

## Research Article

# Study on Synthesis and Service Properties of Anticoagulant Ice Microcapsule Coating Material

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The presence of ice and snow on a road surface in winter will reduce the traffic capacity of the road network, which can easily lead to traffic accidents. In this study, nonchlorine organic snow-melting salt was added to emulsified asphalt to prepare an anticoagulant ice fog seal. Considering the destructive effect of snow-melting salt on the stability of emulsified asphalt, polyvinyl alcohol was used as an encapsulation material to form a stable two-phase system by mixing snow-melting salt with emulsified asphalt. The zeta potential method was used to test the storage stability of the encapsulated salt solution. The results showed that the material and content of the encapsulation had a significant effect on the stability of the emulsified asphalt and the reduction in the freezing point of the encapsulated salt solution. PVA (1.5%) mixed with 24% sodium acetate was used to prepare an encapsulated salt emulsion, which was mixed with anionic emulsified asphalt and sprayed on the road surface. This significantly reduced the freezing point of road surface water. The recommended spraying dosage of the anticoagulant ice fog seal layer was 0.4 kg/m<sup>2</sup>, which could lower the freezing point by at least -8°C while simultaneously meeting the antislip performance condition. This was shown to be a preventive maintenance technology with both anticoagulant ice and maintenance effects.

## 1. Introduction

At the beginning or end of winter, any snow on the road gradually melts under the action of the traffic load, which can easily form a thin layer of ice when the temperature is below freezing. The presence of ice and snow on a road surface will reduce the traffic capacity of the road network, and cars will be prone to skidding, which is particularly detrimental to the driving dynamics and safety of vehicles [1]. The current methods for removing ice and snow from roads can be divided into two categories: external technology (passive snow removal) and internal technology (active snow removal) [2]. The methods included in the external technology category mainly involve spraying snow-melting agents and manual and mechanical removal. Those included in the internal technology category mainly include geothermal and solar thermal ice-melting technology and

physical and chemical ice and snow suppression technology [3].

Mechanical snow removal cannot completely remove all of the snow. At the same time, it causes a certain amount of damage to the road surface, and there are often problems with insufficient personnel and machinery [4, 5]. Snow-melting agents are widely used because of their high efficiency, low price, and easy availability [6]. However, the use of snow-melting agents has seriously impacted the environment alongside highways, mainly by causing the large-scale destruction of green vegetation and severe corrosion of the reinforced concrete in roads and bridges [7]. In addition, snow-melting agents can also affect the properties of the soil and water bodies [8].

The commonly used chemical snow-melting agents are mainly divided into three types: chloride, nonchlorine, and mixed [9]. Inorganic chloride salts with sodium chloride,

calcium chloride, potassium chloride, and magnesium chloride as the main components are called chloride salt-type snow-melting agents, whereas organic snow-melting agents with potassium acetate and other organic substances as the main components are collectively called nonchloride-type snow-melting agents. This type of snow-melting agent mainly consists of salts, amines, and alcohols. Based on the material form of the salt, the salts can be divided into the aggregate, filler, and paint types. In the first two, the salt compound is prepared as coarse particles or a fine powder and used to replace part of the fine aggregate or mineral powder in the asphalt mixture. In the third type, the salt is prepared as an emulsion to be sprayed on the road surface and is often used for short-term salt storage. To increase the slow release effect, the salt material usually requires inclusions. The inclusion materials can be divided into the oleoresin type, inorganic cement type, and porous carrier type [10, 11]. (1) The earliest examples of the oleoresin type are the use of fats and oils, such as linseed oil as coating materials for salt [12]. Later, the use of various resins and water repellents gradually developed [13, 14]. (2) Powder sintering, gel material cementation, and other methods are used for the inorganic cement type [15, 16], where the snow-melting components are consolidated inside the particles, and even the salt-containing gelling material itself can be used as a salt storage structure [17]. (3) In the porous carrier type, porous structures, such as volcanic rock or zeolite materials [18, 19], are mainly used to load snow-melting components. Paint-type salts usually use various emulsions as carriers to prepare salt storage emulsions. Direct spraying in new construction, reconstruction, expansion, and even existing roads can be used for the short-term functions of salt storage and snow melting. A salt storage emulsion can be used for road spraying, as well as a slurry seal, fog seal, and so on [20, 21]. In addition, the adsorption of a snow-melting salt in the prefabricated porous structure of a road or bridge deck can also perform the functions of short-term salt storage, snow-melting, and ice suppression [22].

The long-term anti-icing effect of salt-storing asphalt pavement and the effect of snow-melting salt on the performance of asphalt mixtures need to be verified. In addition, the removal of ice and snow is a seasonal requirement, and high temperatures and rain in summer cause a salt loss in salt-storing asphalt pavements [23].

Paint-type salt can be used for the preventive maintenance of roads, with convenient and simple construction and high flexibility. Some road sections prone to freezing can be sprayed in an emergency based on the weather forecast. The amount of snow-melting agent can be designed based on the climatic conditions of a specific section and region [24]. In this study, a preventive maintenance emulsion with an anti-icing function was prepared by adding a nonchloride salt to the emulsified asphalt. The stability of the emulsified asphalt was greatly reduced by the addition of salt electrolyte materials. According to the Stern electric double layer theory, the mutual repulsive force between the asphalt particles in emulsified asphalt can only be thermodynamically balanced by offsetting the collision and gravity settlement caused by Brownian motion [25]. The repulsive

force of asphalt particles mainly comes from two aspects: the electric double layer around the particles and the interaction between the nonionic substances adsorbed on the surfaces of the particles. The electric double layer consists of two parts. The particles distributed on the surface of the asphalt particles are called positioning ions, which constitute the inner layer; the opposite ions attracted to the outside of the particles are called counterions, which constitute the diffusion layer. A schematic diagram of a bitumen particle electric double layer is shown in Figure 1.

Ionic emulsified asphalt particles have polar charges on their surfaces, and their microstructures follow the electric double-layer model. The zeta potential is generally used as a measure of the electric double layer. According to thermodynamic theory, the zeta potential of the emulsion affects the storage stability of the emulsified asphalt. The zeta potential value is only related to the activity of the ions adsorbed by the asphalt particles in the solution [27]. In the electric double layer, the potentials at different distances from the surfaces of the asphalt particles are also different, as shown in Figure 2. If it is supposed that the concentrations of positive and negative ions at CD are equal, the potential is zero. When a certain amount of charge is adsorbed on the surfaces of the asphalt particles, the potential difference relative to CD is  $\psi$  (i.e., the thermodynamic potential). When the particles are affected by an external electric field and move along the AB surface, a potential difference is generated, which is called the electrokinetic potential ( $\zeta$  electric potential) [28, 29]. As shown in Figure 2, the thickness of the diffusion layer determines the size of the potential, with a thinner diffusion layer resulting in a smaller electrokinetic potential. When the diffusion layer overlaps CD, the electrokinetic potential is zero.

Using the  $\zeta$  electric potential test method, suitable polymer materials were selected for the interface film to wrap the snow-melting salt and form a microencapsulated structure [30]. After mixing with the emulsified asphalt, the two phases reached thermodynamic equilibrium and formed a stable emulsified asphalt-based snow-melting stock solution [31]. Before spraying on the road surface, a fog seal layer was formed. A pull-out test and simulated freezing test were used to evaluate the anti-icing performance of the fog seal. The emulsified asphalt in the anti-icing fog seal layer slowly released the nonchlorinated snow-melting salt after demulsification. In a low-temperature environment in the winter, this can reduce the freezing point of the road surface water and make the road less icy. When extreme icy and snowy weather occurs, it can also achieve good deicing and snow removal effects when combined with other external technologies.

## 2. Experimental Design

### 2.1. Materials

**2.1.1. Asphalt.** Asphalt materials mainly play a cohesive role during use. Asphalt with high penetration is easier to emulsify than asphalt with low penetration. Therefore, high penetration asphalt or wax-free base asphalt should be

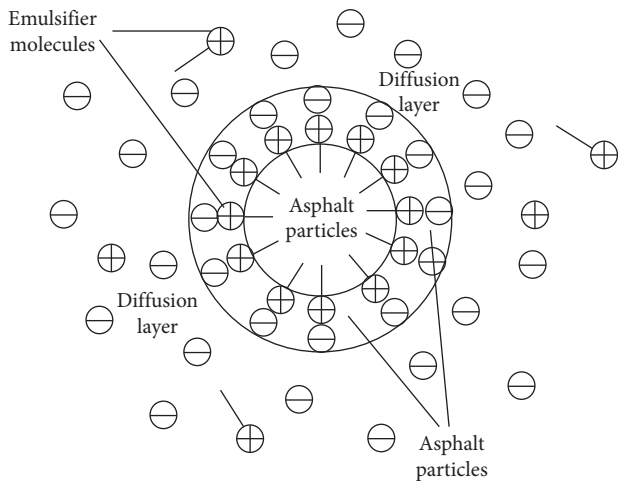


FIGURE 1: Schematic diagram of the electric double layer of the asphalt particle [26].

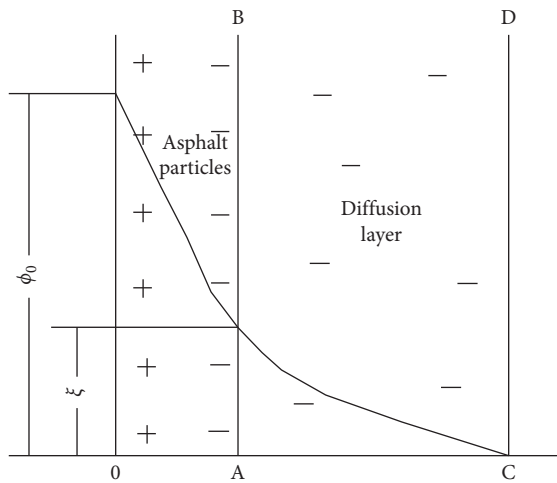


FIGURE 2: Schematic diagram of emulsified asphalt zeta potential [27].

selected as much as possible. In this study, road asphalt No. 90 A grade was selected for the experiment. The basic properties of grade 90 A road asphalt are listed in Table 1.

**2.1.2. Emulsifier.** A cationic quick-cracking emulsifier and an anionic emulsifier were adopted.

The effects of different emulsifier dosages on the stability of the asphalt emulsions were tested (Tables 2 and 3). The emulsifier adopts cationic quick-cracking emulsifier and anionic emulsifier, respectively. When the amount of emulsifier is small, the asphalt cannot be fully emulsified; when the amount of emulsifier is large, the fluidity of the emulsified asphalt is enhanced and the flow rate is faster, so the appropriate amount of emulsifier should be selected. The table shows that different ionic emulsifiers have the same influence on the storage stability (5d) of emulsified asphalt, and the change trend of the absolute value of the zeta potential is also the same.

The stability of emulsified asphalt increases with the amount of emulsifier, and the continuous phase viscosity of the asphalt emulsion continues to increase. The storage stability of emulsified asphalt is basically the same as the absolute value of the zeta potential. Therefore, the absolute value of the zeta potential could be used to evaluate the stability of the emulsified asphalt. Considering the stability and cost of the emulsion, the dosage of the cationic emulsifier was 1.5%, and the dosage of the anionic emulsifier was 2.8%.

**2.1.3. Polymer Encapsulation.** In this study, three polymer encapsulation materials were selected: agar, carboxymethyl cellulose, and polyvinyl alcohol. The agar solution is a colorless, transparent, and viscous liquid. It can form a layer of hydration film on the surface of the asphalt particles when added to the asphalt solution. It has the functions of thickening, stabilizing, and dispersing the emulsified asphalt [32].

After the sodium carboxymethyl cellulose is added to the pitch, the molecules are cross-linked together, and the snow-melting salt is wrapped in the solution to increase the viscosity of the capsule salt emulsion. After being mixed with emulsified asphalt, it can protect the asphalt particles in the emulsion from being affected by external conditions and demulsify so that the storage stability of the snow-melting agent is improved [26].

Polyvinyl alcohol is a macromolecular compound that can protect asphalt particles and help asphalt emulsification. However, if the amount is too large, the extensibility of the asphalt will be reduced [33].

**2.1.4. Stabilizing Agent.** The stabilizing agent was polyacrylamide, which is a white powder with a solid content of  $\geq 88\%$  and cation concentration of 10–60% based on test. Polyacrylamide can increase the consistency of the water phase, decrease the density difference between the oil and water phases, and form a dense interfacial film on the surface of asphalt particles. It can slow down the collision strength of dispersed asphalt particles and prevent coalescence or precipitation. The influence of the stabilizer dosage on the stability of the emulsified asphalt is shown in Figures 3 and 4.

With the increase of the amount of stabilizer, the stability of emulsified asphalt with different ions increases, but when the amount exceeds 0.8%, the 5d storage stability of the emulsified asphalt cannot be significantly improved. Based on economic considerations, the stabilizer is the best. The dosage is 0.8%.

**2.1.5. Nonchloride Snow-Melting Salt.** The nonchlorinated snow-melting salt contained sodium acetate and magnesium acetate.

## 2.2. Experimental Methods

**2.2.1. Bond Strength Test.** In extreme snowy and icy weather, rain and snow condense into ice on a road surface, greatly

TABLE 1: Properties of no. 90 A asphalt.

Items	Unit	Skill requirement	Test results	Experiment method
Penetration 100 g, 5 s, 25°C	0.1 mm	80~100	86	T0604
Softening point $T_{R\&B}$	°C	≥45	46.5	T0606
Dynamic viscosity 60°C	Pa·s	≥160	187.1	T0620
Ductility 5 cm/min, 10°C	cm	≥45	>100	T0605
Ductility 5 cm/min, 15°C	cm	≥100	>100	T0605
Wax content (distillation method)	%	≤2.2	1.7	T0615
Flash point (COC)	°C	≥245	264	T0611
Solubility (trichloroethylene)	%	≥99.5	99.72	T0607
Density, 15°C	g/cm <sup>3</sup>	Measured record	1.028	T0603
Quality change	%	≤±0.8	-0.158	T0609
After TFOT	Residual penetration ratio	≥57	66.2	T0604
	Residual ductility, 10°C	≥8	14	T0605

TABLE 2: Effect of cationic emulsifier dosage on emulsion performance.

Emulsifier dosage (%)	The remaining amount on the sieve (%)	5d storage stability (%)	Zeta potential value (mV)
1.1	0.215	6.12	16.7
1.3	0.117	3.58	20.8
1.5	0.046	2.42	22.1
1.7	0.037	2.01	32.4

TABLE 3: Influence of the amount of the anionic emulsifier on the performance of emulsion.

Emulsifier dosage (%)	The remaining amount on the sieve (%)	5d storage stability (%)	Zeta potential value (mV)
2.0	0.38	9.64	12.3
2.2	0.23	8.75	16.4
2.4	0.16	6.25	28.6
2.6	0.09	5.33	32.3
2.8	0.07	4.21	48.3
3.0	0.03	3.36	51.2
3.2	0.02	3.23	53.6

reducing its antiskid performance. At present, there is no comprehensive method for quantitatively characterizing the bonding strength of ice and roads. Therefore, this study designed and developed a “road surface ice and snow bonding strength test device” to test the bonding strength between the fog seal layer and the ice surface. This device is shown in Figure 5. The device could quantitatively evaluate the freezing point and its effect on melting snow and ice.

The road surface ice and snow bond strength test included the following steps:

- (1) Two sets of asphalt mixture test pieces (300 × 300 × 50 mm) were obtained, with a sprayed anticondensation ice fog sealing layer on the surface of one set of test pieces.
- (2) A thin coating of epoxy resin adhesive was applied to the drawing indenter, and a nonwoven piece of fabric with a thickness of 5 mm was glued to the drawing indenter. The curing time of the adhesive was less than 30 min.
- (3) The drawing indenter was immersed in water to saturate the nonwoven fabric with water and then placed on the surface of the asphalt mixture sample.

They were then kept in a low-temperature environment at -4°C for 4 h.

- (4) At the set test temperature, the drawing test was carried out at a constant speed of 5 mm/min to determine the breaking tensile force when the surface of the asphalt mixture specimen was separated from the drawing indenter, and the bond strength was calculated according to the following formula:

$$S = \frac{F}{A_e}, \quad (1)$$

where  $S$  is the bond strength (MPa),  $F$  is the breaking force (N), and  $A_e$  is the effective contact area between the anticondensation ice fog sealing layer and nonwoven fabric (mm<sup>2</sup>).

**2.2.2. Simulated Freezing Test.** After the anticondensation ice fog seal layer is demulsified under the action of the atmosphere and driving, the salt that continuously precipitates from the cyst combines with the road surface water,

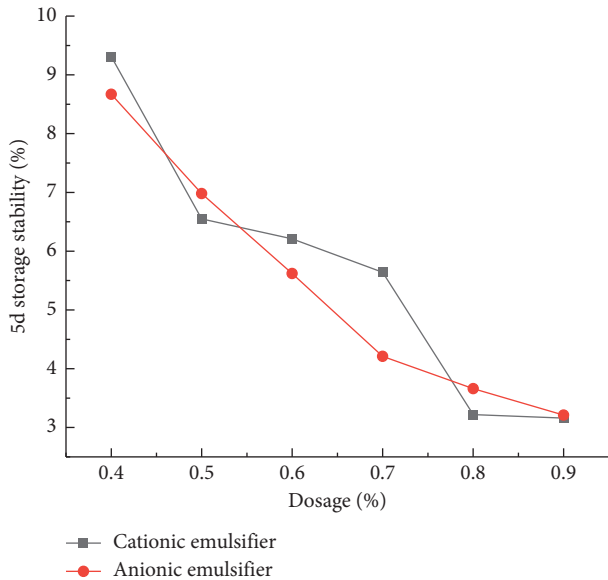


FIGURE 3: The effect of stabilizer dosage on 5d storage stability.

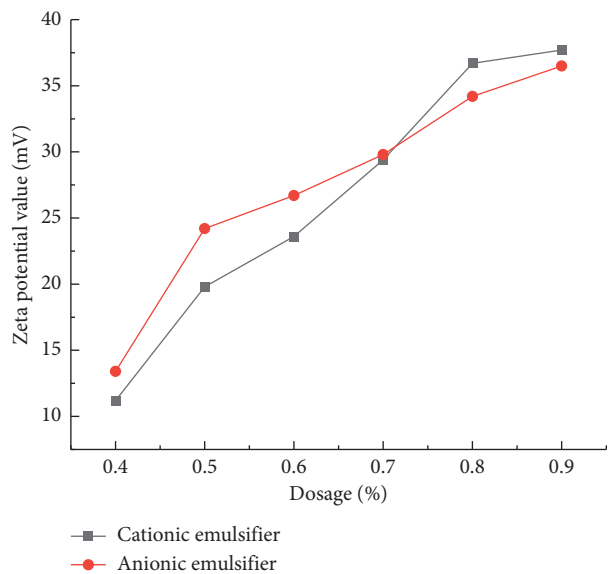


FIGURE 4: The effect of stabilizer dosage on the zeta potential value.

where it reduces the vapor pressure of the water to achieve the effect of reducing the freezing point. When its freezing point is lower than the ambient temperature, snow will change from the solid phase to the liquid phase and will exist as muddy salt water on the road surface. This state will keep ice and snow from freezing for a long time. The test method tested the freezing and slow release effects of the self-melting ice fog seal layer by simulating the freezing and thawing of road surface water. The test steps were as follows:

- (1) Pour 20 mL of the encapsulated salt emulsion (about 1.5 mm in thickness) into a Petri dish and allow it to solidify at rest
- (2) Add water to a thickness of approximately 5 mm to the surface of the completely solidified seal layer

- (3) Place the Petri dish in a low-temperature environment and observe the freezing temperature of the free water on the fog seal layer as the temperature decreases to  $-4^{\circ}\text{C}$  and  $-5^{\circ}\text{C}$ , with an observation time interval of 10 min
- (4) Finally, melt the frozen ice shell on the surface of the seal layer and replace it with pure water to repeat the freezing and thawing cycle to test the slow release effect of the anticoagulation ice fog seal layer

**2.2.3. Skid Resistance Test.** A laboratory sand patch test was used to measure the structural depth (TD) of the anti-condensation ice fog seal layer and to test the attenuation of the structural depth before and after spraying the anti-condensation ice fog seal layer.

**2.2.4. Antiwear Performance Test.** The anti-icing fog seal layer is sprayed on the road surface before snowfall in winter and is subject to the combined actions of cars and rain, which easily causes abrasion and reduces the snow-melting effect. Therefore, a wet wheel abrasion tester was used to study the abrasion resistance of the anti-icing fog seal layer.

### 3. Preparation of the Anticondensation Ice Fog Seal Layer

**3.1. Preparation of Emulsified Asphalt.** The oil-water ratio of the emulsified asphalt used in the fog seal in this study consisted of 55% asphalt and 45% water, and the colloidal mill speed was approximately 2870 r/min. The amount of cationic emulsifier was 1.5%, and the amount of anionic emulsifier was 2.8%.

First, the emulsifier and stabilizer were dissolved and mixed in water at approximately  $70^{\circ}\text{C}$  and added to the colloid mill for shearing for 3 min. Then, the base pitch was heated to  $130^{\circ}\text{C}$ . The results of the related performance tests of the prepared emulsified asphalt are listed in Table 4. The performance of asphalt emulsions prepared by different ionic emulsifiers has little difference, and the prepared asphalt emulsions have good stability. All indexes of emulsified asphalt meet the inspection standards of emulsified asphalt in the petroleum industry. At the same time, the emulsifier improves the original performance of the asphalt after the emulsion is demulsified.

**3.2. Preparation of Encapsulated Salt Emulsion.** In this study, the effect of melting snow and ice was achieved by adding a nonchlorinated snow-melting salt to the emulsified asphalt. However, when a large amount of a salt electrolyte is added to emulsified asphalt, the demulsification speed of the emulsion is accelerated. Therefore, a type of encapsulated emulsion was prepared, and a high-molecular-weight polymer was used to wrap around the salt to form an encapsulated structure and then mixed with the emulsified asphalt so that the two-phase system could exist stably.





FIGURE 5: Bond strength test device.

The compatibility design of the encapsulated salt emulsion was based on the relationship between the freezing point depression value and solute molar concentration:

$$\Delta T_f = k_f \times m, \quad (2)$$

where  $\Delta T_f$  is the freezing point drop ( $^{\circ}\text{C}$ ),  $k_f$  is the molar freezing point drop constant of the solvent ( $k \cdot \text{kg} \cdot \text{mol}^{-1}$ ), and  $m$  is the molarity of the solution ( $\text{mol}/\text{kg}$ ).

Nonchloride salts are generally divided into two types: AB and  $\text{AB}_2$ . Water was used as the solvent, which has a  $K_f$  value of  $1.86 \text{ K kg mol}^{-1}$ . For the AB type strong electrolyte, 2 mol of ions was completely ionized in water, and the  $K_f$  value was  $3.72 \text{ K kg mol}^{-1}$ . For the  $\text{AB}_2$  type of strong electrolyte, 3 mol of ions was completely ionized in water, and the  $K_f$  value was  $5.58 \text{ K kg mol}^{-1}$ . In the preliminary plan to reduce the freezing point to  $-8^{\circ}\text{C}$ ,  $\Delta T_f$  was 8 K.

According to formula (2), when the freezing point drops to  $-8^{\circ}\text{C}$ , the  $K_f$  value of sodium acetate is 3.72, the molecular weight is 82.03, and the dosage is 17.6 g; the  $K_f$  value of magnesium acetate is 5.58, the molecular weight is 214.46, and the dosage is 30.7 g. In laboratory tests, it was found that when the sodium acetate content exceeded 6 g and the magnesium acetate content exceeded 9 g, the emulsified asphalt was demulsified. Therefore, the emulsification effect of the emulsified asphalt was protected by adding a high-molecular-weight polymer to wrap the snow-melting salt and form a capsule structure.

In this study, agar, carboxymethyl cellulose, and polyvinyl alcohol were selected as the encapsulation materials. The stability results obtained using 1.5% encapsulation + snow-melting salt mixed with emulsified asphalt are listed in Table 5. Polyvinyl alcohol was selected as the

encapsulation material based on the compatibility of the encapsulated salt emulsion.

It can be seen that the combinations of the cationic emulsified asphalt with magnesium acetate and the anionic emulsified asphalt with sodium acetate had better uniformity and storage stability. The structure of the encapsulated salt emulsion was observed using a fluorescence microscope, as shown in Figure 6. The microcapsule-encapsulated salt could exist stably in the emulsified asphalt. It was evenly distributed and remained intact. The anionic encapsulated salt solution had good stability, and the demulsification time could be as long as 30 days or more. Encapsulated salt emulsions can be used during the construction period in practical engineering.

After the encapsulated salt emulsion was prepared, it was stored in a closed vertical tank at room temperature, and the emulsified asphalt was properly stirred during storage. There should be no segregation, no freezing, and no demulsification during the storage period.

## 4. Results and Discussion

**4.1. Bond Strength Test.** In this test,  $0.4 \text{ L}/\text{m}^2$  was applied to the asphalt mixture sample, and the bond strength results at different drawing rates at  $-8^{\circ}\text{C}$  are listed in Table 6.

It can be seen from Table 6 that the use of a constant drawing speed of 5 mm/min provided better control in the test, with less data deviation and more accurate results. Therefore, the drawing rate of the drawing tester was adjusted to 5 mm/min, and the breaking strength was measured at different spray rates at  $-6^{\circ}\text{C}$ ,  $-8^{\circ}\text{C}$ ,  $-10^{\circ}\text{C}$ ,  $-12^{\circ}\text{C}$ , and  $-14^{\circ}\text{C}$ . The bond strength results were calculated, as shown in Table 7 and Figure 7.

With the increase of spraying amount, the bond strength at each temperature decreased, and the bond strength was even zero at high temperature. This is because the anti-condensable ice fog seal can reduce the freezing point of the pavement so that it does not freeze or reduce the degree of freezing at lower temperature. When the temperature was higher than  $-12^{\circ}\text{C}$ , the bond strength was about 0~0.2 MPa and test results of Meng's research were 0.11~0.32 MPa [34], which was close to the results obtained in this paper, but the literature did not specify the test temperature. The test results show that a pull-out tester could be used to quantitatively characterize the anti-ice-condensation effect of the fog seal layer.

**4.2. Simulated Freezing Test.** A road surface is constantly subjected to repeated freeze-thaw cycles, alternating between dry and wet states. Considering practical engineering applications, the repeated rolling contact with vehicle tires and the scouring effect during rainfall will produce a great degree of wear on the snowmelt seal. This will cause the salt content in the seal to continue to decrease, which will decrease the reduction effect on the freezing point until it disappears. In this study, the frozen ice crust on the surface of the sealing layer was thawed and replaced with pure water for repeated freezing and thawing, and the performances of antifreezing

TABLE 4: Technical indices of emulsified asphalt.

Test item	Test results		Technical standard		Experiment method	
	Cation	Anion	Cation	Anion		
Particle charge	Cation	Anion	Cation	Anion	T0653	
Demulsification speed	Rapid rupture	Slow rupture	Rapid rupture	Slow rupture	T0658	
The remaining amount on the sieve (1.18 mm) (%)	0.05	0.03	≤0.1	≤0.1	T0652	
5d storage stability (%)	3.39	3.76	≤5	≤5	T0655	
Standard viscosity of asphalt $C_{25,3}$ (s)	18	20	10–25	8–20	T0621	
Evaporation residue content (%)	58	59	≥50	≥50	T0651	
	Ductility (15°C) (cm)	58.2	77.4	40	40	T0605
Evaporation residue	Penetration (25°C) (0.1 mm)	71.6	76.2	50–200	50–300	T0604
	Softening point (°C)	50.7	50.4	≥50	≥50	T0606
	Solubility (trichloroethylene) (%)	98.6	59.2	≥97.5	≥97.5	T0607

TABLE 5: Different effects on emulsion performance.

Emulsified asphalt	Cyst species	Snow-melting salt	5d storage stability (%)	Zeta potential value (mV)
Cationic emulsifier	Agar	Sodium acetate	8.66	16.3
		Magnesium acetate	9.57	11.5
	Carboxymethyl cellulose	Sodium acetate	5.17	21.5
		Magnesium acetate	2.36	42.6
	Polyvinyl alcohol	Sodium acetate	3.62	27.6
		Magnesium acetate	3.33	24.5
Anionic emulsifier	Agar	Sodium acetate	7.65	17.4
		Magnesium acetate	8.93	14.2
	Carboxymethyl cellulose	Sodium acetate	4.66	31.6
		Magnesium acetate	4.53	29.6
	Polyvinyl alcohol	Sodium acetate	1.15	61.7
		Magnesium acetate	2.65	39.4

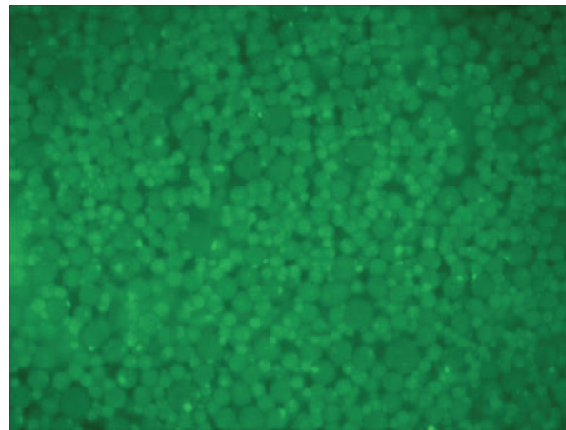


FIGURE 6: Micrograph of encapsulated salt emulsion.

TABLE 6: Bond strength results under different drawing rates.

Constant speed specimen	Bond strength (MPa)			
	20 mm/min	15 mm/min	10 mm/min	5 mm/min
Cationic emulsified asphalt test piece	0.16	0.31	0.21	0.11
Electrode difference	1.27	0.88	0.66	0.12
Anionic emulsified asphalt test piece	1.11	0.57	0.45	0.01
Electrode difference	0.05	0.03	0.03	0.04
Anionic emulsified asphalt test piece	0.66	0.25	0.14	0.06
Electrode difference	0.61	0.22	0.11	0.02

TABLE 7: Pull-out test results for the anticoagulation ice fog seal layer.

Spray amount (L/m <sup>2</sup> )	Temperature (°C)	Ultimate breaking force (N)				Bond strength (MPa)	
		Cationic emulsified asphalt + CMC + magnesium acetate	Cationic emulsified asphalt + PVA + sodium acetate	Cationic emulsified asphalt + CMC + magnesium acetate	Cationic emulsified asphalt + PVA + sodium acetate	Cationic emulsified asphalt + CMC + magnesium acetate	Cationic emulsified asphalt + PVA + sodium acetate
0.3	-6	21.5	24.3	0.030	0.034		
	-8	69.0	45.6	0.098	0.065		
	-10	97.9	65.42	0.139	0.093		
	-12	150.4	111.6	0.213	0.158		
	-14	265.9	215.6	0.376	0.305		
0.4	-6	0	0	0	0		
	-8	34.6	11.4	0.049	0.016		
	-10	86.7	54.3	0.123	0.077		
	-12	233.7	153.2	0.331	0.217		
	-14	732.3	541.6	1.036	0.767		
0.5	-6	0	0	0	0		
	-8	0	0	0	0		
	-10	52.4	0	0.074	0		
	-12	96.3	75.32	0.136	0.107		
	-14	211.5	184.6	0.299	0.261		





FIGURE 7: Pull-out test to determine tensile force at failure.

fog seal layers with different concentrations were tested under repeated freezing and thawing conditions. Emulsified bitumen and encapsulated salt emulsion ratios of 2:1, 1:1, 1:2, and 1:3 were tested (the snow-melting salt concentrations were 8%, 12%, 16%, and 18%, respectively), and the freezing point values after various freeze-thaw cycles are listed in Table 8.

The freezing point of the anticondensation fog seal layer decreased as the number of repeated freezing and thawing cycles increased, and the ability to melt snow and ice gradually weakened. In the fourth freezing test, the freezing point could still be lowered to  $-3^{\circ}\text{C}$  when the snow-melting salt concentration was 18%.

The encapsulation technology encapsulated the snow-melting salt to maintain the stability of the two-phase system of nonchloride salt and emulsified asphalt. It could significantly improve the solubility of the salt compounds in the emulsified asphalt without demulsification and surface salt precipitation and could significantly reduce the freezing point of road surface water. It provided a slow release on the road surface for a long time. With the continuous loss of the heat and dissolution heat of the system, the anticondensation ice fog seal layer could still make the water crystals on the road surface loose and fragile. Therefore, under a paved road condition, a loose ice layer would be easily crushed and broken by passing vehicles and would melt without producing a hard layer of ice adhering to the road surface.

Asphalt pavement with Mafilon material can reduce the pavement freezing point to  $-10^{\circ}\text{C}$  [35]. Zhao et al. [36] prepared sodium chloride slow-release snow-melting agent, which can reduce the freezing point of water to  $-6.04^{\circ}\text{C}$  under the optimal process. In contrast, anticondensation ice fog seal layer with different composition prepared in this paper can reduce the freezing point of pavement water to

$-7.6^{\circ}\text{C}\sim-14.2^{\circ}\text{C}$  during the first freezing and can effectively reduce the freezing point of pavement water to a greater extent.

**4.3. Antiskid Performance Test.** Spraying the anticondensation ice fog seal layer will reduce the antiskid performance of the pavement to a certain extent, and the texture structure between the aggregates will be reduced by being filled with asphalt. The fog seal is used as a preventive maintenance measure, and the recommended spray amount is  $0.23\text{--}0.45\text{ L/m}^2$ .

According to the specifications, the structural depth of the pavement after spraying the anticondensation ice fog seal layer should be greater than  $0.55\text{ mm}$ . Figure 8 shows the attenuation results for the antiskid structural depth of the anticondensation ice-melt snow fog seal under different spray rates.

The anticondensation ice-melting and snow-melting fog seal layers reduced the depth of the road surface structure to varying degrees. The antiskid structural depth of the magnesium acetate-encapsulated emulsion did not meet the requirements when the spray amount was  $0.5\text{ L/m}^2$ . Considering the antiskid performance and cost, the recommended spray rate is  $0.4\text{ L/m}^2$ , and its antiskid and antiwear properties meet the specifications and ensure the safety of traffic.

**4.4. Durability Evaluation Test.** The fog seal layer was sprayed on a test piece at  $0.4\text{ L/m}^2$ , and an immersion wheel abrasion tester was used to test the abrasion resistance of anticondensation ice fog seal layer. Three parallel specimens were tested with an average abrasion value of  $306\text{ g/m}^2$ . The mass loss before and after the experiment was about 6%, and it was similar to the test results of Wu et al. as around 5~8%

TABLE 8: Freezing point test results for the anticondensation ice fog seal layer against repeated freeze-thaw cycles ( $^{\circ}\text{C}$ ).

Matching plan	Cationic emulsified asphalt + CMC + magnesium acetate				Anionic emulsified asphalt + PVA + sodium acetate			
	2:1	1:1	1:2	1:3	2:1	1:1	1:2	1:3
Proportion of freeze-thaw cycles								
First cycle	-7.6	-8.9	-10.6	-12.4	-8.7	-9.6	-11.4	-14.2
Second cycle	-4.2	-6.5	-7.5	-8.9	-6.2	-7.7	-7.9	-9.3
Third cycle	-1.3	-3.3	-5.4	-5.6	-3.5	-4.9	-5.6	-6.3
Fourth cycle	0	-0.6	-2.8	-3.3	0	-2.1	-3.3	-3.6

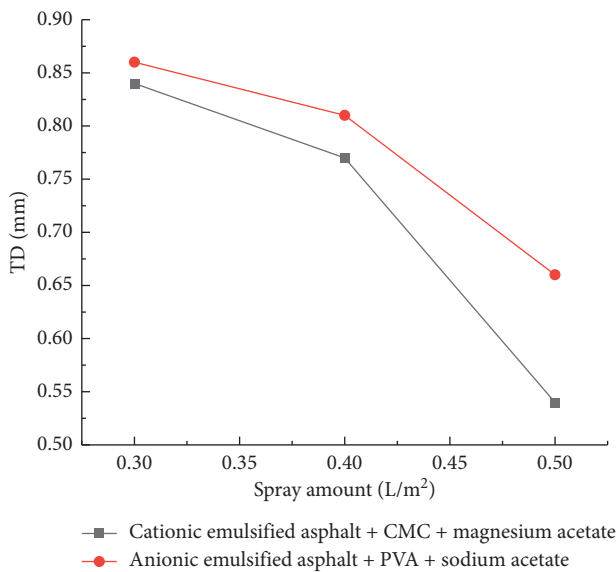


FIGURE 8: Depth of the antisliding structure of anticondensation ice-melting mist seal under different spraying conditions.

[35]. From the test data, it can be seen that the abrasion resistance of the anticondensation ice fog seal met the requirements of the JT/T 1330 specification “Asphalt Pavement Fog Seal Material Emulsified Asphalt Slurry Seal.”

## 5. Conclusion

In this study, an anti-icing environmental protection fog seal was prepared by adding a nonchloride salt to emulsified asphalt, and its antiskid performance and durability were tested. The following main conclusions could be drawn:

- (1) The encapsulation material allowed the freezing point to be reduced for a long time. The collocation schemes of a cationic emulsified asphalt + CMC + magnesium acetate and an anionic emulsified asphalt + PVA + sodium acetate showed the best stability.
- (2) Anionic snow-melting base stock solution has better stability and economy than cationic emulsified asphalt. In practical engineering applications, anionic emulsified asphalt can be given priority.
- (3) Pull-out tests showed that fog seal layers applied using different spray rates could reduce the freezing point to at least  $-8^{\circ}\text{C}$ . When using an anticondensation ice fog seal layer with a snow-melting salt concentration of 18%, the freezing point of the

road surface water could still be reduced to  $-3^{\circ}\text{C}$  after four freezing and thawing cycles.

- (4) The snowmelt fog seal layer reduced the antiskid performance of the road surface. Under the condition of a spraying volume of  $0.4\text{L/m}^2$ , the antiskid performance and durability could still meet the requirements of the specification.

The conclusion shows that spraying the anti-icing fog seal on the road surface can resist the road ice condensation, and the combination of mechanical snow removal can reduce the occurrence of traffic accidents, but the slow release and durability of the anti-icing fog seal need to be further studied. In addition, in order to verify the actual project effect, it is also necessary to conduct on-site testing through the paving test section.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare no conflicts of interest.

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