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Article

Enhancing the Efficiency of Ice-Resistant Materials in Asphalt Road Surfaces: A Comprehensive Performance Analysis

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Abstract: Ice and snow on roads in winter endanger traffic safety. The existing methods of snow and ice removal have various drawbacks, which need further research. Aiming at solving limitations about high labor intensity, low efficiency, serious environmental pollution of traditional snow and ice removal methods, the anti-icing coating technology of high-voltage conductors is used for reference, and in view of the characteristics of asphalt pavement deicing, an ice-suppressing material that can effectively reduce the adhesion between snow, ice and pavement is successfully developed. As there is no perfect evaluation index and method for ice-suppressing materials at present, this paper further evaluates the performance of ice-suppressing materials from the aspects of deicing performance, durability, adhesion and the impact of ice-suppressing materials on pavement performance. The test results show that the ice-suppressing material can effectively reduce the adhesion between the ice layer and the specimen, making it easier to remove. The ice-suppression material has good slow-release performance, and the specimens still have good deicing performance after 7 cycles of tests.

Keywords: ice-suppressing materials; mix design; deicing performance; durable performance

1. Introduction

Snow and ice on road pavements are common in most areas of China in winter, they are reducing factors of road surface adhesion coefficient and skid resistance, thus causing the speed of passing vehicles to decrease, prolonging traffic time, increasing fuel consumption, and even causing traffic accidents[1]. Therefore, snow and ice on road surfaces cause enormous pressure to the traffic, affect people's life, resulting in huge economic losses. Currently, a number of traffic issues brought on by ice and snow on roads are of global issue[2]. As a result, melting snow and ice has become a crucial component of winter road maintenance. Effective snow and ice melting has become a key duty for road maintenance personnel. The ability to effectively and conveniently address a number of issues brought on by wintertime road snow and ice has major economic and social benefits[3].

The problem of snow and ice on roads has become a technical problem puzzling the traffic department, leading to an average annual economic loss of hundreds of millions of yuan due to snow and ice on roads. Therefore, many nations attach great importance to the treatment of road snow and ice, and have carried out a lot of relevant research. Literature have examined a range of solutions, including manual removal, mechanical removal, spreading snow melting agents, heating type pavement, conductive concrete, pavement technology to inhibit freezing, ice-suppressing and coating technologies[4,5].

Ice-suppressing material is a material that can reduce the freezing point by means of a melting material within, such as the ice point inhibitor, or isolate the ice layer from the road surface by hydrophobic materials contained in the material itself, so as to achieve the effect of no icing on the road surface or easy deicing of the road surface. Its principle is to load environment-friendly ice melting and snow removing materials plus hydrophobic materials onto the adsorption carrier materials to make an ice-suppressing material, which is sprayed on the asphalt pavement in the form

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of manual brushing or mechanical spraying[6]. When rain or snow falls, the ice melting and snow removing materials on the carrier will be released to melt snow and ice. Meanwhile, hydrophobic materials in the ice-suppressing material can isolate the ice layer from the pavement layer, successfully reducing the adhesion between the ice layer and the pavement, so that the former can be easily removed. Ice-suppressing and coating technologies compared with traditional deicing technologies have the following characteristics: ①active melting of ice and snow;②excellent environmental protection performance; ③efficient and lasting deicing; ④ preventive function[7].

Hydrophobic ice-suppressing technology was originally applied to the field of high-voltage transmission line icing treatment[1]. The high-voltage wire coating deicing technology is an effective high-voltage wire anti-icing and deicing technical measure. A layer of super hydrophobic nano-deicing coating material is applied on the conductor, which can effectively reduce the formation of ice on the transmission line. Road science and technology workers have developed anti-icing and thin ice removal coatings based on hydrophobic deicing technology for high-voltage transmission lines[8]. Ma et al. studied the anti-icing performance of asphalt pavement based on hydrophobic surface and thin ice easy to remove pavement coating application technology, and prepared a coating technology with hydrophobic properties, with similarity to the deicing mechanism of high-voltage conductors. A hydrophobic film is constructed on the surface of asphalt pavement to isolate the ice layer without the function of self-melting and only a small number of test sections have been conducted without summarizing the construction process and technology, and without developing special construction machinery and equipment[9]. The idea of environmental friendly asphalt pavement melting snow and ice coating technology was first put out by Yang. On the one hand, the eco-friendly asphalt pavement melting snow and ice coating technology offers hydrophobic properties that lessen the adhesion between the ice layer and the pavement, as well as a slow-release snow melting and deicing capabilities. The performance of the coating has been investigated, and the necessary test sections have been paved, but no construction technical indicators or requirements have been proposed, nor have any specific construction tools and machinery been developed in accordance with the coating's features[10,11]. According to the principle of ice and snow melting and ice-suppressing and the design of a series of tests, some scholars have examined the performance of ice-suppressing material, and explored construction technologies[4,12]. An anti-freeze, ice-suppressing material for asphalt pavement by adding an appropriate amount of slow-release anti-icing agent (Mafilon) to the emulsified asphalt was designed and synthesized. The deicing effect evaluation test and conductivity test were conducted with various Mafilon contents, finally an experiment on the optimum spraying thickness of the ice-suppressing material was conducted. Siegmund Werner et al. used porous adsorption materials to adsorb self melting snow additives, and achieved long-term snow melting function through slow-release[13]. Kaemereit Wilhelm et al. successfully prepared 0.5~1mm granular self melting snow additive material by using cement as carrier material through the solidification performance of cement. V-260 snow melting agent developed by Verglimit Company in Switzerland is made of calcium chloride coated hydrophobic material, which is widely used at present[14,15]. The Japanese self snow melting technology usually uses porous zeolite as an absorbent to adsorb the salt, and adds it to the asphalt mixture in the form of powder to replace fine aggregate or mineral powder in the mixture[16]. The purpose of snow melting and ice removal is achieved through the release of the salt. China first introduced imported self snow melting technology or materials around 2000. In recent years, many domestic road researchers began to study self snow melting technology[17]. Zhou et al. adopted Japanese snow melting technology to research and develop self snow melting additives[18]. Ma et al. has researched and developed the granular snow melting admixture Iceguard, which is slow-release and non corrosive, safe and environmental friendly to the metal components of bridge and road structures[5]. Shan et al. measured the wettability of the pavement following the application of a hydrophobic coating, the change in stone absorption rate, the length and density of the cracks in the ice layer following the impact of a steel ball[19]. Zheng et al. analyzed and evaluated the performance of the deicing coating from different aspects, namely the anti-ice-snow performances, the durability of the coating materials, and the impact on the skid resistance of the pavement[20]. Wu et al. has established

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a regression model for long-term snow melting performance through research, and has given a calculation formula, which can be used to calculate the precipitation amount of additives on self melting asphalt pavement in different regions of the country[21]. The long term snow melting performance of asphalt mixtures with Iceguard was evaluated by comparing with foreign products and testing roads, combined with rapid dissolution tests to determine the service life of Iceguard[22,23].

Through the research and application of ice-suppressing materials both in China and abroad, it can be seen that the current technologies of ice-suppressing materials are at an initial and exploratory stage. A complete set of technical evaluation indicators and quality control standards for ice-suppressing materials have not been formed, and the current project application is in the test stage[24,25].

The ice-suppressing material developed in this paper has the characteristics of: active deicing, zero negative impact on roads, bridges and other ancillary facilities and vegetation, preventive maintenance for the pavement, and continuous deicing in winter, providing a new method and way for road deicing. The composition design method of the ice-suppressing material is proposed. According to the characteristics of the ice-suppressing material, the performance test evaluation method of the material is proposed and its performance is evaluated, which provides a theoretical basis for the promotion of asphalt pavement ice-suppressing material.

2. Design and preparation of ice-suppressing material composition

2.1. Deicing performance test methods of ice-suppressing materials

An important functional role of ice-suppressing materials is the deicing effect. Anti freezing/anti-icing test, hydrophobic property test, adhesion property test and ice melting property test are used to evaluate the deicing performance of ice-suppressing materials.

2.1.1. Anti-icing test method

In this paper, the kinetic energy generated by the free fall of the steel ball is used to equivalently simulate the force of removing ice from the road surface, and the magnitude of the adhesion force between the ice and the road surface is characterized by the cracking of the ice layer, the test principle is shown in Figure 1.

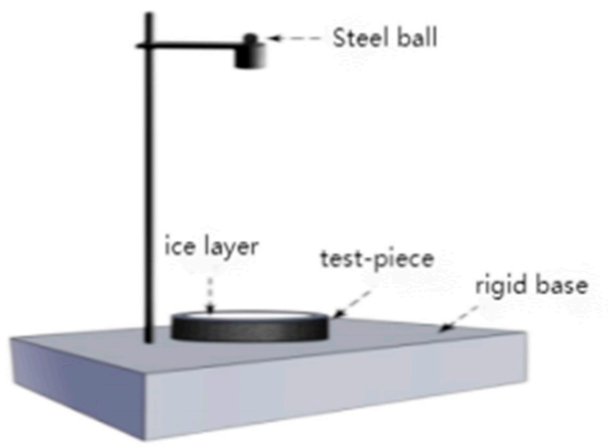

Figure 1. Principle diagram of falling ball impact test.

A qualitative method was used to observe the cracking and breaking condition of the ice surface to evaluate the anti-icing effect as shown in Table 1.

Table 1. Anti-icing effect evaluation method.

Anti-icing effect	Ice surface condition
Excellent	Significant breakage and peeling on the ice surface
Good	Small amount of breakage and cracks on the ice surface
Medium	Only a few cracks on the ice surface
Bad	The only marks on the ice surface are from the impact of the steel ball

In order to evaluate the ice-suppressing material's anti-icing effect more accurately, drawing on the pavement structure layer damage evaluation index, the breakage rate index is proposed to evaluate the anti-icing effect, and the breakage rate calculation formula is shown in Equation 1[26].

$$B_R = \frac{B_A + \lambda L}{A} \tag{1}$$

Where: B_R - breakage rate, expressed in percentage, %.

B_A -Total area of crushing and cracking, cm^2 .

L -extended single crack length, cm.

λ -Influence factor for converting single cracks to area, generally taken as 0.3.

A -Total area of the test, cm^2 .

2.1.2. Hydrophobic performance test method

The hydrophobic performance of the ice-suppressing material is extremely critical to the deicing effect of asphalt pavement, so it is necessary to evaluate its hydrophobic performance after spraying. The hydrophobic performance of the material can be evaluated by the size of the contact angle θ. It is usually considered that when θ> 90°, the material is is hydrophobic, and when θ < 90° it is a hydrophilic material. A larger contact angle θ indicates that the hydrophobic performance of the material is better, currently the methods for measuring contact angle mainly include angle measuring method, height measuring method, force measuring method, droplet image analysis method, transmission method, etc[27] .

With the development of image processing technology, the droplet image analysis method is used to calculate the contact angle with higher accuracy, and the measurement method becomes simpler. In this paper, the contact angle is calculated by droplet image analysis fitting method[28] . Following are the detailed steps:

① Acquisition of droplet edges. The methods of acquiring droplet edges can be divided into automatic image processing or manual image processing. Both have their own advantages and disadvantages. The automatic image processing acquisition method has a fast acquisition speed, and the anti-interference performance needs further research. The manual method has strong anti-interference ability, but the workload is particularly large.

② Calculate the contact angle. The contact angle can be calculated by the tangent method, circle fitting method, ellipse fitting method, Young-Laplace method and polynomial fitting method.

Based on the above theory and method, the contact angle can be calculated by making a sample of ice-suppressing material, using a high-resolution digital camera to photograph the droplet morphology, and combining with Image-Pro Plus or CAD image processing software. The specific steps are as follows:

① Preparation of samples of ice-suppressing material.

② Spraying the prepared sample of ice-suppressing material onto the surface of the glass slide/microscope slide and leaving it at room temperature to cure.

③ Spraying droplets onto the surface of the glass slides coated with cured deicing material.

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④ Recording and photographing the process of droplet morphology change using a high pixel digital camera lens perpendicular to the plane of the slide.

⑤ The contact angle is plotted and calculated using image processing software, as shown in Figure 2.

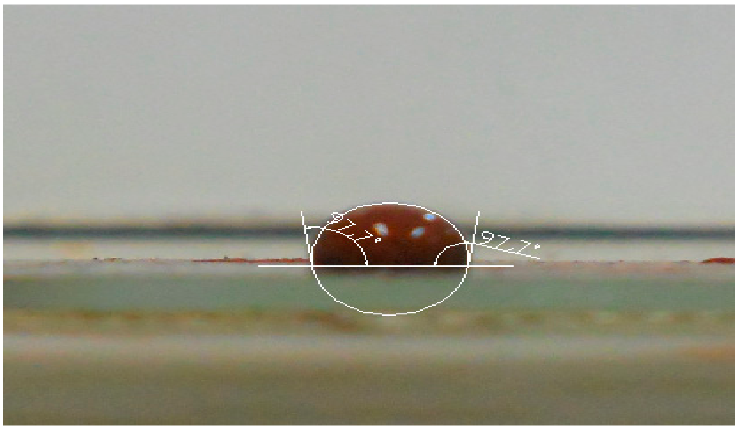

Figure 2. Contact angle determined by image processing software.

2.1.3. Adhesion performance test method

The Bonding material bonding force per unit area is called bond strength. Common methods for measuring bond strength include three-point bending test, shear strength test and tensile strength test. The main purpose of tensile test and shear test is to quantitatively test the adhesion between the sprayed specimen of the ice-suppressing material and ice cubes; in order to reveal clearly the deicing ability of the test pieces of the coating ice-suppressing material, the test pieces of the spraying group and the control group were used for comparative tests; two cylindrical specimens of asphalt mixture were prepared, fixed, water was stored in the middle, and finally freezed in the freezer; In order to simulate more accurately the actual situation, the test temperature was set at - 30 °C, and the freezing time is 12h. Then the test piece were taken out of the freezer and immediately the tensile test and shear test on a 100KN universal testing machine were conducted. The principles of tensile test and shear test are shown in Figure 3 and Figure 4 respectively.

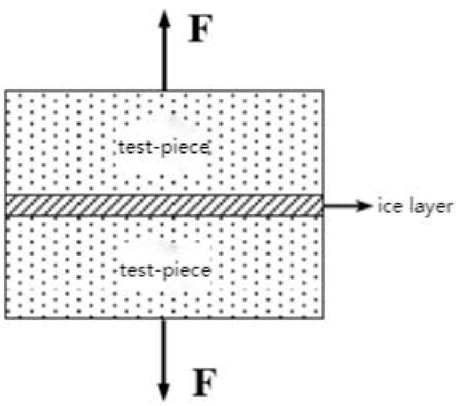

Figure 3. Tensile test schematic.

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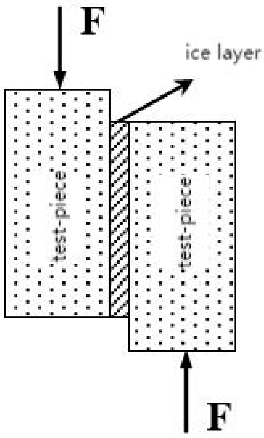

Figure 4. Shear test schematic.

2.2. Design of the composition of the ice-suppressing material

In order to increase the deicing function of the pavement without reducing the skid performance of the pavement, a systematic experimental study was conducted to develop an ice-suppressing material with long-lasting and slow-release characteristics. The final design of the ice-suppressing material includes film-forming component A, adhesive component B and ice suppression component C.

2.2.1. Modified ice suppression component C composition design

According to the design of the ice suppression function of the ice-suppressing material, component C should include the freezing point inhibitor C1, which needs porous adsorption carrier C2 for adsorption. Therefore, the ice-suppressing material should include porous adsorption carrier C2. To avoid the pollution of the color of the ice-suppressing material on the road surface, a small amount of carbon black component C3 is added to enhance the color of the ice-suppressing material powder; the ice suppression component powder was adjusted using a modified coupling agent C4 in order to increase its dispersibility.

The adsorption capacity of porous adsorption carrier material C2 on the freezing point inhibitor C1 can be quantitatively expressed by the mass change before and after the porous adsorption carrier adsorbs the freezing point inhibitor, i.e the adsorption rate. Specific test steps are as follows: weigh the porous adsorption carrier material C2 with a mass of m0 (accurately up to 0.01g) after drying, and then soak it in a saturated solution of ice point inhibitor C1 prepared in advance, and take it out 24 hours later, Weigh the mass m1 after drying in a low-temperature drying oven at 110℃, and calculate the adsorption rate of porous adsorption carrier material according to the above formula(2).

$$S_a = \frac{m_1 - m_0}{m_0} \quad (2)$$

Where: m_1 is the mass of the material after immersion.

m_0 is the mass of the material before immersion.

S_a is the adsorption rate of the porous adsorption carrier material.

The optimal ratio of freezing point inhibitor C1 to porous adsorption carrier C2 can be determined using the above adsorption rate test method, and the test results are shown in Table 2.

Table 2. Adsorption performance test results.

Time (h)	Drying adsorption carrier quality m0 (g)	Drying weight m1 (g)	Adsorption rate (%)

2	100	122.21	22.21
4	100	134.31	34.31
6	100	144.33	44.33
8	100	149.42	49.42
10	100	152.17	52.17
12	100	153.32	53.32
14	100	154.02	54.02
16	100	154.33	54.33
18	100	154.45	54.45
20	100	154.45	54.45
22	100	154.45	54.45
24	100	154.45	54.45

It can be seen from Table 2 that the adsorption rate of the porous adsorption carrier increases with time, and the rate of increase tends to be gradual. After 18h, the adsorption rate of the porous adsorption carrier material does not increase and tends to be stable, indicating that the porous adsorption carrier has reached the saturation state. From this, it can be concluded that the mass ratio of the porous adsorption carrier C2 to the freezing point inhibitor C1 is C2: C1=100:54. The proportion of carbon black C3 and modified silane coupling agent C4 to composite freezing point inhibitor C1 and porous adsorption carrier C2 can be obtained according to practical experience and adsorption performance test, as shown in Table 3.

Table 3. Modified ice suppression component C composition ratio.

Ingredients	Proportion of each component (%)
Complex freezing point inhibitor C1	54
Porous adsorption carrier C2	100
Carbon Black C3	2.5
Modified silane coupling agent C4	1.6

2.2.2. Composition design of film-forming component A

According to the hydrophobic function design of the ice-suppressing material, the composition of the film-forming component A should include the road bonding hydrophobic material silicone-rubber lotion A1, various additives and fillers, including reinforcing agent A2, filler A3, film-forming agent A4, plasticizer A5, catalyst A6, leveling agent A7, defoamer A8, diluent water A9, and anti-skid material quartz sand A10. The role of additives is to promote the plastic flow and elastic deformation of silicone rubber lotion, improve the bonding performance, thereby enhancing and facilitating the effectiveness of the lotion to film-forming. The function of filler is to reinforce silicone rubber and improve the tensile strength of silicone rubber lotion.

The ratio of silicone rubber lotion A1 and diluent was analyzed by hydrophobic and adhesive tests. Several portions of organic silicone rubber lotion with a mass of 100g and a solid content of 20%~60% were weighed, and the organic silicone rubber lotion was mixed with diluent water A9 according to 20g-300g respectively. The hydrophobic property test and adhesion property test were conducted respectively, the contact angle was measured with the height method, and the tensile force and shear force was measured with a UTM machine. The test results are shown in Table 4.

Table 4. Hydrophobic and adhesion test results.

Silicone Rubber Emulsion (g)	Diluent (g)	Contact angle (°)	Hydrophobic grade	Tensile force (N)	Shear force (N)
100	20	90.2	HC1	1644	10506
100	60	96.3	HC1	1478	8056
100	100	102	HC1	1354	6537

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Silicone Rubber Emulsion (g)	Diluent (g)	Contact angle (°)	Hydrophobic grade	Tensile force (N)	Shear force (N)
100	140	108.5	HC1	1259	5245
100	180	112.1	HC1	1215	4165
100	220	109.3	HC1	1242	5148
100	260	107.4	HC1	1340	6449
100	300	98.2	HC1	1537	8730

According to the hydrophobic and adhesion test results in Table 4, the contact angle of the hydrophobic test increases first and then decreases with the increase of the diluent quality, and the tensile force and shear force of the adhesion test decrease first and then increase with the increase of the diluent quality, indicating that with the gradual increase of the diluent quality, the hydrophobicity of the ice-suppressing material increases first and then decreases, and the adhesion property decreases first and then increases; when the contact angle is at its maximum, and the tensile force and shear force are minimum, the mass of the diluent is 180g. At this time, the anti-icing performance of the ice-suppressing material reaches the best. At the same time, the ratio of silicone rubber lotion A1 and diluent A9 is the best, A1: A9=100:180. Based on practical experience, hydrophobic property test, and adhesive property test, as indicated in Table 5, it is possible to identify the optimal ratio of each component in the film-forming component.

Table 5. Composition ratio of film-forming component A.

Ingredients	Proportion of each component (%)
Silicone rubber emulsion A1 with a solid content of 20~60%	100.0
Reinforcing agent A2	4.0
Packing A3	3.0
Film-forming agent A4	4.0
Plasticizer A5	4.2
Catalyst A6	1.7
Levelling agent A7	3.0
Defoamer A8	0.3
Diluent A9	180.0
Anti-slip quartz sand A10	3.0

2.2.3. Adhesive component B composition design

The role of the adhesive component is to accelerate the reaction speed between the components of the ice-suppressing material and speed up the time of opening traffic. The adhesive component is composed of cross-linking agent B1 and coupling agent B2. Based on actual experience, the proportion of the components of the cross-linking agent and coupling agent is usually taken as shown in Table 6.

Table 6. Composition ratio of gluing component B.

Ingredients	Proportion of each component (%)
Cross-linking agent B1	29
Coupling agent B2	71

2.2.4. Ice-suppressing material A, B, C composition ratio

(1) Determination of the mass ratio of component B

Prepare components A and C according to the optimum composition of each component determined by components A and C in advance. The principle of preparation is that component C is dispersed into component A evenly and does not agglomerate. The A: C mass ratio is 100:2. Slowly

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pour component C into component A, and prepare the mixture of components A and C according to this ratio. Add different quality of components B into the mixture of components A and C prepared in advance to prepare the ice-suppressing material. Under conditions where the spraying temperature is 5 °C and the spraying amount of the ice-suppressing material is 0.5kg/m2, Marshall test pieces are made according to the anti-icing test method.

The three components of the ice-suppressing material will undergo curing reaction after mixing. The curing time of the ice-suppressing material includes the curing time in the spraying equipment and the interval of time from when the ice-suppressing material is sprayed on the road to the time it is completely solidified. The curing time of the ice-suppressing material in the spraying equipment is defined as pre-curing time, the time from when the ice-suppressing material is sprayed onto the road surface to the time when the it is completely solidified is defined as post-curing time; the post curing time of Marshall test pieces was measured and the "falling ball impact test" was conducted. The test results are shown in Table 7.

Table 7. Falling ball impact test results.

(A+C) Component mass (g)	Mass of component B (g)	Post-curing time (h)	Breakage rate (%)
100	0.5	7.2	17.9
100	1.0	5.3	17.8
100	1.5	3.8	17.7
100	2.0	3.1	17.6
100	2.5	2.5	15.5
100	3.0	1.7	12.4
100	3.5	0.6	9.9
100	4.0	0.2	6.2

It can be seen from Table 7 that the post-curing time of the test piece gradually decreases with the increase of the mass of component B, and the damage rate of the test piece decreases with the increase of the mass of component B. When component B is less than 2g, the damage rate declines slowly, and when component B is greater than 2g, the damage rate declines dramatically, indicating that when component B is more than 2g, the deicing performance decreases significantly. Considering the deicing performance of the ice-suppressing material and the impact of post-curing time on traffic, the weight of component B should be 2g, and the mass ratio (A+C): B=100:2.

(2) Determination of the mass ratio of component A and C

In the conditions of mass ratio (A + C):B = 100:2, in accordance with different proportions, A and C components formulate the ice-suppressing material, and in accordance with the anti-icing test method for "falling ball impact test" and bonding performance test, the test results obtained are as shown in Table 8.

From the results of Table 8, it can be observed that with the gradual increase in the mass of the component C, the breakage rate gradually increased, the rate of increase tends to level off when component C is greater than 3g, the tensile force and bonding force gradually decreased with the increase in the mass of component C, plus the rate of reduction tends to level off. It is advised that the mass ratio of component A and C be 97:3 in order to fully consider the deicing performance of the ice-suppressing material.

In summary, the mass ratio of component A, B and C obtained is as follows:

mA : mB : mC= 97: 2: 3.

Table 8. Falling ball impact test and bonding performance test.

Mass of component A (g)	Mass of component C (g)	Mass of component B (g)	Breakage rate (%)	Tensile force(N)	Shear force (N)
99.5	0.5	2.0	5.8	1753	10513
99.0	1.0	2.0	9.8	1629	9238

98.5	1.5	2.0	12.9	1537	8295
98.0	2.0	2.0	15.4	1454	7450
97.5	2.5	2.0	17.4	1379	6697
97.0	3.0	2.0	18.2	1304	6148
96.5	3.5	2.0	18.4	1237	5685
96.0	4.0	2.0	18.6	1181	5282
95.5	4.5	2.0	18.7	1151	4906
95.0	5.0	2.0	18.7	1129	4549
94.5	5.5	2.0	18.7	1110	4275
94.0	6.0	2.0	18.7	1095	4034

3. Ice-suppressing Material Deicing Performance Test Results Analysis

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.Ice-suppressing material is a new type of active environmental protection deicing material. At present, there is little research and evaluation on its performance, and no perfect evaluation index and method have been formed. Therefore, it is necessary to study its anti-icing performance according to its deicing characteristics. Performance evaluation and analysis of the ice-suppressing materials need to be developed.

3.1. Analysis of anti-icing test results

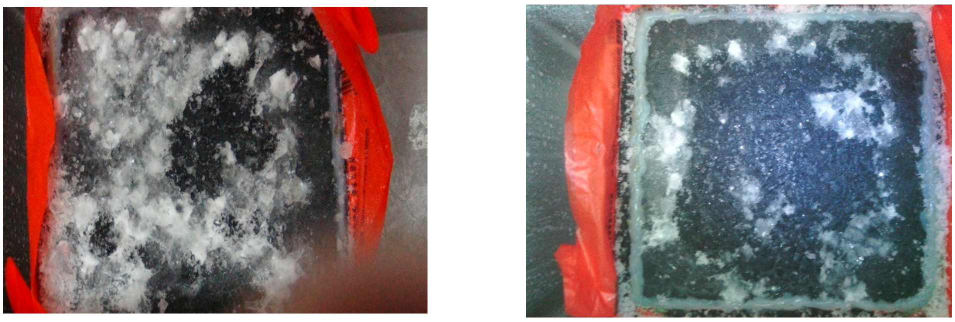
Two groups of Marshall specimens and rutting plate specimens were made with AC-13 grade asphalt mixture, with 5.0% asphalt aggregate ratio. One group of Marshall specimens and rutting plate specimens were sprayed with 0.5kg/㎡ sprinkling amount of ice-suppressing material, and the other group of Marshall specimens and rutting plate specimens were let intact without any treatment. The test was conducted according to the anti-icing test procedure, the falling ball impact test and the Marshall specimens after the falling ball impact test and the gravity knockdown test are shown in Figure 5 and 6, respectively, and the rutting plate specimens after the falling ball test are shown in Figure 7.

Unsprayed Sprayed

Figure 5. Marshall specimens after falling ball impact test.

Sprayed group specimen Unsprayed group specimen

Figure 6. Marshall specimens after gravity knockdown test.



Without spraying group specimen Sprayed group specimen

Figure 7. Rutting plate specimens after falling ball impact.

From Figure 5, it can be concluded that the Marshall specimen contrast group(left) surface has only the steel ball impact marks and pits, while on the right figure, the Marshall specimen spraying group surface can be seen clearly with broken boundaries, and the broken place is without any residual ice adhesion, the anti-icing effect of the ice-suppressing substance can therefore be qualitatively assessed as being better. The ice broken area obtained is 12.72 cm2, measured through indoor measurement of the Marshall specimen spraying group , the calculated breakage rate is 16.2%.

It can be seen from Figure 6 that the ice layer on the surface of the sprayed Marshall specimen can be removed as a whole after being struck by gravity, and there is no dark ice on the surface of the test piece, while the Marshall specimen in the contrast group(unsprayed) has a lot of dark ice, hence, it can qualitatively be assessed that the adhesion between the ice layer and the Marshall test piece in the contrast group is greater than the adhesion between the ice layer and the test piece in the spraying group.

From the falling ball impact test of the rutting plate specimen as shown in Figure 7, it can be concluded that the ice layer of the rutting plate specimen in the contrast group appears to fall off partly in a small area after the impact, and most of the ice layer is attached to the rutting plate specimen, while the ice layer of the rutting plate specimen sprayed with ice-suppressing material appears to fall off in a large area, and there is no dark ice on the rutting plate after the falling, which means that the ice-suppressing material plays a good role in isolating the ice layer and the specimen. The ice layer of the specimen sprayed with ice-suppressing material is very easy to fall off.

3.2. Analysis of hydrophobic performance test results

According to the test procedure of droplet image analysis method, water drops were placed on the surface of glass slides not coated with the ice-suppressing material and glass slides coated with the ice-suppressing material, and photographed at different times (5s, 30s, 2min, 4min, 6min, 8min, 10min, 12min, 14min, 16min, 18min, 20min). Comparison of the static contact angle of the test results

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are shown in Figure 8, where in each picture, the droplets on the left side are on ordinary glass slides (contrast group), and the droplets on the right side are on slides coated with ice-suppressing material (spraying group), and the change of droplet contact angle with time is shown in Figure 9.

Figure 9 illustrates the change in the contact angle of droplets over time. The contact angle gradually decreases with the gradual increase of time, the reason for the decrease of contact angle is mainly due to the evaporation of droplets of water and the gradual expansion of droplets with the plane of the slide, therefore, in order to reduce errors and obtain a more realistic contact angle, the time to measure the contact angle is as short as possible. The contact angle of droplets on slides coated with ice-suppressing material was 99.5°at 5s, which became smaller gradually with the increase of time and was 83.3° at 20min. The contact angle of droplets on ice-suppressing material varied from 99.5° to 83.3°, while the contact angle of droplets on clean slides varied from 39.2° to 29°. From the data comparison, it can be concluded that the ice-suppressing material has good hydrophobic properties and can significantly reduce the adhesion between the ice layer and the road surface.

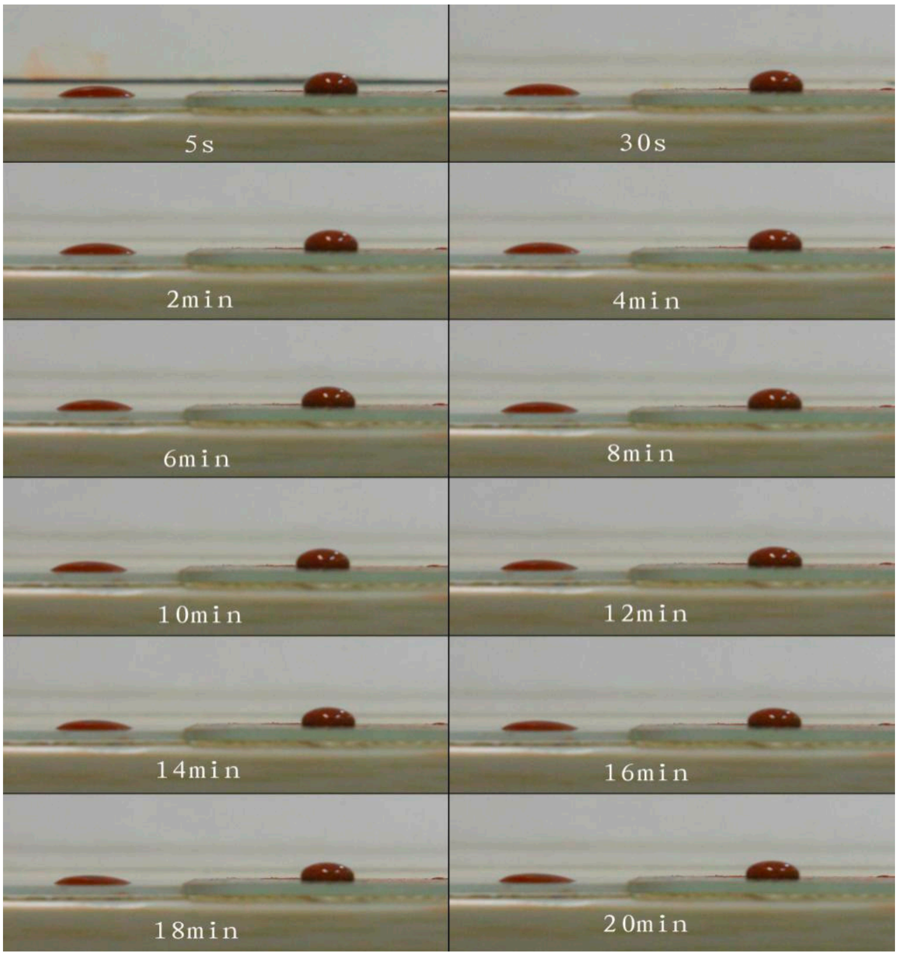

Figure 8. Real time image of liquid drop contact angle.

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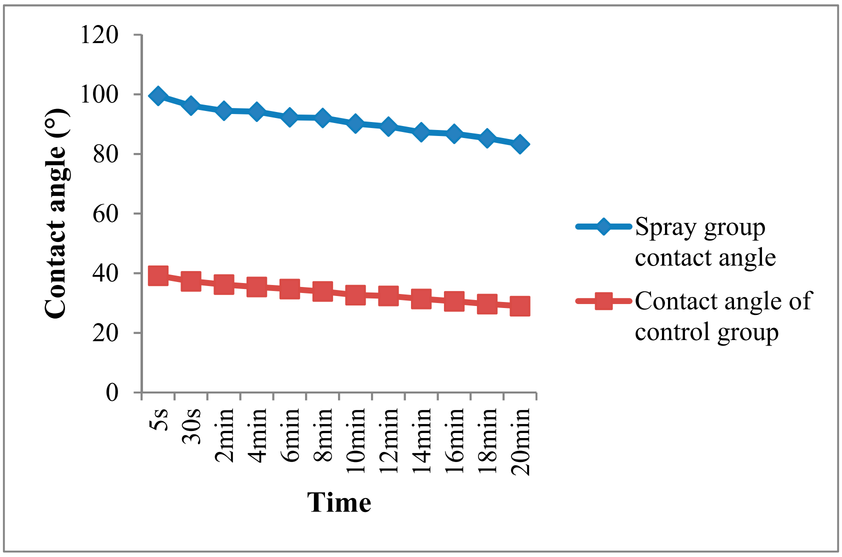

Figure 9. Plot of droplet contact angle over time.

3.3. Analysis of adhesion performance test results

According to the test methods and procedures of adhesion performance, the tensile test and shear test of the sprayed asphalt mixture specimens and the unsprayed contrast asphalt mixture specimens were produced. The interface between the ice layer and the specimens after tensile and shear tests are shown in Figure 10 and Figure 11, the results of tensile and shear tests are shown in Figure 12.

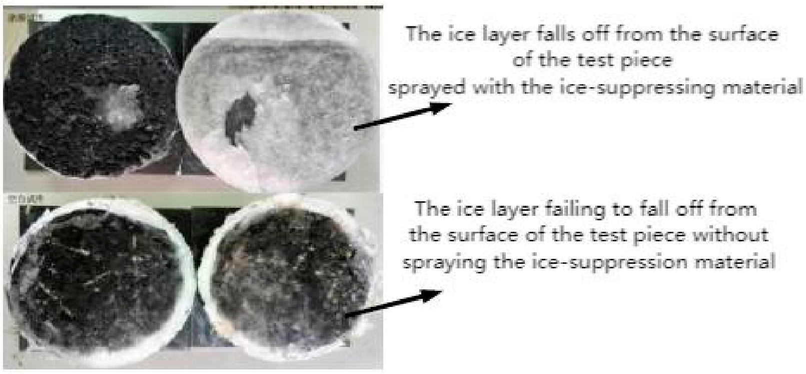

Figure 10. Ice-sample interface after tensile test damage.

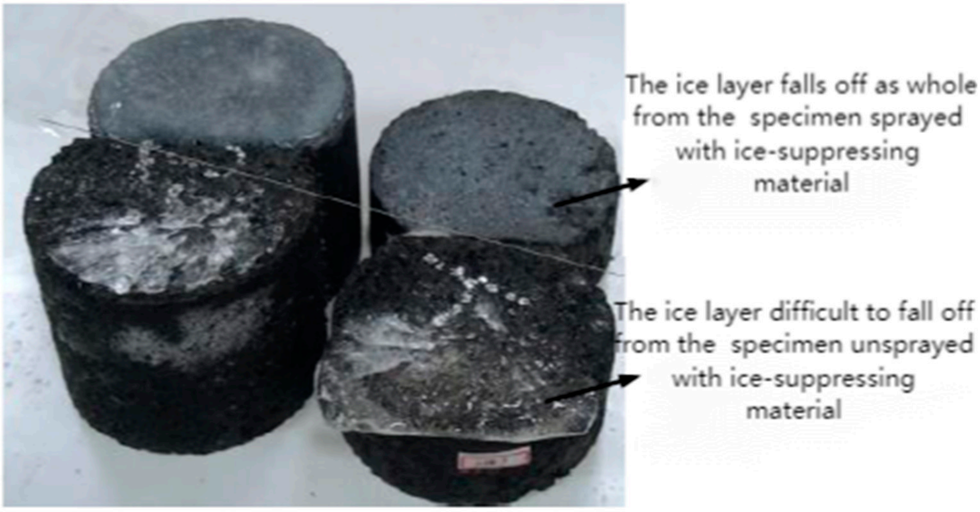

Figure 11. Ice-sample interface after shear test damage.

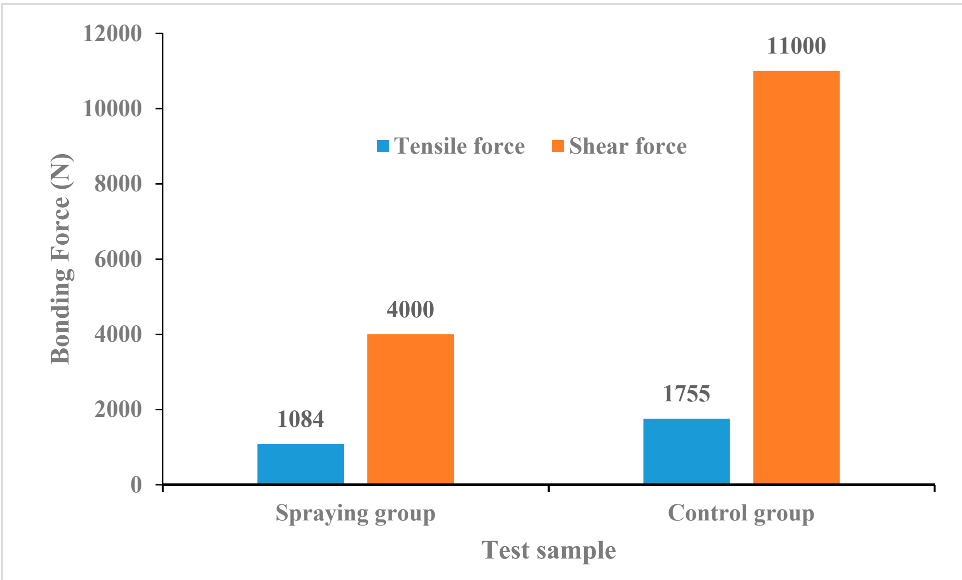

Figure 12. Test results of adhesion performance of specimens in spraying group(left) and unsprayed contrast group(right).

The tensile test results from Figure 12 show that when the tensile force of the sprayed group specimen is 1084N, the ice layer is detached from the specimen, and almost no dark ice exists on the surface of the specimen, and the cross-section is flat, which is due to the chemical action of the freezing point inhibitor resulting in the strength of the interface becoming less than the strength of the ice. The fracture occurs at the interface. And when the tensile force between the ice layer and the specimen of the unsprayed contrast group specimen reaches 1755N, the ice layer is detached from specimen, and the two specimens are broken from the middle of the ice layer. A large amount of dark ice still existed on the surface of the specimen, and the cross section between the test piece and the ice layer is conical. The tensile force between the ice layer and the surface of the test piece after brushing with the ice-suppressing material is 38.2%, lower than that between the ice layer and the test piece without the ice-suppressing material. The lower tensile force indicates that the adhesive force between the ice-suppressing material test piece and the ice layer is lower, and the ice layer is easier to remove.

Shear test results show that when the spraying group specimens under shear force reached 4000N, the specimen and the ice layer detached, and almost no dark ice exists on the surface of the specimen, the cross-section is flat. The unsprayed contrast group specimens under the tensile force reached 11000N, the specimen and the ice layer detached, the two specimens are broken from the middle of the ice layer, A large amount of dark ice still existed on the surface of the specimen, and the cross section between the test piece and the ice layer is conical, the test results are similar to the tensile test results. The shear force between the ice layer and the surface of the specimen is reduced by 63.6% after the ice-suppressing material is applied. A lower shear force is favorable for the wheel to crush the ice layer.

3.4. Ice melting performance test and result analysis

The ice melting performance of ice-suppressing material is the key factor affecting the separation of ice and asphalt pavement, as a result the ice-suppressing material melt the lower surface of the ice layer, thus making the ice layer separated from the asphalt pavement, in order to simulate the melting performance of ice-suppressing materials on the ice layer.

According to the test method and procedure of ice melting performance test, the Marshall test pieces of the spraying group and the Marshall test pieces of the unsprayed contrast group were made respectively. The ice mass of the two groups of test pieces was 60g at -30℃, and the temperature increased by 2℃ every hour. In order to reduce the impact of temperature increase on the change of ice mass, the maximum temperature was increased up to 0℃. The ice melting performance test results are shown in Table 4 and Figure 13.

Table 4. Ice melting performance test results.

Temperature (℃)	Sprayed group ice mass (g)	Unsprayed group ice mass (g)
-30	60	60
-25	57	59
-20	51	57
-15	43	52
-10	32	45
-5	19	35
0	4	23

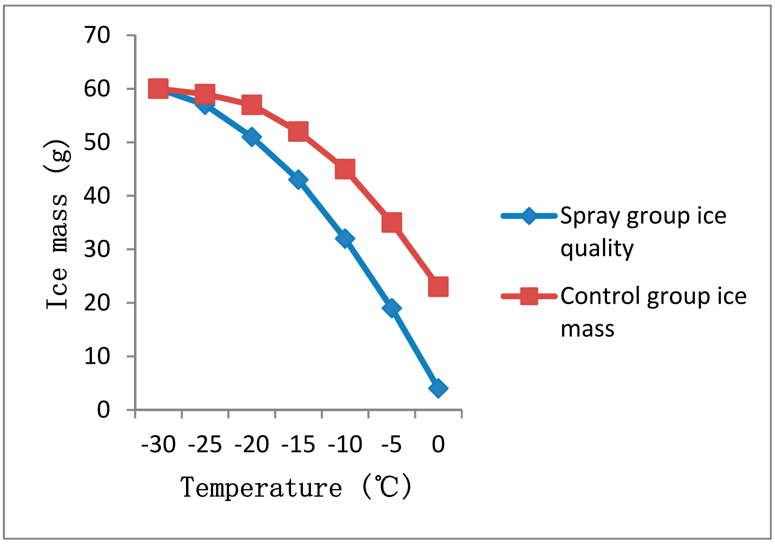

Figure 13. Ice melting performance test results graph.

It can be seen from Figure 13 that with the increase of temperature, the mass of ice cubes decreases gradually, and the rate of mass reduction increases gradually; at the same temperature, the mass reduction rate of the unsprayed group's ice cube is significantly lower than that of the sprayed group's ice cube. Excluding the influence of temperature rise on the change of ice cube's mass, indicating that the ice-suppressing material has a good ice melting performance.

4. Conclusions

In view of the characteristics of the ice-suppressing material, the test method for the deicing performance of the ice-suppressing material, the key technologies of the ice-suppressing material and the selection principle of the key component materials are proposed. Through the evaluation of the deicing performance method, the composition proportion of each component of the ice-suppressing material is obtained. Its performance is studied and analyzed from the aspects of its deicing performance and durability. The main conclusions are as follows:

(1) According to the characteristics of the ice suppressing material, an evaluation method for the deicing performance is proposed. The hydrophobicity of the material was evaluated by measuring the contact angle using the droplet image analysis method. Tensile test and shear test were used to evaluate the adhesion of the material to the ice layer.

(2) According to the characteristics of the ice-suppressing material, the proposed evaluation method for the deicing performance is used to design the components of the ice-suppressing material. Through analysis, the mass ratio of component A, component B and component C is m_A: m_B: m_C=97:2:3.

(3) The ice-suppressing material has a good isolation effect on the ice layer and the test piece, and the ice layer of the test specimen sprayed with ice-suppressing material is very easy to fall off.

(4) The contact angle of water droplets on glass slide coated with ice-suppressing material θ with a variation range of 99.5°~83.3°, while the contact angle of water droplets on the clean glass slide is 39.2°~29°. The larger the contact angle is, the stronger the hydrophobicity is, thus the stronger the ice-suppressing material's hydrophobicity.

(5) The tensile strength of the ice layer and the coated ice-suppressing material specimen decreased by 38.2%, the shear strength decreased by 63.6% compared with the uncoated ice-suppressing material specimen, indicating that the ice-suppressing material can effectively reduce the adhesion between the ice layer and the specimen, making it easier for the ice layer to remove.

(6) Under external conditions with temperature lower than 0°C, at the same temperature, the mass reduction rate of the uncoated group's ice cube is obviously lower than that of the coated group's ice cube. The influence of temperature rise on the change of ice cube's mass is ruled out, which indicates that the ice-suppressing material has good ice melting performance.

(7) The ice-suppressing material has a good slow-release performance, and still has good deicing performance after 7 cycles of tests.

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