set as an initial ambient temperature of −3°C, a wind power level of 0, and an ice thickness of 5 cm to explore the melting time and power consumption with three different heating powers of 260 W/m^2, 320 W/m^2, and 400 W/m^2 and deicing impact. The surface temperature change curve of the specimen at different powers is shown in Figure 9.

Figure 9 shows that when the heating power is 400 W/m^2 and the heating time is 0.67 h, the surface temperature of the test specimen can reach 0°C; at this time, the ice layer begins to melt. When it is heated for 2.33 h, the surface ice layer is melted. At this time, the temperature is 3.32°C and the total power consumption is 0.93 kW h/m^2. When the heating powers are 320 W/m^2 and 260 W/m^2, the surface temperature can reach 0°C after the heating times exceed 1.17 h and 2.01 h, respectively, and the ice begins to melt at this time. When heating for 3.83 h and 5.5 h, the surface ice layer melts. At this time, the temperatures are 3.14 °C and 2.58 °C and the total power consumptions are 1.23 kW h/m^2 and 1.43 kW h/m^2, respectively.

In the ice-melting tests at the three powers, when the heating power is increased from 260 W/m^2 to 320 W/m^2, the time for the complete melting of the ice layer is shortened by 1.67 h, and the power consumption is approximately 14.0% less than that in the case of 260 W/m^2. When the heating power is increased from 260 W/m^2 to 400 W/m^2, the time to completely melt the ice layer is shortened by 3.17 h, and the power consumption is reduced by 35.0% compared with that of the case of 260 W/m^2.

The rate of temperature increase of the specimen surface at different powers is shown in Table 10. Comparing the rates of temperature increase under the three working conditions within 0~2.33 h shows that at 260 W/m^2, when the surface temperature of the specimen increases from −2.931 °C to 0.199 °C, the rate of temperature increase is 1.357 °C/h. At 320 W/m^2, when the surface temperature of the specimen increases from −2.973 °C to 1.134 °C, the rate of temperature increase is 1.763 °C/h. At 400 W/m^2, the surface temperature of the specimen increases from −2.962°C to 3.321°C, and the rate of temperature increase is 2.683 °C/h.

In summary, at heating powers of 260 W/m^2 and 320 W/m^2, the rates of temperature increase are close to and less than the rate of temperature increase at 400 W/m^2. Combining the ice-melting time and power consumption analyses at different powers shows that as the heating power increases within a certain range while keeping the other factors constant, the time required for ice melting and the power consumption are reduced. In addition, the heating effect is best at a heating power of 400 W/m^2; this condition is economical and practical, and deicing is more efficient.

3.2.2. Ice Thickness. The set working conditions are a heating power of 400 W/m^2, Class 0 wind, and an ambient temperature of −3°C, and the effects of three different ice thicknesses of 5 mm, 10 mm, and 15 mm on the time required for ice melting and power consumption are explored. The surface temperature curve of the specimen with different ice layer thicknesses is shown in Figure 10.

Figure 10 shows that when the thickness of the ice layer is 5 mm and heating for 0.533 h, the surface temperature of the test specimen can reach 0°C; at this time, the ice layer begins to melt. When it is heated for 2.27 h, the surface ice layer is

Table 9: Rate of the temperature increase of the specimen surface at different wind levels.

Wind rating	Initial ambient temperature (°C)	Average temperature after heating for 2.93 h (°C)	Rate of temperature increase (°C/h)
0	−3.131	4.891	2.738
1	−3.021	3.684	2.288
2	−3.094	1.798	1.670

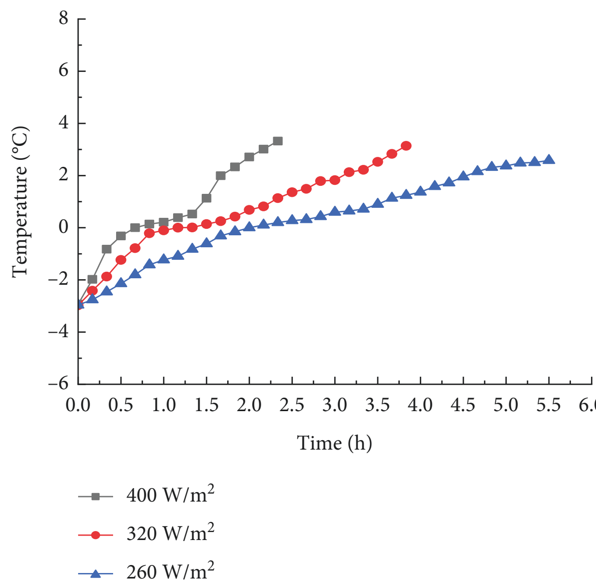

Figure 9: Curve of the surface temperature change of the test specimen at different powers.

Table 10: Rate of the surface temperature increase of the test specimen at different powers.

Heating power (W/m^2)	Initial ambient temperature (°C)	Average temperature when heating for 2.33 h (°C)	Rate of temperature increase (°C/h)
260	−2.931	0.199	1.357
320	−2.973	1.134	1.763
400	−2.962	3.321	2.683

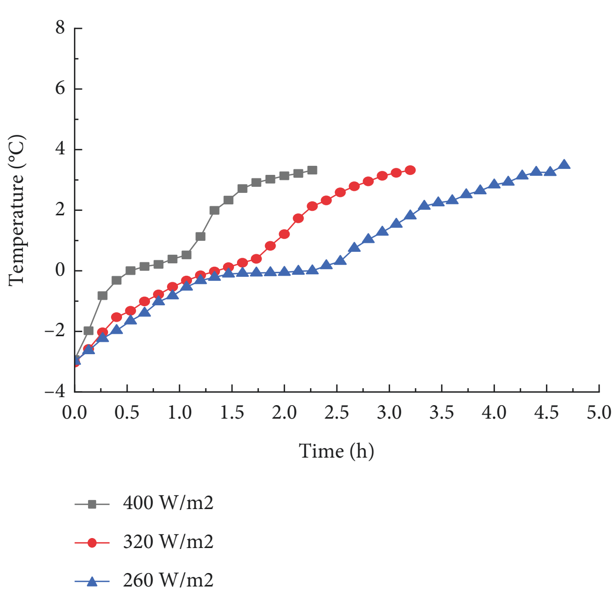

Figure 10: Temperature change curve of the specimen surface with different ice thicknesses.

completely melted. When the temperature is 3.32 °C, the total power consumption is 0.93 kW h/m^2. When the thicknesses of the ice layer are 10 mm and 15 mm and the heating times exceed 1.467 h and 2.267 h, respectively, the surface temperature can exceed 0 °C. Now, the ice begins to melt. When heating is continued for 3.21 h and 4.67 h, the surface ice layer melts. At this time, the temperatures are 3.322 °C and 3.482 °C, and the total power consumptions are 1.28 kW h/m^2 and 1.87 kW h/m^2, respectively.

In the three ice-melting tests with different ice thicknesses, when the thickness of the ice layer is increased from 5 mm to 10 mm, the complete melting time of the ice layer increases by 0.94 h, and the power consumption increases by approximately 37.6% compared with that of the case where the thickness of the ice layer is 5 mm. When the thickness of the ice layer is increased from 5 mm to 15 mm, the time for the ice layer to completely melt increases by 2.4 h, and the power consumption increases by 101.1% compared with that of the case where the ice layer thickness is 5 mm.

The rates of temperature increase of the specimen surface with different ice layer thicknesses are shown in Table 11. Comparing the rates of temperature increase under

Table 11: Rate of temperature increase of the specimen surface with different ice thicknesses.

Ice thickness (mm)	Initial ambient temperature (°C)	Average temperature when heating for 2.27 h (°C)	Rate of temperature increase (°C/h)
5	−2.931	3.321	2.754
10	−3.031	2.133	2.275
15	−2.983	0.001	1.315

the three working conditions within 0~2.27 h shows that when the ice layer thickness is 5 mm and the surface temperature of the specimen increases from −2.931°C to 3.321°C, the rate of temperature increase is 2.754 °C/h. When the ice layer thickness is 10 mm and the surface temperature of the specimen increases from -3.031°C to 2.133°C, the rate of temperature increase is 2.275 °C/h. When the ice layer thickness is 15 mm and the surface temperature of the specimen increases from −2.983°C to 0.001°C, the rate of temperature increase is 1.315 °C/h.

In summary, under certain conditions, as the thickness of the ice layer increases, the rate of temperature increase decreases. The analyses of the snow-melting time and power consumption at different snow thicknesses show that as the thickness of the ice layer increases within a certain range while keeping the other factors constant, the time required for the ice layer to melt and the power consumption increase. The power loss is large.

4. Conclusion

In this paper, an experimental study on snow melting and ice melting has been carried out, and the main conclusions are as follows:

(1) As the heating power increases within a certain range, the time required for the snow and ice layers to melt and the power consumption decrease. Under certain conditions, to ensure the rapid melting of snow and ice layers on the surface of road bridges, a heating power of 400 W/m^2 is selected. At this time, the heating effect is the best, and this method is economical and practical.

(2) As the ambient temperature decreases or the thickness of the ice layer increases within a certain range while keeping the other factors constant, the time required for the snow to melt and the power consumption increase, and the power consumption is relatively large.

(3) With the increase in the wind level within a certain range while keeping the other factors constant, the uniformity of the overall temperature distribution on the surface of the specimen worsens, the snow-melting time increases, and the temperature rises. The rate of temperature increase decreases. Therefore, in actual engineering applications, when the wind speed is too high, the methods of manually or mechanically removing snow can increase the snow removal rate on bridge decks. And it provides a theoretical reference for the actual construction of bridge decks in the future.

Data Availability

The data used to support the findings of this study are included in the article. Some or all data, models, or codes that support the findings of this study are available from the corresponding authors on request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

T.Y., H.X., and J.X. performed investigation and validation. Z.S. performed conceptualization, investigation, and formal analysis and wrote the original draft. All authors have read and agreed to the published version of the manuscript.

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