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A Study on Evaluation and Application of Snowmelt Performance of Anti-Icing Asphalt Pavement

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Abstract: This paper presents a quantitative estimation of anti-icing asphalt mixture snow-melting performance and provides the application guidance for the mixture under study. The regression model of snowmelt quality evolution was established and experimentally verified for different values of snowfall intensity, temperature and blending content of anti-icing filler. The deicing performance of anti-icing asphalt mixtures was evaluated via the impact load tests. The results obtained indicate that the application temperatures of the anti-icing asphalt mixture should exceed −10 °C for moderate or light snow conditions and exceed 0 °C for heavy or blizzard snow conditions. A linear dependence between the snowmelt quality of anti-icing asphalt mixture and time is observed for all tested values of snowfall intensity and temperature. On the other hand, under the same snowfall intensity conditions, a two- to threefold increase of the melting rate with temperature is observed. The available records for the last 30 years in different regions under study concerning variation ranges of three meteorological factors (namely, the extremely minimum temperature, snowfall intensity and the coldest month's average temperature), the most suitable temperature for application of anti-icing asphalt pavement was identified for each particular region.

Keywords: anti-icing asphalt pavement; self-snow-melting performance; deicing performance; linear dependence; climate zone

1. Introduction

For the past years, the natural environment has experienced a severe deterioration worldwide, with frequent occurrence of extreme weather events, including snow appearance in unusual seasons and locations. Consequently, ice formed by melted and refrozen snow on roads deteriorates their skid resistance, i.e., the force developed when a tire that is prevented from rotating slides along the pavement surface, which makes the motion of vehicles very unsteady, especially during braking or maneuvering [1]. Given this, anti-icing asphalt mixtures have been applied in Switzerland, Austria, the United States, and some other countries for the construction of snow- and ice-melting roads, which are also referred to as self-ice-melting pavements [2–6]. The engineering experience in the United States, Japan, Germany, and some other countries has shown that the traffic accident rate related to pavement icing or snowing in winter can be reduced by 91.4% in the case of pavement mixing with the proposed anti-icing filler [7,8]. Thus, snow- and ice-induced traffic congestion can be effectively alleviated to ensure a safer and smoother ride of vehicles.

According to the "Evaluation Test Method Manual" sponsored by the US Strategic Highway Research Program, three methods were introduced for testing the deicing performance—ice melting test, ice penetration test and ice undercutting test [9–11]—and these tests have already been improved by some researchers [12–14]. Although the shear, disbandment, and scraping tests have been developed, and these tests have shown a realistic representation of field parameters, their results are not yet standardized [15–18]. Many researchers evaluate the ice-breaking effect of the self-ice-melting pavements by measuring the numerical value of swing, also referred to as British Pendulum Number (BPN), which is widely used for skid resistance assessment [5,19]. When exploring the salt dissolving-out progression in the anti-icing asphalt mixtures, the conductivity test is applied [20]. Japanese scholars developed an experimental vehicle with built-in drums, which can be used to evaluate the effect of tires with different textures and anti-freezing agent on snow- and ice-frozen roads [21]. The Pavement Research Center of Chang'an University, Xi'an, China, has developed a pavement ice-melting simulation tester, which can simulate the ice-melting performance of the snow-melting pavement [22]. Scholars from Harbin Institute of Technology, Harbin, China, developed an adhesion force measurement system, which allows measuring the adhesion between ice and asphalt pavement [23].

In general, some ice-melting tests fail to separate the entire melted portion from the remaining ice. In the studies of salt dissolution, certain problems with the variation range identification arose when the salt dissolving-out amount reached a certain high value. Some experimental tools being applicable only to particular areas, the respective results are reduced to indirect qualitative evaluation of the snow-melting ability. There are scarce data on the climatic zones of anti-icing asphalt mixture application. The respective evaluation techniques either involve the direct observation methods to evaluate the ice-breaking effect or evaluate the melting of self-ice-melting pavements visually and indirectly. The modified ice penetration test, which is used for measuring deicer performance based on the penetration capacity as a function of time, fails to measure the theoretical or extended time of ice penetration capability [24]. Furthermore, the modified ice undercutting test measures the deicer performance based on the undercut area but fails to measure the ice undercutting capability for the theoretical or extended time instants [25].

Given the above, the developed experimental instruments should be able to separate the melted portion from remaining snow and determine the melting quality more accurately, evaluating the relationship between melting quality and time. The anti-freezing performance of anti-icing asphalt mixture can be evaluated by measuring the loading times. Based on the analysis of qualitative changes of snow on the road invoked by the effects of road loads, snow intensity, filler dosage and temperature, this study advances a regression model of the melting quality evolution, verifies the regression model, evaluates the snowmelt performance, identifies the climate zones and provides recommendations on application of self-ice-melting pavements.

2. Materials and Experiment

2.1. Materials

2.1.1. Asphalt and Aggregate

Anti-icing asphalt mixtures are primarily used in low-temperature regions, which require a good stability at a low temperature. Hence, Styrene Butadiene Styrene Block Polymer (SBS) modified asphalt was used in this study, as the main parameters listed in Table 1.

Table 1. Styrene Butadiene Styrene Block Polymer (SBS) modified asphalt technology index.

Technical Indicators	Measured Values	Standard Values	Test Method [26]
Penetration 25 °C (0.1 mm)	57	40–60	T0604
Penetration Index PI	0.125	≥0	T0604
Softening point $T_{R\&B}$ (°C)	85	≥60	T0606
Ductility (5 °C, 5 cm/min)/cm	23.3	≥20	T0605
Kinematic viscosity 135 °C (Pa·s)	1.12	≤3	T0625
Flashing point (°C)	326	≥230	T0611
Solubility (%)	99.6	≥99	T0607
Elastic recovery 25 °C (%)	88	≥75	T0662
48 h Thermal storage softening point difference (°C)	1.8	≤2.5	T0661
Density (g·cm^{-3})	1.023	Measured	T0603
Quality change (%)	0.04	≤1.0	T0609
Penetration ratio 25 °C (%)	75.9	≥65	T0604

Chloride ions, the anti-icing filler, will accelerate the peeling of asphalt. To ensure the mixture's adhesion and the pavement's performance, the adhesion of asphalt and aggregate is up to level 5 and water absorption of aggregate is less than 1%. The coarse aggregates were the diorites from Shangzhou City in Shaanxi Province, China and the fine aggregates were limestones from Pucheng City in Shaanxi Province, China. The mineral powders were ground limestones provided by Jinghe Stone Factory in Beijing, China. Technical details are shown in Tables 2–4.

Table 2. Coarse aggregate test results.

Technical Indicators		Measured Values	Standard Values	Test Method [27]
Crushing value (%)		11.9	≤26	T0316
Abrasion value (%)		10.5	≤28	T0317
Clay content (%)		0.75	≤3	T0314
Adhesivity with asphalt		Level 5	Above level 4	T0616
Apparent density (g·cm^{-3})	9.5–16 mm 4.75–9.5 mm	2.924 2.927	≥2.6	T0304
Gross bulk density (g·cm^{-3})	9.5–16 mm 4.75–9.5 mm	2.898 2.887	-	T0304
Needle flake content (%)	≥9.5 mm <9.5 mm	4.23 6.40	≤15.0 ≤20.0	T0312
Bibulous rate (%)	9.5–16 mm 4.75–9.5 mm	0.47 0.73	≤2.0	T0304

Table 3. Fine aggregate test results.

Technical Indicators		Measured Values	Standard Values	Test Method [27]
Apparent density (g·cm^{-3})	2.36–4.75 mm 0–2.36 mm	2.729 2.722	≥ 2.5	T0328
Gross bulk density (g·cm^{-3})	2.36–4.75 mm 0–2.36 mm	2.667 2.661	-	T0304
Sand equivalent		97	≥60	T0334
Clay content		1.3	≤3.0	T0333
Bibulous rate		0.85	-	T0330

Table 4. Mineral powder test results.

Technical Indicators		Measured Values	Standard Values	Test Method [27]
Apparent relative density (g·cm^{-3})		2.468	-	T0352
Size range (mm)	0.6 mm	100.00	100	T0351
	0.3 mm	99.75	90–100	
	0.15 mm	93.00	90–100	
	0.075 mm	83.50	75–100	
Appearance		Qualified	Non-caking	-
Hydrophilic coefficient		0.74	<1	T0353

2.1.2. Anti-Icing Filler

V-260 is the product of Switzeand Verglimit Anti-Icing Road Surface Limited Company, Geneva, Switzerland and Iceguard (IGD) is anti-icing developed by Chang'an University of China. The melting points are both 260 °C the major constituent is $CaCl_2$, the salinity contents of IGD and V-260 are 58.8% and 94.6% respectively, the cost of IGD is 60% as that of V-260, the appearances are both white granules, as shown in Figure 1. The specific physical performance indicators are shown in Table 5.

(**a**) IGD (**b**) V-260

Figure 1. The particle form of the anti-icing material.

Table 5. Physical performance index.

Technical Indicators		V-260	IGD	Test Method [27]
Proportion (g·mL^{-1})		1.8	2.07	Data from manufacturer
Particle diameter (mm)		0.1–5	0.1–4	
Melting point (°C)		260	260	
Solution PH value		11–12	10–11	
Salt content (%)		94.6	58.8	
Apparent density (g·mL^{-1})		0.84	0.94	
Passing percentage (%)	<0.6 mm	72.6	4.1	T0327
	<2.36 mm	2.1	47.7	
	<4.75 mm	100	100	

2.2. *Anti-Icing Asphalt Mixture*

2.2.1. Design of Ingredient

Conventional asphalt mixture used AC-13, which is widely used as the wearing course in China, and satisfied the specifications set forth by Chinese Ministry of Transportation (MOT), as shown in Figure 2.

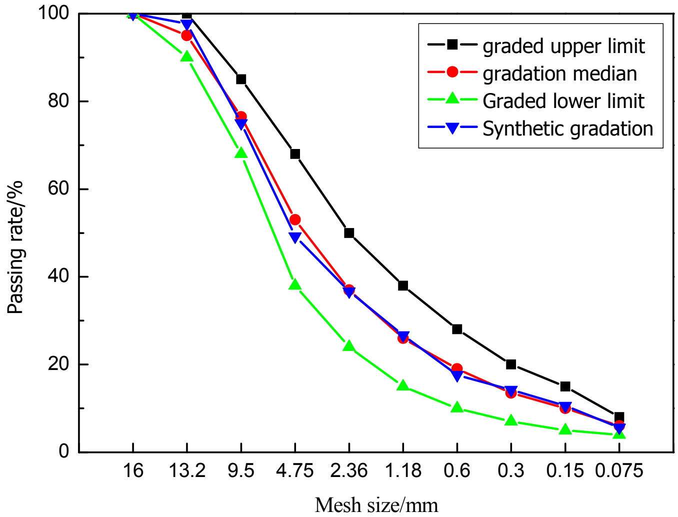


Figure 2. Aggregate gradation figure.

With the method of Marshall design, the void volume was 3–6% and the physico-mechanical index was calculated. Through optimization, the asphalt–aggregate ratio was 4.8% and the amount of mineral powder was 5 wt %. V-260 and IGD were added as additive to conventional asphalt mixture to increase its density, accounting for 5 wt % of the asphalt mixture, and other parameters were the same as those of conventional asphalt mixture. The experimental results are depicted in Table 6 and the pavement performances are described in Table 7.

Table 6. Marshall testing results of asphalt mixture added.

Asphalt-Aggregate Ratio (%)	Void Volume (VV)/%	Voids in Mineral Aggregate (VMA)/%		Aggregate Voids Filled with Asphalt (VFA)/%	Marshall Stability (MS)/KN	Flow Value (FL)/mm
Anti-icing asphalt mixture with V-260	4.8	3.0	13.3	77.0	15.48	3.8
Anti-icing asphalt mixture with IGD	4.8	3.0	13.4	80.1	14.23	3.4
Conventional asphalt mixture	4.8	3.1	13.5	73.4	16.15	3.6
Standard values [28]	-	3–6	>12.5	65–75	≥8	2–4
Test method [26]	-	-	-	-	T0709	T0709

Table 7. Test results of asphalt mixture performance.

Technical Indicators	Residual Stability (%)	Freeze-Thaw Splitting Strength Ratio (%)	Dynamic Stability (times/mm)	Maximum Flexural-Tensile Strain (με)	Standard Flying Loss (%)	Flooding Flying Loss (%)
anti-icing asphalt mixture with V-260	89.7	87.2	8579	4834	1.6	2.51
anti-icing asphalt mixture with IGD	90.14	87.8	7969	4257	1.8	2.72
Conventional asphalt mixture	96.5	92.6	6997	4531	1.69	1.73
Standard values [28]	85	80	2800	2500	15	15
Test method [26]	T0709	T0729	T0719	T0715	T0733	T0733

Asphalt mixture type and asphalt-aggregate ratio are measured as test variables in this section. Many characteristic parameters were measured, such as void volume, aggregate voids filled with asphalt, voids in mineral aggregate, Marshall stability, flow value, residual stability, freeze-thaw splitting strength, dynamic stability, maximum flexural-tensile strain and so on. There are 81 specimens in total.

Table 7 compares with the water stability, high-temperature stability and low-temperature crack resistance between conventional asphalt mixture and the anti-icing asphalt mixture. It can be observed that the addition of anti-icing filter reduced the mixture's residual stability and tensile strength ratio and simultaneously enhanced the maximum flexural-tensile strain. The residual stability and freeze-thaw splitting strength ratio of anti-icing asphalt mixture with IGD are slightly larger than anti-icing asphalt mixture with V-260. The reason is that the salt content of IGD is lower than that of V-260, and the salt is soaked in water, the change of void volume of anti-icing asphalt mixture with IGD is relatively small, and it is denser than anti-icing asphalt mixture with V-260.

2.2.2. Determination of Anti-Icing Filler Distribution

The asphalt mixture specimens containing 5% of V-260 were made according to the gradation in Section 2.2.1. The cross-sectional image of anti-icing asphalt mixture specimens were obtained by CT scanning technology and then processed by digital image processing technique [29,30]. The anti-icing filler was separated from the asphalt mixture. Taking the Marshall specimen as an example, the images were firstly extracted along both longitudinal and transverse directions, and then equally divided into 12 pieces with equal areas; the number of anti-icing filler points in each piece was counted. The variance of the number was calculated. The uniformity of anti-icing filler distribution in the image can be characterized by Equations (1) and (2):

$$U = -\log(S) \tag{1}$$

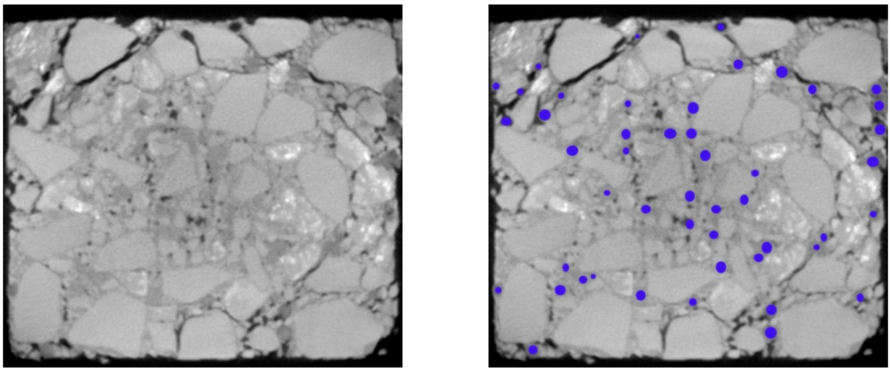
$$S = \frac{\sum_{i=1}^{12}(x_i - \overline{x})^2}{12} \tag{2}$$

where U is distribution uniformity value, S is variance, x_i is number of anti-icing filler points, and $\overline{x}$ is average of the number of anti-icing filler points.

The calculated distribution uniformity value (U) in Equation (1) represents the uniformity of anti-icing filler distributed in the entire image. A greater value of U reflects more favorable uniformity of the distribution of characteristic points. If U is greater than or equal to -2, the uniformity is good; otherwise, the uniformity is poor [31].

2.2.3. Longitudinal Distribution Evaluation

In the course of scanning the Marshall specimen, nine images were evenly extracted in the longitudinal direction at an interval of 10.15 mm. Each image was further divided into 12 equal segments from four directions (vertical, horizontal, 45° and 135°, respectively), and these segments were then referred to as directional image blocks. The anti-icing filler points were labeled in Photoshop CS6. Then, the coordinates were added after image segmentation. Figures 3 and 4 show the processed results of Image 2 which is the second image in the longitudinal direction.



(**a**) Before image processing (**b**) After image processing

Figure 3. Image partition.

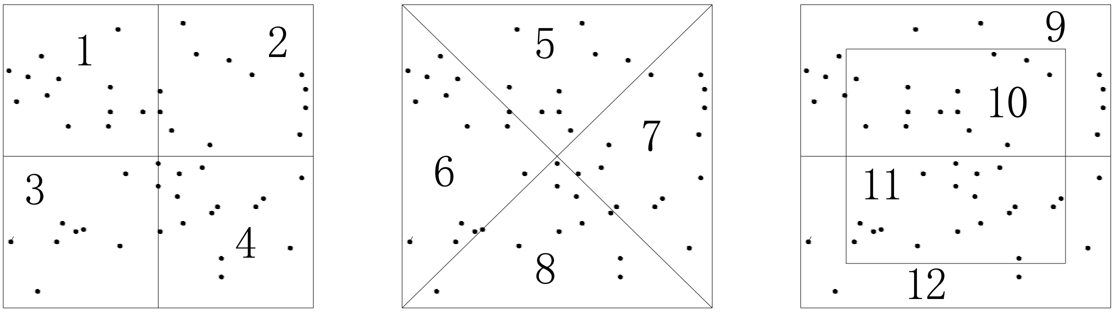


Figure 4. Extract scatter.

In Figure 4, the numbers of anti-icing filler points in the 12 blocks are 12, 12, 9, 14, 9, 14, 14, 11, 11, 13, 18, and 5. The variance S is 9.81. The U value is equal to -0.99 (more than -2), representing a great uniformity in the longitudinal direction.

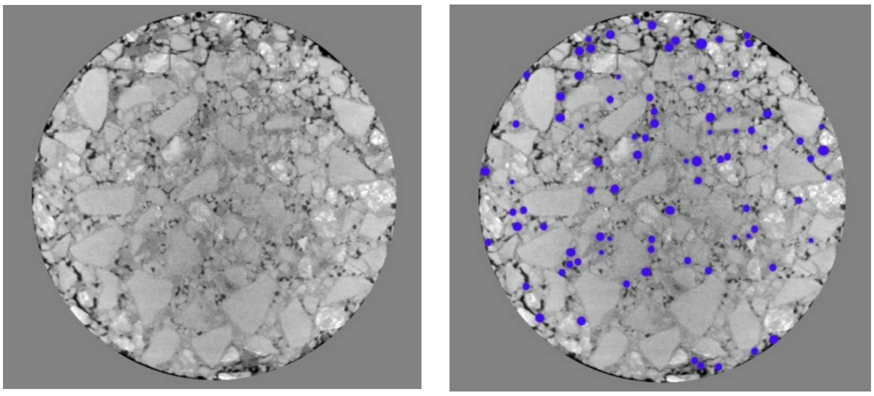
The statistical results of the remaining images are described in Table 8.

Table 8. Calculation results of longitudinal uniformity.

Number	Region													
	1	2	3	4	5	6	7	8	9	10	11	12	Variance	Uniformity
1	7	6	6	6	1	10	9	5	3	10	8	4	7.02	−0.85
3	23	22	16	17	27	13	18	19	29	19	10	20	26.58	−1.42
4	21	23	15	16	28	16	14	16	25	21	16	12	22.08	−1.34
5	23	23	17	18	24	21	18	18	21	25	16	19	8.19	−0.91
6	22	23	18	17	17	24	19	20	21	22	21	16	6.17	−0.79
7	21	22	18	17	25	15	17	21	26	19	13	20	13.42	−1.13
8	17	15	11	17	16	17	12	15	18	11	13	18	6.33	−0.80
9	14	8	8	11	12	6	11	12	13	11	7	10	5.69	−0.75

2.2.4. Transverse Distribution Evaluation

Likewise, in the transverse direction, the specimen was scanned with Computed Tomography (CT) at an interval of 13.5 mm. Each image was divided into 12 segments for the evaluation of distribution uniformity. After Image 1 was segmented, anti-icing filler points were marked, as illustrated in Figures 5 and 6.



(**a**) Before image processing (**b**) After image processing

Figure 5. Image partition.

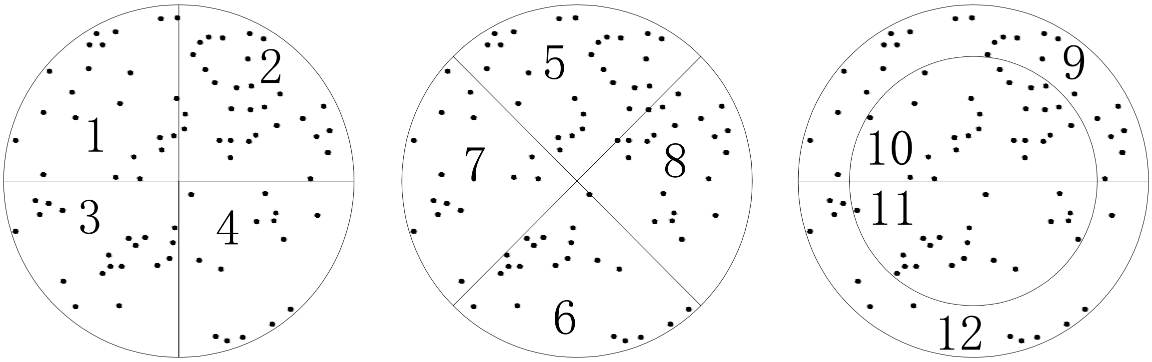


Figure 6. Extract scatter.

In Figure 6, the numbers of anti-icing filler points in Segments 1–12 are 22, 29, 19, 14, 28, 21, 15, 20, 26, 25, 20, and 13, respectively. The variance S is 25.83. The U value is equal to −1.41 (more than −2), indicating a great uniformity in the transverse direction. The results of the other five images are shown in Table 9.

Table 9. Calculation results of horizontal uniformity.

Number	Region													
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Variance**	**Uniformity**
2	23	25	18	24	20	19	13	19	25	16	19	22	12.52	−1.10
3	22	22	27	24	19	25	27	29	28	16	17	21	17.08	−1.23
4	24	28	20	16	25	22	27	18	24	24	19	23	12.08	−1.08
5	19	15	22	25	20	21	20	24	23	22	20	25	7.39	−0.87
6	18	25	20	26	19	20	25	24	21	26	21	21	7.47	−0.87

The average longitudinal and transverse uniformity values are −0.999 and −1.094, respectively. Both are more than −2, indicating that the anti-icing filler was uniformly distributed in the asphalt mixture.

When the anti-icing filler is uniformly distributed inside of the asphalt mixture, the salting-out is uniform, so the snow melt effect of every part of the pavement is consistent and the asphalt mixture performances are less affected. Because of the uniform salting-out, the void volume will not increase sharply in certain parts. As a result, uniform changes of pavement performances can be guaranteed.

2.3. Experimental

2.3.1. Evaluation of Self-Snow-Melting Performance

In this study, using a self-developed experimental device (as shown in Figure 7), the effect of the load of vehicles was simulated under different snowfall intensities and different temperature for quantitatively evaluating the snow-melting performance of the anti-icing asphalt pavement.

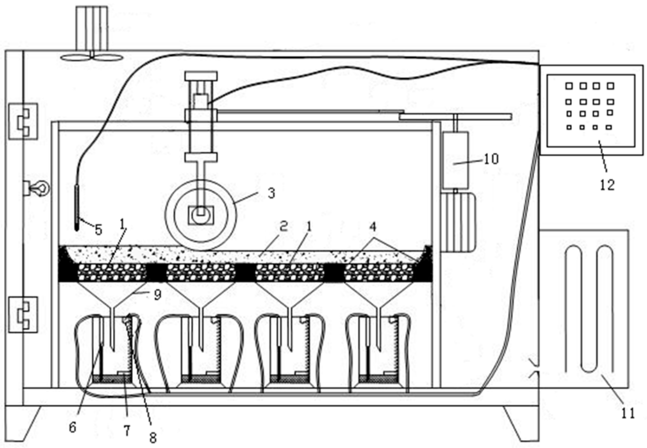


Figure 7. Melting ice-snow quality measuring device of self-ice-melting pavement: (**1**) specimen; (**2**) snow; (**3**) wheel; (**4**) waterproof material; (**5**) temperature sensing device; (**6**) density meter; (**7**) floater; (**8**) volume measuring device; (**9**) diversion meter; (**10**) loading device; (**11**) external refrigeration system; and (**12**) control system.

2.3.2. Determination of Snow Amount

Generally, snowfall intensity can be classified into four levels: light snow, moderate snow, heavy snow and blizzard. Taking the condition in China as an example, light snow has snowfall of less than 1.0 mm in 12 h or less than 2.5 mm in 24 h; moderate snow has snowfall of between 1.0 and 3.0 mm in 12 h or between 2.5 and 5.0 mm in 24 h; heavy snow has snowfall of between 3.0 and 6.0 mm in 12 h or between 5.0 and 10.0 mm in 24 h; and blizzard has snowfall of greater than 6.0 mm in 12 h or greater than 10.0 mm in 24 h. One millimeter of snowfall means 0.001 m^3 of water added over 1 m^2 of area. When using visibility or the other indexes for measuring snowfall intensity, the accumulative snow thickness within 12 or 24 h can be acquired and the corresponding relationships are then established.

The dimensions of the specimen are 100 mm (length) × 100 mm (width) × 50 mm (height). The surface area S is 0.01 m^2:

$$(S = a \times b = 0.1 \times 0.1\ \mathrm{m}^2). \tag{3}$$

Hence, 1 mm of snowfall on the specimen surface corresponds to 10^{-5} m^3:

$$(V = 0.001\ \mathrm{m} \times S = 0.001 \times 0.1\ \mathrm{m}^3 = 1 \times 10^{-5}\ \mathrm{m}^3) \tag{4}$$

or 10 g of water; water density is 1.0 g/cm^3 and:

$$M = V \times \rho_1 = 1 \times 10^{-5}\ \mathrm{m}^3 \times \frac{1000\ \mathrm{kg}}{\mathrm{m}^3} = 0.01\ \mathrm{kg} = 10\ \mathrm{g} \tag{5}$$

In other words, the icing layer thickness h is 1.1 mm; ice density is 0.9 g/cm^3 and:

$$h = \frac{M/\rho_2}{S} = \frac{10/0.9}{1 \times 10^2}\ \mathrm{cm} = 0.11\ \mathrm{cm} = 1.1\ \mathrm{mm} \tag{6}$$

The corresponding snow layer thickness *H* is 15 mm; snow density is 1/15 of water density. The thickness values of icing layer and snow layer in different snowing weathers are depicted in Table 10.

Table 10. Snowfall scale.

Snowfall Intensity	Index			
	Snowfall (mm)	**Water Quality (g)**	**Ice Thickness (mm)**	**Snow Thickness (mm)**
Light snow	0.1–2.5	1–25	0.1–2.8	1.5–37.5
Moderate snow	2.5–5.0	25–50	2.8–5.6	37.5–75.0
Heavy snow	5–10	50–100	5.6–11.1	75.0–150.0
Blizzard	10–20	100–200	11.1–22.2	150.0–300.0

2.3.3. Determination of the Freezing Point of Anti-Icing Filler Solutions

Calcium chloride and sodium chloride are two main components used in the anti-icing products in China and abroad. Thus, calcium chloride is the main ingredient in both V-260 and IGD. To better compare the freezing points between V-260 and IGD, another anti-icing product—Mafilon (Beijing Mafilon Anti-Icing Technology Limited Company, Beijing, China) (MFL)—is introduced, and it's main components are silicon dioxide, sodium chloride, calcium chloride and calcium carbonate; among these components, the sodium chloride content is about 55% of the total mass.

V-260, IGD, and MFL were separately dissolved in water to prepare 600 mL of solutions (5.0 wt %), and the quality of the anti-icing fillers was 30 g. These solutions were denoted by numbers 2, 3, and 4, while 600 mL water solution, denoted by 1, was adopted as the control group. These solutions were placed into an environmental chamber at a certain temperature. The freezing condition of each solution was observed, and the results are listed in Table 11.

Table 11. Different time and different temperature Salt storage solution freezing conditions.

Time (h)	1# (water)	2# (V-260)	3# (IGD)	4# (MFL)	Temperature (°C)
1	Thin layer of ice	Ice free	Ice free	Ice free	0
5	Completely frozen	Ice free	Ice free	Most of the ice, with a small amount of water	−5
6	Completely frozen	The surface began to have thin ice	Thin layer of ice	Appearance completely frozen	−7
8	Completely frozen	Most of the ice, with a small amount of water	Appearance completely frozen	Appearance completely frozen	−18
10	Completely frozen	Appearance completely frozen	Appearance completely frozen	Appearance completely frozen	−19

As shown in Table 11, MFL, IGD, and V-260 were completely frozen at −7, −18 and −19 °C, respectively, indicating that IGD and V-260 have lower action temperatures and can more effectively prohibit freezing. The reason is that the main component of IGD and V-260 is $CaCl_2$, the MFL is NaCl, and the freezing point of $CaCl_2$ solution is lower than that of NaCl solution at the same concentration. The salt content in V-260 is higher than that in IGD.

2.3.4. Experimental Procedure

The mixtures were compacted to a block of the size 300 mm (length) × 300 mm (width) × 50 mm (height). Three groups were independently added with 4%, 5%, and 6% of V-260. The fourth group was the conventional asphalt mixture as reference group.

Each specimen was cut into a standard size (100 mm × 100 mm × 50 mm) in a dry state. After the side wall was encapsulated with the waterproof materials, the specimen was placed on a porous plate in the environmental chamber.

The specimens were frozen at −15, −10, −5, 0 and 5 °C according to the results in Table 11. In order to prevent the effects of environment temperature on experimental results and simulate the pavement's actual conditions, the specimens were pre-frozen under the corresponding temperatures until the specimens' surface temperature equaled the temperature of the environmental cabinet. Generally, the pre-freezing time was set within 2–4 h.

Based on the snowfall intensity level in Table 10, corresponding quality of water was taken and injected to the specimen container; the water was separately frozen in the environmental cabinet and the ice was made into snowflakes by an ice crusher, then the snowflakes were evenly spread on the specimen surface.

The testing device was started and the specimen was subjected to a load of 0.7 MPa. The values of density meter and volume measurement device are read every 1 h. According to:

$$M = \rho \times V \tag{7}$$

The quality of melted snow is calculated, and average value is obtained. The mass of melted ice and snow was the dependent variable and time was the independent variable.

The test variables are asphalt mixture type, snowfall intensity, temperatures, and (anti-icing filler) content. There are 328 specimens in total. The parameters measured are the time and melting quality of snow.

2.3.5. Evaluation of Deicing Performance

Freezing rains and the melted snows refreeze at low temperatures, which will also increase the occurrence of traffic accidents. Anti-icing filler can effectively suppress the freezing of rain and snow water. In this study, the Marshall specimen was not demolded and the edge was sealed with hot asphalt. The specimen was placed in a −20 °C environmental chamber. A certain amount of water corresponding to the snowfall intensity was poured on the Marshall specimen. The conventional asphalt mixture was frozen for 10 h as well as asphalt mixture containing 5% of V-260.

The frozen specimens were placed on a Marshall Compaction Apparatus, (Chang Sha Ya Xing Digit-Control Limited Company, Changsha, China) and the impact load produced in the hammer's free fall was calibrated with an impact sensor. The height was adjusted so that the impact load equaled to 100 KN (standard axial load). According to the frequency of the vehicles passing through a section, the impact frequency was 30 times per minute. The number of impact was recorded until the ices over the specimen were completely cleared.

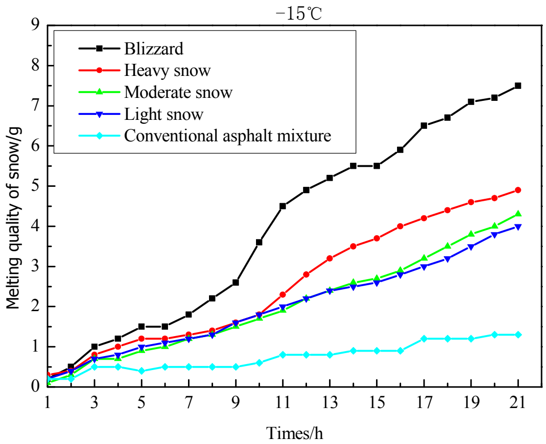
The test variable is asphalt mixture type. There are eight specimens. The parameter measured is the frequency of load application.

3. Results and discussion

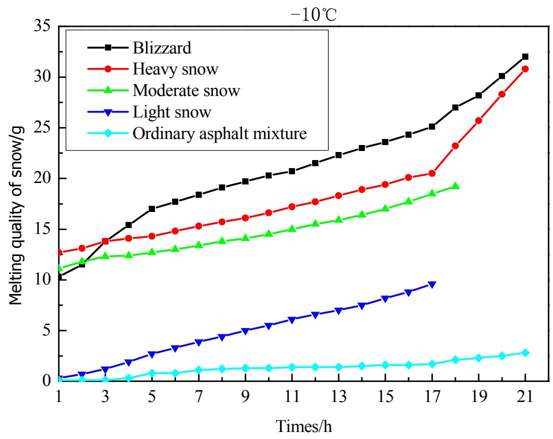
3.1. Self-Snow-Melting Test

3.1.1. Effect of Snowfall Intensity

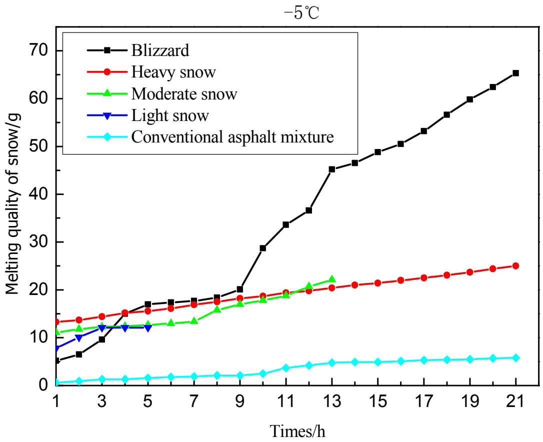
With the asphalt mixture containing 5% of V-260, the effect of different snowfall intensity on the melting quality of snow at −15, −10, −5, 0, and 5 °C is illustrated in Figure 8.



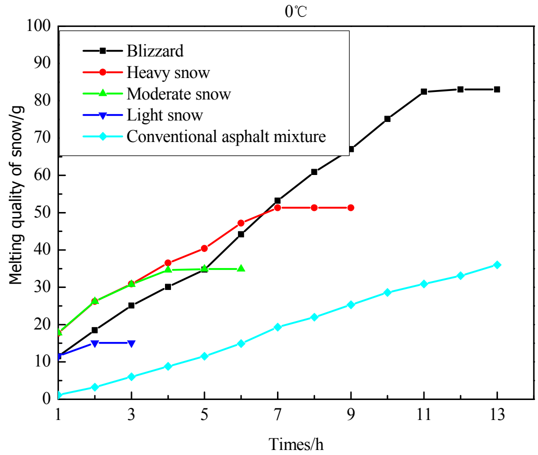
(**a**) effect of snowfall intensity at −15 °C



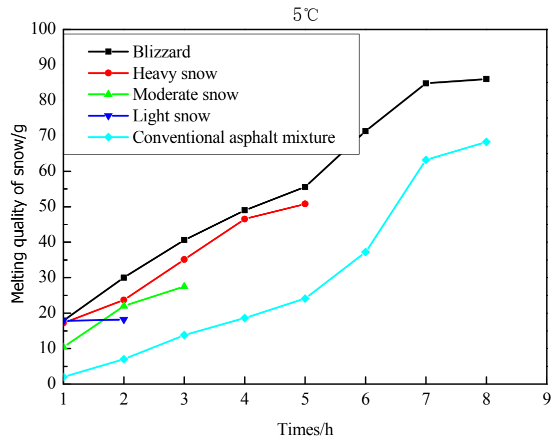
(**b**) effect of snowfall intensity at −10 °C



(**c**) effect of snowfall intensity at −5 °C



(**d**) effect of snowfall intensity at 0 °C



(**e**) effect of snowfall intensity at 5 °C

Figure 8. The effect of different snowfall intensity on the melting quality of snow at different temperatures.

The following conclusions are drawn:

1. At the five different temperatures, the anti-icing asphalt mixture exhibited a higher snow melting efficiency compared with the conventional asphalt mixture. The reason is that the snow increased the air humidity, which promoted the precipitation of anti-icing filler and formed a salt solution. The salt could be transferred from inside the high-concentration zone to the low-concentration surface, further promoting the precipitation of anti-icing filler and thereby accelerating the snow melting.

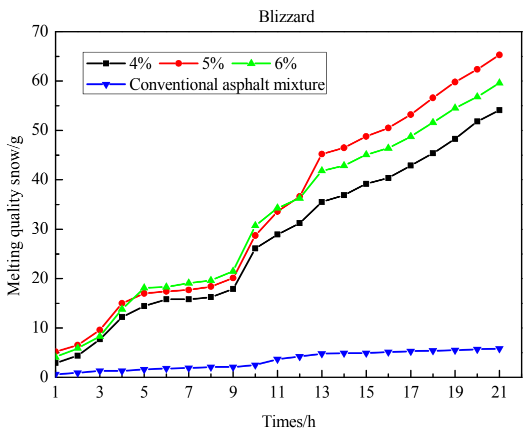
2. Under the condition of moderate or light snow, the appropriate application temperature of the anti-icing asphalt mixture is not less than −10 °C. Under the condition of heavy snow or blizzard, the appropriate application temperature is not less than 0 °C, because snow was evidently melted at these temperature ranges. At below 0 and −10 °C, respectively, in both cases, snow was rarely melted. However, the brine solution can lower the adhesion between pavement and ice-snow layer, and the snow-removing efficiency can be improved when other snow-removing methods are applied.

3.1.2. Effect of the Dosage of Anti-Icing Filler

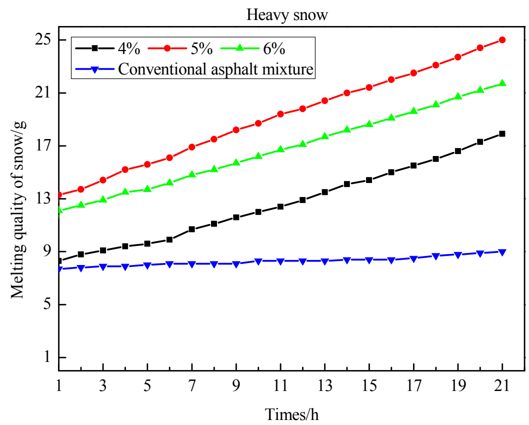
At −5 °C in the environmental chamber, when the snowfall intensity was blizzard, heavy snow, moderate snow, and light snow, the quality of melted snow with the V-260 addition of 4%, 5%, and 6% were determined, respectively.

Figure 9 shows the following results:

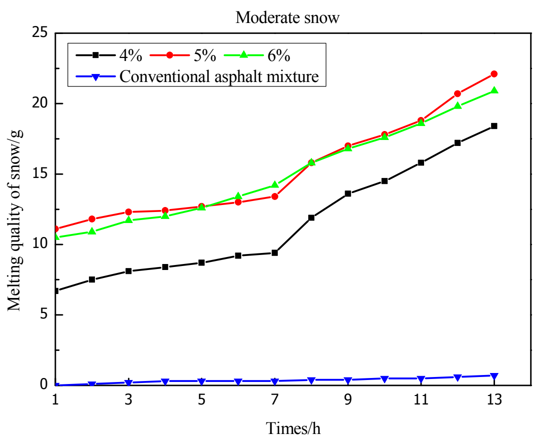
1. Compared with the conventional asphalt mixture, the asphalt mixtures with different amounts of V-260 addition all exhibit an obviously improved ice and snow melting performances.
2. At −5 °C, the effect of the amount of anti-icing filler had a minor influence on the melting quality of snow. At −15, −10, 0, and 5 °C, the results of these effects were similar, as shown in Figures 10–13. This can be attributed to low addition amounts and short test times.



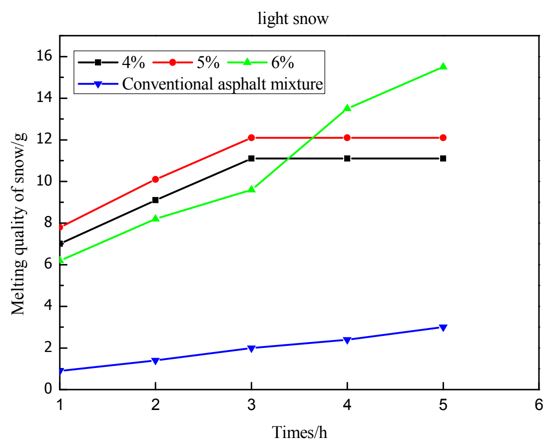
(**a**) blizzard



(**b**) heavy snow

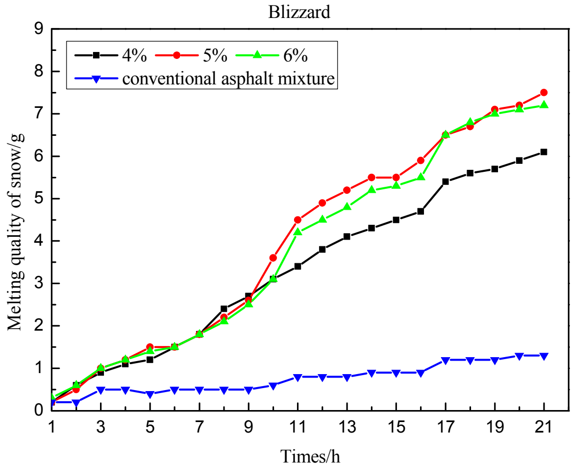


(**c**) moderate snow

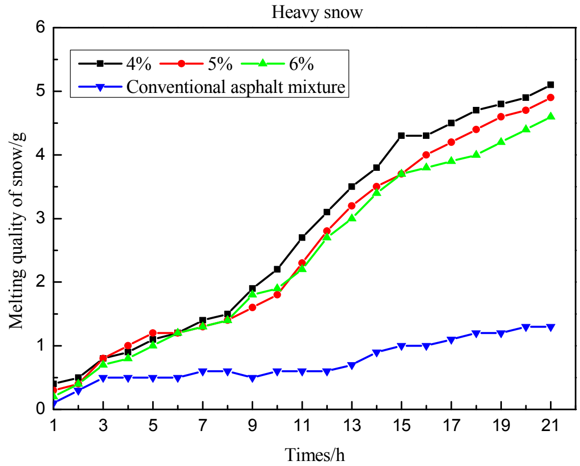


(**d**) light snow

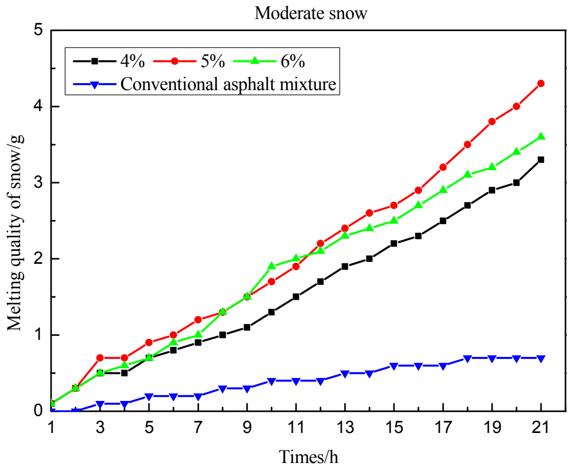
Figure 9. The effect of different dosage of anti-icing filler on the melting quality of snow at different snowfall intensity and −5 °C.



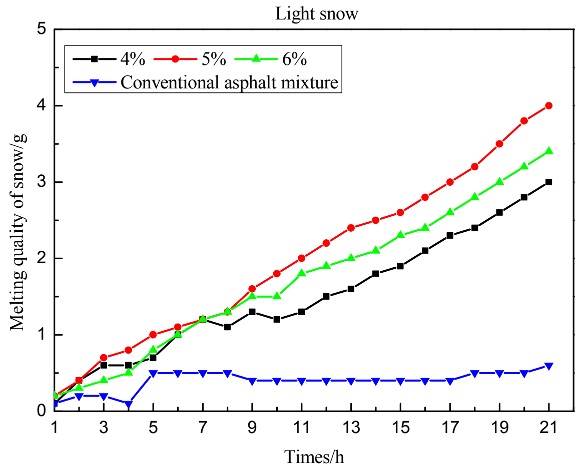
(**a**) blizzard



(**b**) heavy snow

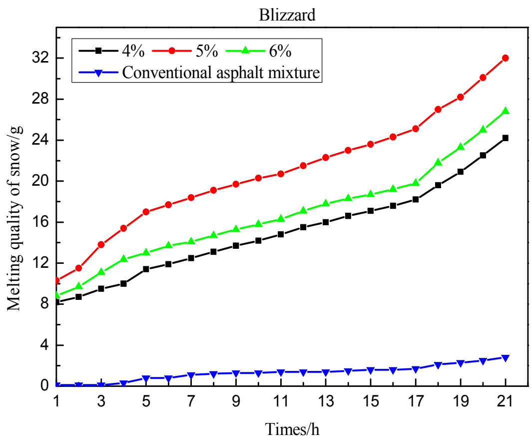


(**c**) moderate snow

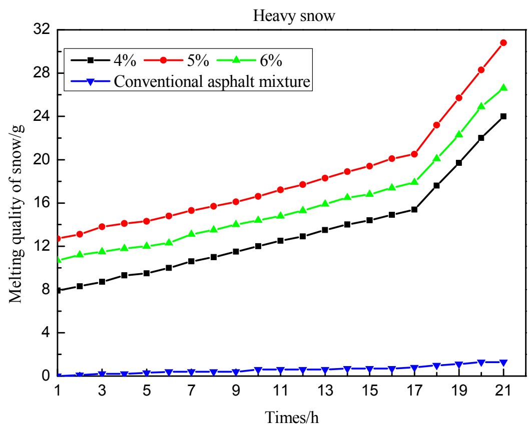


(**d**) light snow

Figure 10. The effect of different dosage of anti-icing filler on the melting quality of snow at different snowfall intensity and −15 °C.

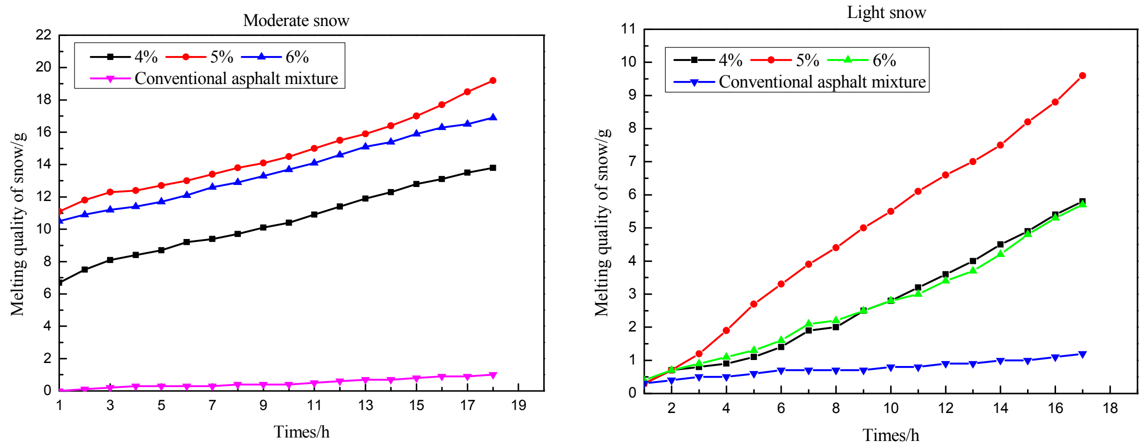


(**a**) blizzard



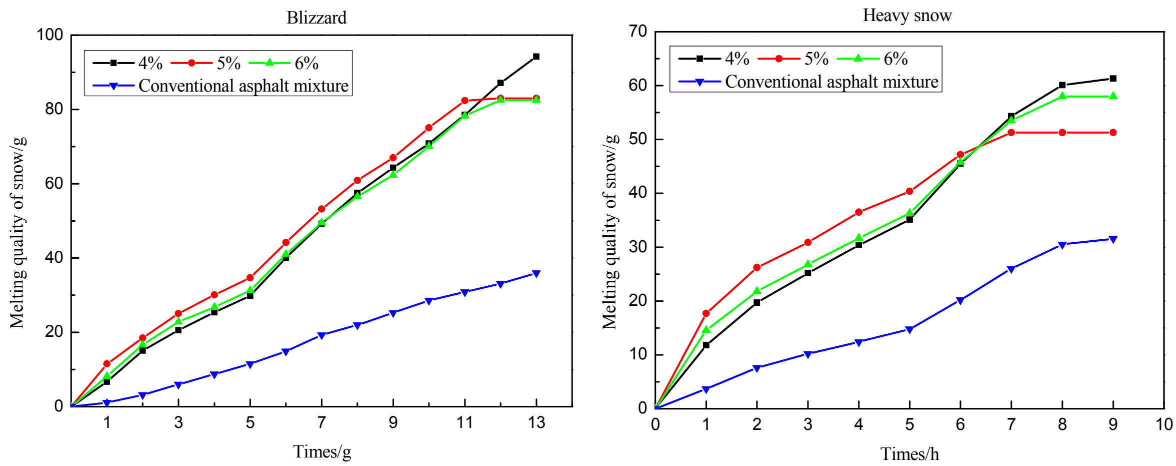
(**b**) heavy snow

Figure 11. *Cont.*

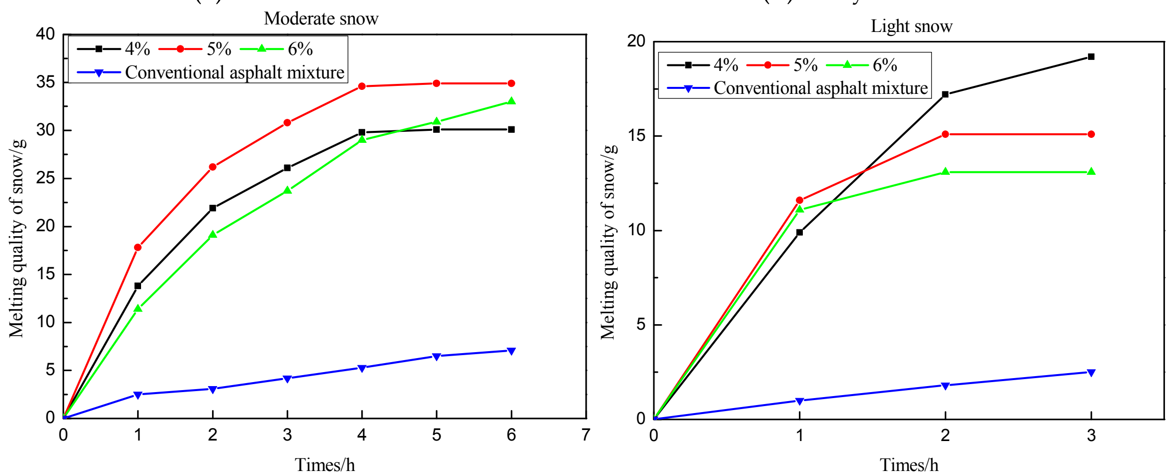


(**c**) moderate snow (**d**) light snow

Figure 11. The effect of different dosage of anti-icing filler on the melting quality of snow at different snowfall intensity and −10 °C.

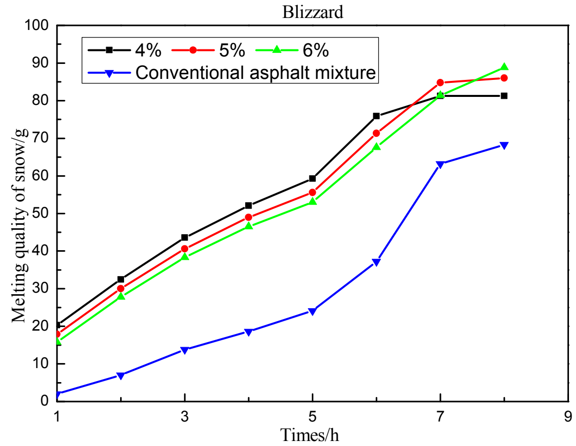


(**a**) blizzard (**b**) heavy snow

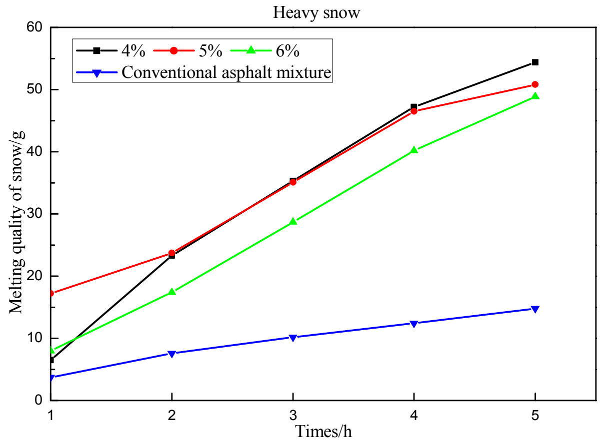


(**c**) moderate snow (**d**) light snow

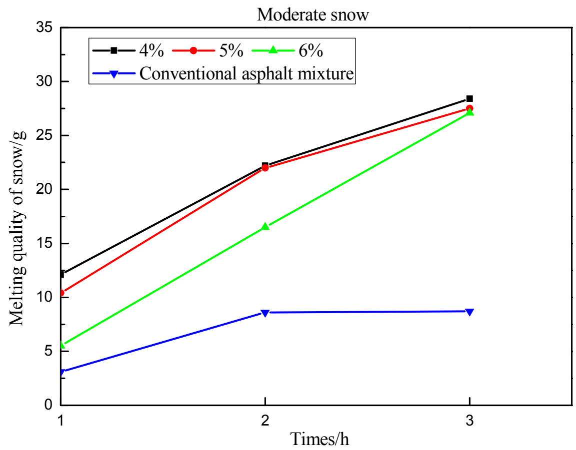
Figure 12. The effect of different dosage of anti-icing filler on the melting quality of snow at different snowfall intensity and 0 °C.



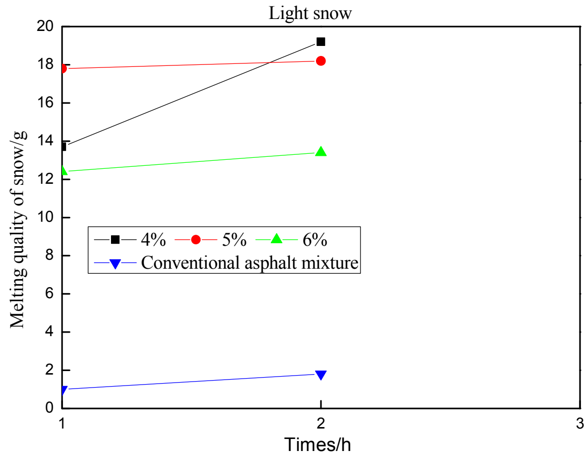
(**a**) blizzard



(**b**) heavy snow



(**c**) moderate snow

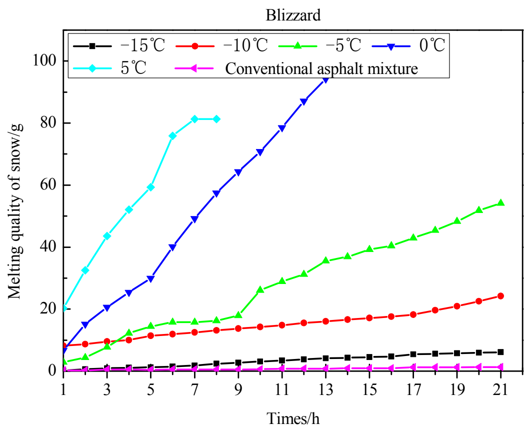


(**d**) light snow

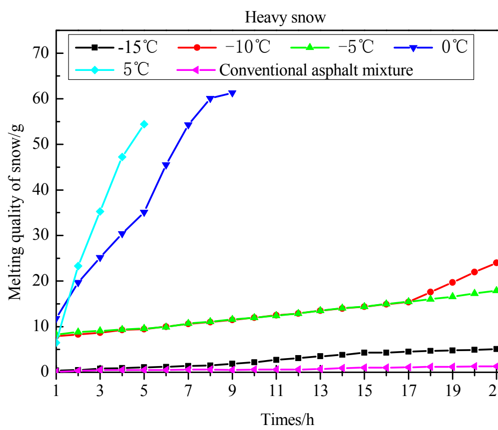
Figure 13. The effect of different dosage of anti-icing filler on the melting quality of snow at different snowfall intensity and 5 °C.

3.1.3. Effect of Temperature

With the asphalt mixture containing 4% of V-260, the quality of melted snow at different temperatures and snowfall intensities was studied, as shown in Figure 14.

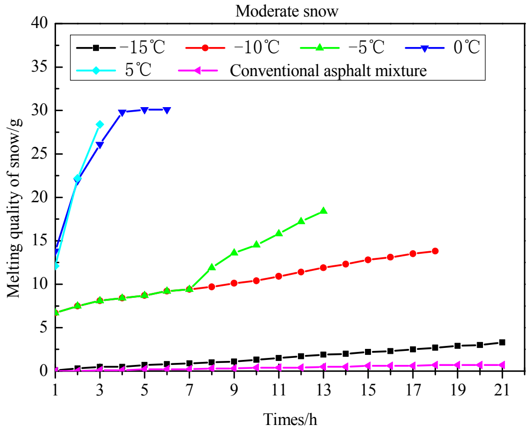


(**a**) blizzard

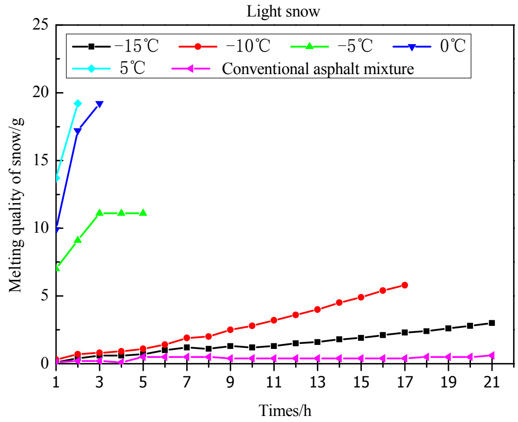


(**b**) heavy snow

Figure 14. *Cont.*



(**c**) moderate snow



(**d**) light snow

Figure 14. The effect of different temperatures on the melting quality of snow at different snowfall intensity.

It can be observed that moderate snow was melted within 18, 13, 6 and 3 h at −10, −5, 0, and 5 °C, respectively; light snow was melted within 17, 5, 3 and 2 h at −10, −5, 0, and 5 °C, respectively; snow from a blizzard was melted within 13 and 5 h at 0 and 5 °C, respectively; and heavy snow was melted within 9 and 8 h at 0 and 5 °C, respectively. The melting rate rose with the increase of temperature. Under same snowfall intensity, anti-icing filler spent less time on melting the snows with same masses at a higher temperature. It is indicated that the snow-melting effect of anti-icing admixture is strongly dependent on temperature. The melting effect is weak at low temperatures.

3.1.4. Regression Analysis of Snow Melting Effect

The profile in Figure 8 was regressed following the model ($y = ax + b$, where x is the time; y is the melting quality of snow with the use of V-260; a and b are coefficients) and the regression formula and the determination coefficient (R^2) are listed in Table 12. The determination coefficients reflect that the regression is reliable.

Table 12. Regression formula between melting quality and times of anti- icing asphalt mixture.

Temp. (°C)	Blizzard	Heavy Snow	Moderate Snow	Light Snow
−15	$Y = 0.3945 \times X - 0.4067$ $R^2 = 0.9794$	$Y = 0.2481 \times X - 0.1905$ $R^2 = 0.9767$	$Y = 0.2016 \times X - 0.1743$ $R^2 = 0.9896$	$Y = 0.1812 \times X + 0.0119$ $R^2 = 0.9931$
−10	$Y = 0.9108 \times X + 10.981$ $R^2 = 0.9685$	$Y = 0.7427 \times X + 10.24$ $R^2 = 0.8598$	$Y = 0.4408 \times X + 10.496$ $R^2 = 0.978$	$Y = 0.5728 \times X - 0.2904$ $R^2 = 0.9976$
−5	$Y = 3.1771 \times X - 0.9438$ $R^2 = 0.9779$	$Y = 0.5817 \times X + 12.759$ $R^2 = 0.9988$	$Y = 0.9016 \times X + 8.9885$ $R^2 = 0.9248$	$Y = 1.06 \times X + 7.66$ $R^2 = 0.7721$
0	$Y = 6.5769 \times X + 5.4$ $R^2 = 0.9832$	$Y = 4.3533 \times X + 17.433$ $R^2 = 0.9381$	$Y = 3.2971 \times X + 18.327$ $R^2 = 0.8165$	$Y = 1.06 \times X + 7.66$ $R^2 = 0.7721$
5	$Y = 10.112 \times X + 8.8964$ $R^2 = 0.9857$	$Y = 9 \times X + 7.66$ $R^2 = 0.9808$	-	-

All the regression results in Table 12 show a significant linear relationship between time and the mass of melted snow. On the other hand, with the increase of temperature, the melting rate was 2–3 times increased under the same snowfall intensity. At the same temperature, the melting rate varied slightly under different snow intensities, consistent with the results in Section 3.1.1.

Moreover, IGD was also selected as the anti-icing filler for validating the above-described regression results. The experiments were conducted following the gradation in Section 2.2.1 (4.8% asphalt-aggregate ratio, 5.0% mass ratio of IGD to asphalt mixture, and 5.0% mineral powder). The experimental results are shown in Figure 15, and the regression results are shown in Equations (8) and (9). The melting rate also corresponds with the linear relationship, and the melting rate of the above two temperatures has a nearly twofold relationship. Besides, the snow melting performance of anti-icing asphalt mixture with IGD is approximate to that of anti-icing asphalt mixture with V-260 in a short term.

$$y = 0.9125x + 1.0581\ (R^2 = 0.9375)\ (\text{at} - 10\ ^\circ\text{C}) \quad (8)$$

$$y = 0.5086x + 0.5058(R^2 = 0.9547)\ (\text{at} - 15\ ^\circ\text{C}) \quad (9)$$

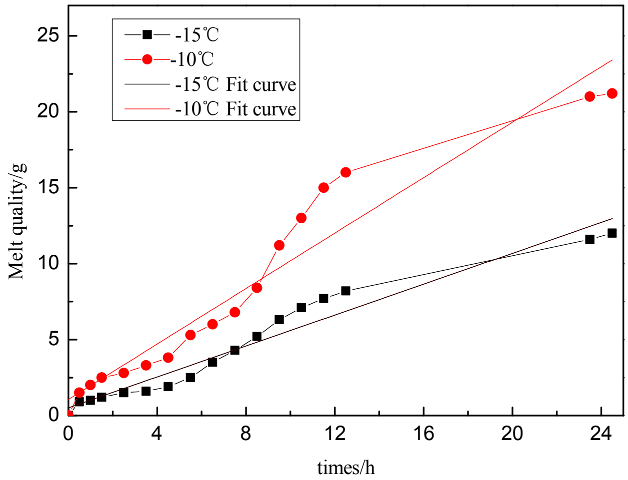


Figure 15. The effect of asphalt mixture with IGD on the melting quality of snow at blizzard.

3.2. Deicing Test

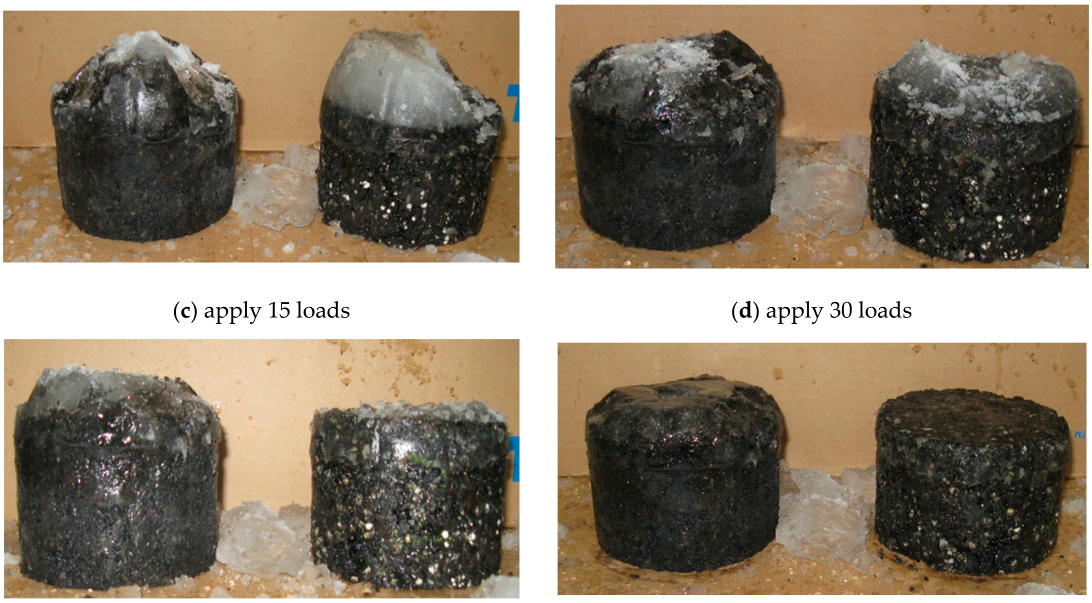
Deicing test processes of the conventional (left specimen) and anti-icing (right specimen) asphalt mixtures with V-260 are shown in Figure 16.

During the freezing process, the anti-icing filler precipitated from the inside, and thus the surface of the anti-icing asphalt mixtures was white. By contrast, the ice on the top of conventional asphalt mixture was nearly transparent. After 46 impact loads, the ice over the anti-icing asphalt surface was completely removed, while the ice over the normal asphalt mixture was completely removed after 61 impact loads. Affected by the loads and humidity, the anti-icing filler continuously precipitated to form a salt solution. The freezing point was hence decreased and a small amount of ice was melted, reducing the adhesion between the specimen and ice. Therefore, the ice is more easily to be removed on the anti-icing asphalt surface, especially when subjected to impact loads. According to deicing test results, self-ice-melting pavements are recommendable when ice and snow freeze on the pavement under a great snowfall intensity at a low temperature since it can accelerate the removal of ice and snow.

(**a**) no load applied

(**b**) apply 5 loads

Figure 16. *Cont.*



(c) apply 15 loads

(d) apply 30 loads

(e) apply 40 loads

(f) apply 46 loads

Figure 16. Dropping experiment with different loading times.

3.3. Climate Zone of the Anti-Icing Asphalt Mixture

Because the climatic conditions in different regions of the world are very different, the climate zone of the anti-icing asphalt pavement is presented for ensuring that the anti-ice asphalt road can adapt to the climate. Firstly, the extremely minimum temperature, snowfall intensity and the coldest month's average temperature of a region in the last 30 years should be considered to ensure the continuous self-snow effect of anti-icing filler. Secondly, the high temperature indicators and the rainfall are considered to make anti-ice asphalt pavement performance to meet the requirements. Taking China as an example to introduce the method of climate zone, the climate zone index is shown in Table 13, the climate zone boundaries are shown in Figure 17.

Region 1: The area with the extremely minimum temperature in the last 30 years between −9 and −21.5 °C is chilling region. In this region, the average temperature in the coldest month is above −10 °C; in terms of snowfall intensity, moderate and light snows frequently fall. Because snow can be melted in a short time, the anti-icing asphalt mixture is most applicable.

Region 2: The area with the extremely minimum temperature in the last 30 years between −21 and −37 °C is cold region. In this region, the average temperature in the coldest month is above −15 °C. Moderate snowfalls frequently occur while heavy snowfalls occasionally occur. Because of the variance of temperature, the anti-icing asphalt mixture is also applicable.

Region 3: The area with the extremely minimum temperature in the last 30 years above −9 °C is warm region. In this region, the average temperature in the coldest month is above 0 °C. Light snowfalls most frequently occur. The frozen rain or melted snow in some regions could be iced again, and hence the anti-icing asphalt mixture can be paved in some special sections such as bridges and tunnel entrances.

Region 4: The area with the extremely minimum temperature in the last 30 years below −37 °C is severely cold region. Moderate and heavy snowfalls dominate the snowfalls in this region, and blizzard occasionally occur. The anti-icing filler is ineffective for a long time in this region. Hence, the anti-icing filler is not suitable in this region. However, the afore-mentioned experiments in Section 3.2 proved that the application of the anti-icing filler can reduce the adhesion between pavement and ice-snow. Hence, anti-icing asphalt mixtures are applicable to some special sections such as bridges and tunnel entrances for accelerating the removal of ice and snow.

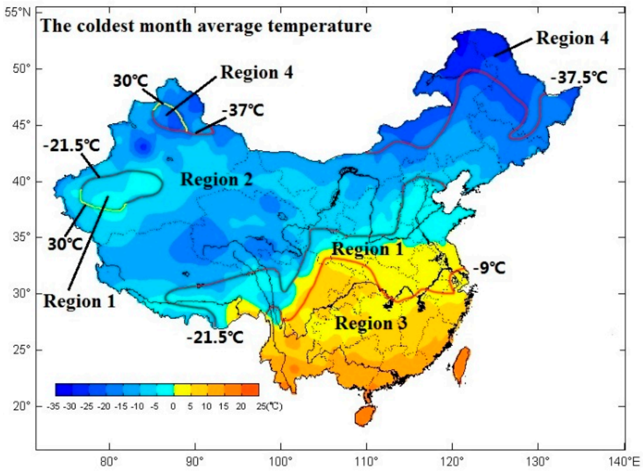


Figure 17. Climatic Division of anti-icing asphalt mixture.

Table 13. Climatic Division of anti-icing asphalt mixture.

Climatic Division	Applicable Situation	Extreme Minimum Temperature of 30 Years	Average Temperature of the Coldest Month	Snow Intensity
Region 1	Most suitable	−9 to −21.5 °C	≥−10 °C	Light snow (Mostly) Moderate snow (Occasionally)
Region 2	suitable	−21 to −37 °C	≥−15 °C	Light snow and Moderate snow (Mostly), Heavy snow (Occasionally)
Region 3	Special section	>−9 °C	≥0 °C	Light snow, Frozen rain or snow after melting ice (Occasionally)
Region 4	Special sections combined with other snow removal methods	<−37 °C	≤−20 °C	Moderate snow and Heavy snow (Mostly), Blizzard (Occasionally)

4. Conclusions

1. The application temperatures of the anti-icing asphalt mixture should exceed −10 °C for the moderate or light snow conditions and exceed 0 °C for heavy or blizzard conditions.
2. A linear dependence between the anti-icing asphalt mixture snowmelt quality and time was observed for all tested values of snowfall intensity and temperature. On the other hand, under the same snowfall intensity conditions, a two- to threefold increase of the melting rate with temperature was observed. At the same temperature, only a slight variation of the melting rate for different snowfall intensities was observed.
3. The anti-icing asphalt mixture has the function of deicing performance so that the adhesion between ice and pavement can be reduced.

Four regions of the anti-icing asphalt mixture application climate zone have been identified as follows: Region 1, which is denoted as the chilling region, and the extremely minimum temperature range is between −9 and −21.5 °C; Region 2, which is denoted as the cold region, and the extremely minimum temperature range is between −21 and −37 °C; Region 3, which is denoted as the warm region, and the extremely minimum temperature is above −9 °C; and Region 4, which is denoted as the severely cold region, and the extremely minimum temperature is below −37 °C.

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Conflicts of Interest: The authors declare no conflict of interest.

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