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Microwave Deicing Efficiency: Study on the Difference between Microwave Frequencies and Road Structure Materials

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Abstract: A method of deicing using microwave heating is proposed to make scientific and economical road deicing in a cold area, and to make up for deficiencies in the existing methods for melting snow and ice. This paper proposes to define microwave deicing efficiency as the heating rate of a concrete surface when heated to 0 °C (the efficiency of deicing is equal to the difference divided by heating time, which is between 0 °C and the initial temperature at the junction of ice and concrete). Based on the mechanism of microwave heating and deicing, a method combining the finite element simulation model with indoor experiments was proposed to study the deicing efficiency of microwaves, and the effects of different microwave frequencies and different road structure materials on microwave deicing efficiency were analyzed. The results show that the microwave frequency and road structure materials have a great influence on microwave deicing. For asphalt concrete, the ice melting efficiency of 5.8 GHz is 4.31 times that of 2.45 GHz, but the heating depth is less than that of 2.45 GHz. At 2.45 GHz, the melting efficiency of cement concrete is 3.89 times that of asphalt concrete. At 5.8 GHz, the melting efficiency of cement concrete is 5.23 times that of asphalt concrete. Through the consistency of the simulation and experimental results, the validity of the simulation model based on the finite element theory is verified. The results provide theoretical guidance and a practical basis for future applications of microwave deicing.

Keywords: microwave de-icing efficiency; microwave frequency; road structure materials; simulation model; indoor simulation experiment

1. Introduction

The snow-icing phenomenon of roads is a common and urgent problem, which is serious in North America, northern Europe, Russia, and northeast China. At present, countries generally use mechanical snow removal or a snow melting agent for melting ice [1]. The snow removal efficiency of traditional machinery is high, but most of them are only suitable for removing fresh snow that has not been roller compacted. The removal efficiency of thin or thicker ice accumulations on frozen road sections is not ideal, and the road surface is seriously damaged by forced eradication, resulting in additional costs for road maintenance [2,3]. The vast majority of snow melting agents are inefficient, costly, and are pollutants, causing serious corrosion to pavements and bridge decks [4]. Considering the harm of ice and snow in cold areas to road traffic and the defects of existing snowmelt ice methods, how to achieve scientific, effective, and environmentally-friendly economic road (especially alpine region) has become an urgent problem to be solved nowadays.

Considering the deficiencies of traditional deicing methods, in the field of de-icing agents, people began to consider how to reduce harm to the environment and the main project, tending to adopt environmentally-friendly snow-removing agents [5]; in terms of snow-melting ice technology, researchers focused on the suppression of frozen pavements, thermal heating, energy conversion, and other new technologies for melting snow [6,7]. Among them, the road deicing technology using microwave heating for de-icing has been widely popularized and applied. The new method of thermal snowmelt ice-melting has demonstrated incomparable advantages to other deicing methods in practical engineering. The microwave deicing method utilizes a microwave heating technique to increase the road surface temperature, thereby melting and separating the contact layer between the ice layer and the road surface, and then breaking the separated ice layer through other mechanical actions [8,9].

The microwave deicing method has a high deicing efficiency, and does not leave ice slag after clearing the ice layer. It is an environmental protection method that has no damage to the road and has promising prospects. In the 1970s, some developed countries began to study the application of microwave heating technology in the pavement thermal regeneration field, using microwave energy to heat the road surface and achieve thermal protection of it [10]. In 1987, Jack Monson studied the winter road non-contact deicing project and designed a microwave deicer. The project failed to be implemented because the deicing efficiency was too low [11,12]. Lindroth Ye et al. established the microwave deicing model, designed the microwave deicing test vehicle [13,14], and conducted further research on road microwave deicing technology. In 2003, Xu Yugong proposed the idea of using microwave heating technology to deicing roads for the first time in China. Microwave deicing experiments were conducted using microwave ovens. The results show that microwave deicing is feasible. The deicing efficiency of different road materials were studied through design experiments, and it was proposed that different road materials have different microwave deicing efficiencies [15,16]; In 2004, the NRRI (National Regulatory Research Institute) organization in Minnesota of the United States proposed to build a pavement with strong microwave absorption capacity using the twill rock asphalt mixture. It is advantageous for pavement rapid microwave repair and microwave deicing, and to use this technology to build a microwave road test section [17,18]. Tang et al. analyzed the application of 5.8 GHz microwaves in the deicing of asphalt pavements. Through comparison of numerical simulations and indoor experiments, it was proposed that the 5.8 GHz microwaves' heating time and penetration depth were shortened by one quarter compared with the 2.45 GHz microwaves, and 5.8 GHz microwaves have better application prospects in road microwave deicing [19,20]. Jiao et al. proposed the application of 5.8 GHz magnetrons in asphalt pavement maintenance. By comparing the price, temperature rise, and heating depth of 2.45 GHz and 5.8 GHz magnetrons, it was found that the 5.8 GHz magnetrons can be effectively used for asphalt pavement maintenance [21,22]. Tang et al. concluded that the microwave deicing efficiency is proportional to the microwave frequency and material dielectric loss using the CST (CST Studio Suite v2008 SP6, CST China Ltd., Shanghai, China), Matlab (Matlab2007b, MathWorks, Natick, MA, USA)., and ANSYS (ANSYS9.0, ANSYS, Pittsburgh, PA USA) simulation software. It was proposed that high frequency microwaves can improve the deicing efficiency [23]. In 2009, Zanko et al. conducted an in-depth study of the road performance and microwave absorption capability of the taconite asphalt pavement, and further analyzed the prospects of its application in highways [24–26]. In 2017, Gao et al. used the reflection properties of metals for microwaves to incorporate steel slag into asphalt mixtures to increase the microwave de-icing efficiency of asphalt pavements [27,28].

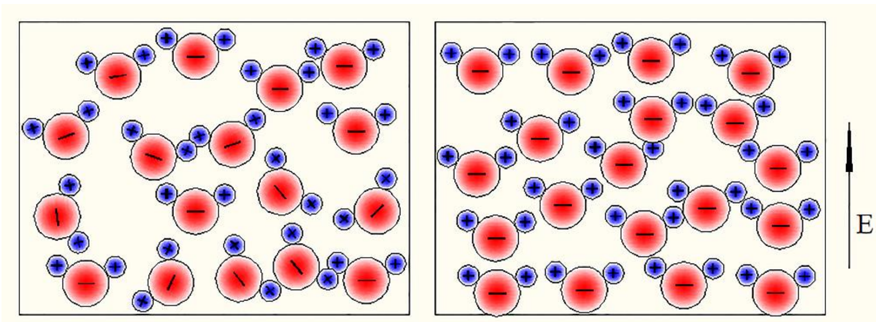
The research on microwave heating technology has been going on for more than 30 years since the 1980s. However, there are still many problems that need to be solved when the microwave heating technology is applied to removing snow and ice on the road. The research on microwave deicing is mainly about the analysis of the factors that affect the deicing efficiency. In this paper, the microwave deicing efficiency is defined as the heating rate of the concrete surface when heated to 0 °C. Based on the analysis of the mechanism of microwave heating and deicing, the effects of different microwave frequencies and different road structure materials on microwave deicing efficiency are analyzed. Based on the finite element theory, a simulation model is established to analyze the influencing factors of the deicing efficiency, and the simulation model is verified by an indoor experiment. The accuracy of the model is proved. It provides theoretical guidance and a practical basis for the popularization and application of microwave deicing technology.

2. Mechanism Analysis

2.1. Microwave Heating Principle

A microwave is a kind of electromagnetic wave, its frequency range is 0.3 GHz–300 GHz, and its wavelength range is 0.001 m–1 m. This difference is usually related to the complex permittivity of the material, especially the size of the loss angle constant, $\tan\delta$. The higher the loss angle constant, $\tan\delta$, the material has, the stronger the ability of absorbing microwave energy into heat. On the contrary, the weaker it is.

Dielectric materials contain non-polar molecules and polar molecules. The polar molecules in the medium are generally randomly distributed, and they are rearranged in the direction of the polarity of the electric field when in an electromagnetic field. Under the action of high-frequency alternating electromagnetic fields, polar molecules generate a large amount of mutual motion and friction, thereby generating a large amount of heat. As the heat increases, the temperature of the medium continuously rises. Figure 1 shows the polarization profile of the medium in an electric field.



(**a**) No electric field (**b**) Electric field

Figure 1. Diagram showing dielectric polarization.

2.2. Microwave Ice Melting Mechanism

According to the theory and practice of microwave heating, it can be known that microwave heating is actually a process of consuming power, and the formula for the microwave power to be consumed for heating a unit volume of a substance is:

$$P = 0.556 f \varepsilon_r' \tan\delta \cdot E^2 \times 10^{-12} \quad (1)$$

where P is the power consumed on a per unit volume basis; f is the microwave frequency; E is the electric field intensity; ε_r' is the relative dielectric constant; and $\tan\delta$ is the loss angle constant.

From formula (1), the main performance parameters that affect the absorption of microwave energy by the material are the relative dielectric constant and the loss angle constant. The smaller the relative dielectric constant and the loss angle constant are, the worse the absorbing ability of the material is. Table 1 shows the relative dielectric constant and the loss angle constant of various materials.

Table 1. Relative dielectric constant and loss angle constant of materials.

Material	Relative Dielectric Constant	Loss Angle Constant
Water	76.7	0.157
Ice	3.2	0.0009
Asphalt concrete	4.5–6.5	0.015–0.036
Cement concrete	8	0.048

It can be seen from Table 1 that the relative dielectric constant of ice at −12 °C is 3.2, and the value of the loss angle constant is 0.0009, which is relatively small. It can be known from formula (1) that the power loss of microwaves in ice is extremely small when $\tan\delta = 0.0009$. Therefore, when microwave heating is applied to the icing of road pavements, the microwave energy is minimally depleted in the ice layer, the ice layer on the road surface hardly absorbs microwave energy, and the ice layer is equivalent to "transparent" for microwaves. Microwave energy can penetrate the ice directly, just as light can penetrate transparent glass. After the microwave penetrates the ice layer, it directly acts on the road surface. The surface materials, such as asphalt concrete and cement concrete, can absorb part of the microwave energy and convert the microwave energy into heat energy, thereby melting the ice at the junction between the road surface layer and the ice layer. When the ice at the junction is melted into water, the liquid water can also absorb microwave energy in a large amount, which will greatly accelerate the melting of the ice formed at the junction between the road surface layer and the ice layer, thereby reducing the bond stress between the ice and the surface layer. When the bond stress is zero, it will make the road deicing easier. Only by adding machinery or manpower can it be easy to remove ice from the road and achieve ice melting on the road. In actual projects, the thickness of the asphalt concrete surface layer on highways and urban roads is generally between 12–20 cm. For supporting load pavement, the thickness may be as high as 30 cm or more. When heating the asphalt concrete pavement with microwaves, the effective heating depth is generally between 0 to 15 cm. Therefore, in the simulation of asphalt concrete pavement, to simplify the simulation, when microwave heating the pavement, only the road surface layer, which is the asphalt concrete surface layer, is heated. In the two-dimensional simulation, the length and width of the simulated area are all 15 cm, and the upper layer covered 5 cm of ice.

3. Research Methods

3.1. Finite Element Simulation Model

(1) Two-dimensional Thermoelectric Coupling Model

The thermoelectric coupling model of microwave heating asphalt concrete involves electromagnetic field control equations and heat transfer control equations. Theoretically, the heat transfer performance, dielectric properties, and magnetic permeability of asphalt concrete depend on the temperature. It is not realistic to accurately measure the relationship between all attribute parameters of asphalt concrete with temperature. Additionally, only the main attribute parameters can be selected, while the rest of the parameters are considered constant. The two-dimensional non-linear thermo-electric coupling model was established by selecting the asphalt (cement) concrete dielectric constant and the specific heat capacity, C_P, as the temperature change parameters and the rest of the property parameters being constants.

(2) Assumptions in Simulating Microwave De-icing

The melting of ice and snow is a very complicated process, which involves the conversion of microwave energy into heat energy, which then conducts heat energy to the surface. To simplify the entire process of melting snow, some assumptions are made during the simulation.

The ice cover on the pavement layer is uniform; asphalt concrete characteristics of the pavement layer are uniform. Ignore the change in volume when water is formed into ice. It is considered that the whole analytical region is adiabatic on all four sides, that is, there is no heat loss. Loss of heat inside the concrete is used to heat the junction of the ice layer and the surface layer. Under microwave radiation, the sum of the absorbed microwave heat is a constant. The propagation of the microwave is propagated in the form of a plane wave.

(3) Selection of Related Parameters

According to the mechanism of microwave icing and the references related, the two-dimensional non-linear thermo-electric coupling model was established considering the asphalt (cement) concrete dielectric constant, loss angle constant, density, conductivity coefficient, and the specific heat capacity, C_p, as the temperature change parameters. When using software to simulate the process of microwave melting snow, set the ambient temperature, ice temperature, and the initial temperature of the asphalt concrete to -10 °C, microwave emission power of 1000 W, frequency of 2.45 GHz, 5.8 GHz, and air convection of 12.5 W/m^3. The relative dielectric constant and the loss angle constant of the material are shown in Table 1, and other relevant parameters that need to be used are shown in Table 2.

Table 2. Parameters related to temperature characteristics of materials.

Material Type	Density kg/m^3	Conductivity Coefficient W/(m·°C)	Specific Heat Capacity J/kg·°C
Water	1000	0.6	4200
Ice	920	2.31	2100
Asphalt concrete	2350	0.55	2090
Cement concrete	2300	1.8	880

(4) The Establishment of the Heat Transfer Model for Melting Snow

The finite element simulation software, Abaqus (Abaqus6.14, SIMULIA, Providence, RI, USA), is used to simulate the heat conduction in the snow melting process. The simulation used a two-dimensional model and meshed the area, ABCD, of the simulation, as shown in Figure 2.

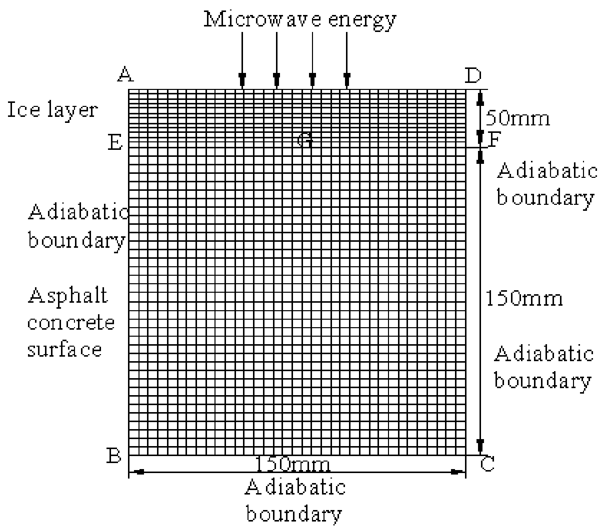


Figure 2. Grid division diagram of the microwave deicing.

Heat transfer in asphalt concrete: In heat transfer analysis, only the heat conduction is considered, the regular of the temperature distribution, T, of the asphalt concrete changing with time is determined by the heat conduction equation, i.e.,

$$\rho C_P(T)\frac{\partial T(\mathrm{x,y,t})}{\partial \mathrm{t}} = \mathrm{k_{eff}}\left[\frac{\partial^2 T(\mathrm{x,y,t})}{\partial^2 \mathrm{x}} + \frac{\partial^2 T(\mathrm{x,y,t})}{\partial^2 \mathrm{y}}\right] + P^*(\mathrm{x,y}) \quad (2)$$

where ρ is the asphalt concrete density; k_{eff} is the thermal conductivity constant; and C_P is the specific heat capacity, as a function of temperature. Additionally, the boundary conditions of the area is:

① Boundary conditions of AE, BE, DF, and CF.

Considering the microwave heating and heat transfer depth, and to simplify the simulation calculations when modeling, it is assumed that the boundary conditions of AE, BE, DF, and CF are adiabatic boundaries. The boundary condition equation is:

$$-\lambda \frac{\partial t}{\partial n} = 0 \tag{3}$$

② Boundary conditions of AD.

Because ADEF has been ice during the entire simulation process, its temperature has remained below zero degrees Celsius. The thermal conductivity of ice is very low, as the entire system is a layer of "insulation layer". So, its boundary condition equation is:

$$-\lambda \frac{\partial t}{\partial n} = 0 \tag{4}$$

3.2. Laboratory Experiments

According to "Technical Specifications for Construction of Highway Asphalt Pavements" (JTG F40-2004), the gradation of the mixed material using in actual engineering is selected, and the composition ratio of asphalt concrete specimens is shown in Table 3. The ratio of oil to stone is 5%, and SBR (Styrene Butadiene Rubber) modified asphalt is used. After verifying the effect, the absorbing properties of ordinary asphalt concrete will be further studied.

Table 3. Asphalt mixture synthesis grading calculation table.

Grading Type	The Quality Percentage Passing through the Following Mesh (mm)									
	16.0	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
Percentage (%)	100	95	76	53	37	26	19	14	10	6

The coarse aggregate and fine aggregate used in this paper is the basalt and limestone, respectively, which are used commonly in highway engineering. The coarse aggregate of basalt processed by sieving is shown in Figure 3. The aggregate is clean, dry, non-weathered, and free of impurities. After testing, the test results of various technical indicators are shown in Table 4. The test results of various technical indexes of limestone are shown in Table 5. It is known from the test results that the technical indexes of basalt and limestone aggregates are in line with the provisions on the aggregate quality of the asphalt surface layer in the Technical Specification for Construction of Highway Asphalt Pavement (JTGF40-2004).

Figure 3. Processed basalt aggregate.

Table 4. Test results of various indicators of basalt coarse aggregate.

Test Index	The Technical Requirements of Aggregate	Test Results	Experiment Method
Crush value (%)	$\ngtr$26%	9.8	T 0316-2005
Apparent relative density (t/m^3)	$\nless$2.6	3.88	T 0304-2005
Water absorption (%)	$\ngtr$2.0	0.23	T 0304-2005
Adhesion	$\nless$Level5	Level5	T 0616-2000
Sturdiness (%)	$\ngtr$12%	0.8	T 0314-2000
Needle and plate particle content (mixture) (%)	$\ngtr$15%	5.2	T 0312-2005
The particle size is greater than 9.5 mm (%)	$\ngtr$12%	3.1	
The particle size is less than 9.5 mm (%)	$\ngtr$18%	5.9	
PSV	$\nless$42	48	T 0321-2005

Table 5. Test results of various indicators of limestone fine aggregate.

Test Index	The Technical Requirements of Aggregate	Test Results	Experiment Method
Bulk volume density	/	2.79	T0330-2005
Apparent relative density	$\geq$2.5	2.763	T0328-2005
Water absorption	$\ngtr$2.0	0.53	T 0330-2005
Sand equivalent	$\geq$70	73	T 0334-2005
<0.075 mm Content (%)	$\leq$15	9.8	T 0327-2000
Angularity (s)	$\geq$30	46.7	T 0345-2000

The rutting plate specimens (300 mm $\times$ 300 mm $\times$ 50 mm) are prepared according to the above mixing ratio, and then cut into 150 mm $\times$ 150 mm $\times$ 50 mm specimens as the asphalt mixture specimens for microwave deicing and the snow test. Then, the 150 mm $\times$ 150 mm $\times$ 150 mm cement concrete specimens are prepared in the mixture ratio of 300 kg of cement, 128 kg of water, 4 kg of superplasticizer, 662 kg of sand, and 1405 kg of stone per 1 m^3. The specimens are cured in an environmentally-controlled room at 20 C and 95% relative humidity for 28 days.

An ice layer is prepared in a refrigerator at a temperature of -20 °C, and then placed on the test piece. After that, an appropriate amount of water was added to bond the ice layer and test piece in a low temperature environment to prepare an experimental ice-covered specimen. The microwave deicing device for testing is a kind of simple microwave dark room developed for the development of open microwave equipment. The dark room cavity size is about 1.5 m $\times$ 1 m $\times$ 2 m. The device consists of a magnetron, a waveguide, a height adjustment plate, a ruler, a cooling system, and a circuit system. The microwave darkroom and the internal simple diagram of the device are shown in Figure 4. The microwave radiation generated by the magnetron propagates downward along the direction of the waveguide and reaches the waveguide opening. It will continue to spread to the ice surface of the test sample, then through the ice layer, radiate to the concrete surface, then heat the concrete, and, under microwave radiation, the surface temperature of the concrete increases. According to the IEC (International Electrotechnical Commission) standard, at a distance of 5 cm from the microwave emitter, the electric field intensity (E) is about 5 kv/m, where the measured microwave radiation intensity is much higher than 5 mW/cm^2, indicating that the microwave radiation has a certain influence on the test personnel. Electromagnetic radiation has a certain accumulation effect. In the test, it is necessary to strengthen the protection. At the same time, the testers need to wear shielded clothing and the test needs to be completed in a closed environment. The distance from the surface of the fixed test sample to the waveguide mouth is 50 mm, the thickness of the ice layer is 50 mm, and a thermocouple is placed at the interface between the concrete surface and the ice layer to record the temperature change.

The efficiency of deicing is equal to the difference divided by the heating time, which is between 0 °C and the initial temperature at the junction of the ice and concrete. The calculated equation is as follows:

$$V = \frac{T_1 - T_2}{\mathrm{t}} \tag{5}$$

where T_1 indicates that the temperature is 0 °C; T_2 is the initial temperature at the junction of the ice and concrete; and t is the time taken for the junction of the ice and concrete to be from the initial temperature to 0 °C.

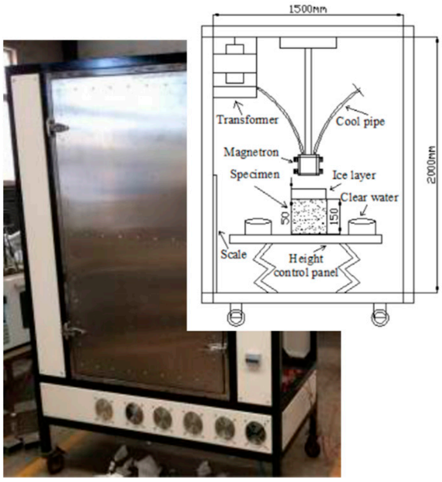


Figure 4. Microwave deicing test device.

4. Results and Discussion

4.1. Microwave Frequency

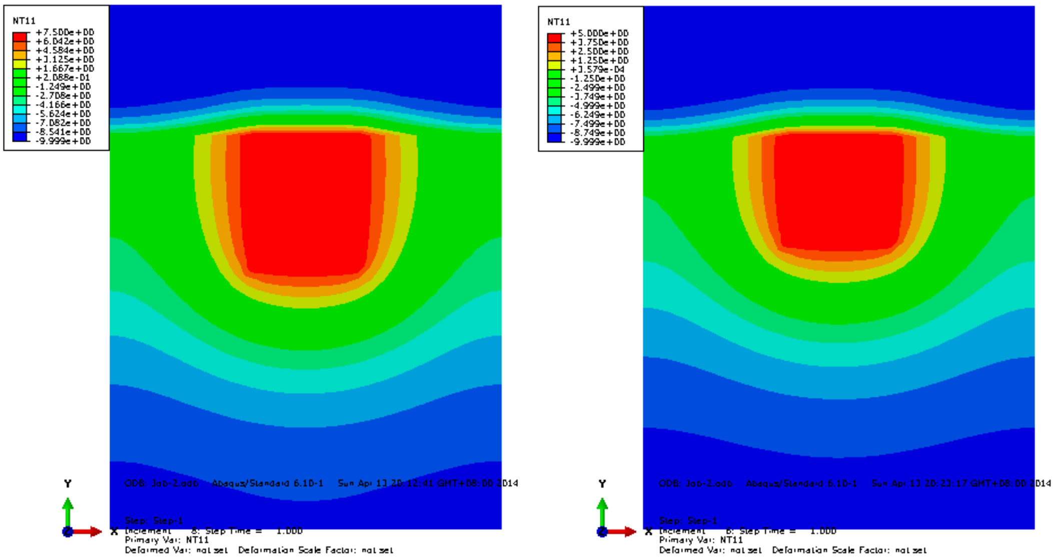
Microwave energy is absorbed as it passes through the material, and the ability to convert to heat energy is related to the microwave frequency. The depths of microwave heating road materials with different frequencies are different, which will cause different microwave energies to be concentrated on the surface of the road surface, thus changing the time when the junction between the ice layer and the road reaches 0 °C, and change the deicing efficiency. 2.45 GHz magnetron is widely used in microwave ovens or industrial microwave equipment, and its average market price is about 100 yuan, while the average price of 5.8 GHz magnetron is over 10,000 yuan, and the unit price is more than 100 times compared with that of 2.45 GHz magnetron. The cost is high, and the price comparison chart of different frequencies is as shown in Table 6. The working frequency of industrial microwave heating is 915 MHz or 2.45 GHz. Compared with 2.45 GHz radiation, the heating efficiency of 5.8 GHz radiation is higher and the penetration depth is smaller. Microwave de-icing efficiency increases with microwave frequency increasing. Combined with the current microwave deicing study, the frequency of 2.45 GHz is used, and the deicing of 5.8 GHz microwave is proposed to improve the microwave deicing efficiency. In this paper, the de-icing efficiency at the common microwave frequencies of 2.45 GHz and 5.8 GHz is studied from finite element simulations and indoor experiments.

Table 6. Comparison of different microwave frequency prices.

Frequency (GHz)	Range (MHz)	Market Average Price (CNY)	Penetration Depth
2.45	±50	100	Deeper
5.8	±75	10,000	Lighter

4.1.1. Simulation Research

When the initial temperature of the ice layer and asphalt concrete surface layer is −10 °C, the output power of the microwave is 1000 W, the ice layer thickness is 50 mm, and the emitter is 50 mm away from the ice surface. The model is used to analyze the de-icing process with microwave emission frequencies of 2.45 GHz and 5.8 GHz. The simulation of the temperature field under different frequencies is shown in Figure 5.



(**a**) Microwave frequency 2.45 GHz (**b**) Microwave frequency 5.8 GHz

Figure 5. Distribution of the temperature field at different microwave frequencies.

As shown in Figure 6, when the microwave emission frequencies are 2.45 GHz and 5.8 GHz, respectively, the temperature at the center point, G, changes with time.

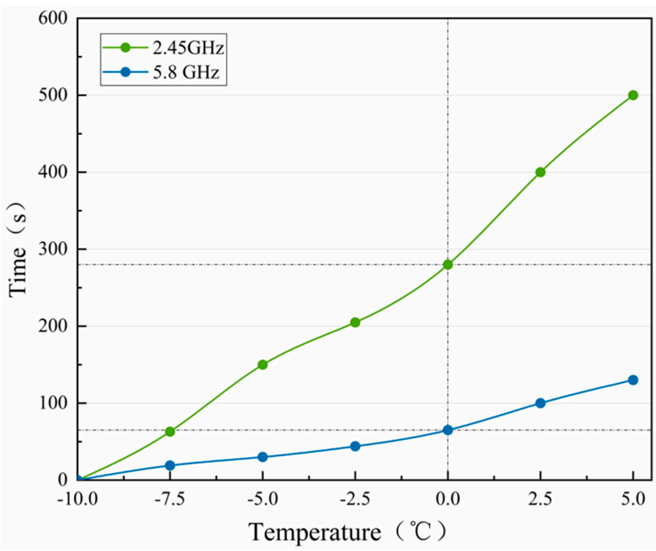


Figure 6. Comparison of temperature changes at different frequencies at point G.

It can be seen from Figure 6 that the temperature at the center point, G, rises continuously as time increases under the influence of the microwave energy. At different transmission frequencies, the time for point G to reach 0 °C is different, and its time is 280 s and 65 s, respectively. It can be concluded that the 5.8 GHz ice-melting efficiency is 4.31 times more than that of 2.45 GHz. Under the same conditions, the deicing efficiency at the frequency of 5.8 GHz was greatly improved, and the ice-melting time only required 65 s. From a molecular point of view, microwaves polarize molecules and cause regular and intense movements of the molecules. This movement causes molecules to rub against each other and produce a lot of heat, which causes the material to be heated. When the frequency is changed from 2.45 GHz to 5.8 GHz, the speed and amplitude of polar molecules will increase accordingly, and the motion will become even stronger. The more heat the friction generates, the faster the ice at the interface will melt into water. Water can absorb a large amount of microwave energy and accelerate the melting of ice on the junction between the road surface and the ice layer. Therefore, the ice melting time is reduced and the efficiency is improved at high frequencies. Therefore, increasing the microwave frequency can improve the deicing efficiency.

The temperature field distribution of asphalt concrete is shown in Figures 5 and 7. When the surface temperature of asphalt concrete specimen reaches 0 °C, the temperature of the ice surface is the lowest, and the concrete specimen first rises with the depth, and reaches the peak value of 12 mm. After that, the temperature decreases as the depth increases. Under 2.45 GHz microwave radiation, the depth of the temperature rise is even higher. The reason for this phenomenon may be that on the one hand, the microwave heating time of 2.45 GHz (280 s) is longer than the microwave heating time of 5.8 GHz (65 s), and the sample under 2.45 GHz absorbs more heat. On the other hand, from the perspective of energetics, when the microwaves heat the road surface, the microwave energy absorbed by the surface of the road is the most. As the depth of the road surface increases, the transformed microwave energy absorbed by the deeper position of the pavement layer is gradually reduced, and this process appears as an exponential decay. Therefore, there is a heating depth indicator when heating the road surface by microwaves. Heating depth refers to the depth of the node from the surface when the microwave power decays from the surface of the material to an initial value, $\frac{1}{e}$, or 0.3679 times. The heating depth, D, is calculated as follows:

$$D = \frac{\lambda_0}{\pi\sqrt{2\varepsilon'\left(\sqrt{1+\tan^2\delta}-1\right)}} \tag{6}$$

The formula for calculating the wavelength and frequency is:

$$f = \frac{c}{\lambda} \Leftrightarrow \lambda = \frac{c}{f} \tag{7}$$

where λ_0 is the free space wavelength of the microwave; ε'_r is the relative dielectric constant; $\tan\delta$ is the loss angle constant; and $c = 3 \times 10^8$ m/s.

The heating depth is given by Equations (5) and (6):

$$D = \frac{\text{c}}{\pi f\sqrt{2\varepsilon'\left(\sqrt{1+\tan^2\delta}-1\right)}} \tag{8}$$

D is an inverse function of the microwave emission frequency. Compared to the microwave emission frequency of 2.45 GHz, the heating depth decreases when the frequency is 5.8 GHz. That is, the microwave energy is mainly absorbed by the surface layer of the pavement and converted into heat energy, which can quickly transfer the thermal energy of the surface layer to the junction of the ice layer and the surface layer, and quickly melt the ice. On the contrary, when the microwave emission frequency is 2.45 GHz, the heating depth increases; that is, the microwave energy is absorbed within a relatively large depth, and the heat transfer time is correspondingly increased, so the efficiency of deicing and snow removal is correspondingly reduced. Therefore, it can be concluded that microwaves with a frequency of 5.8 GHz are more suitable for road deicing.

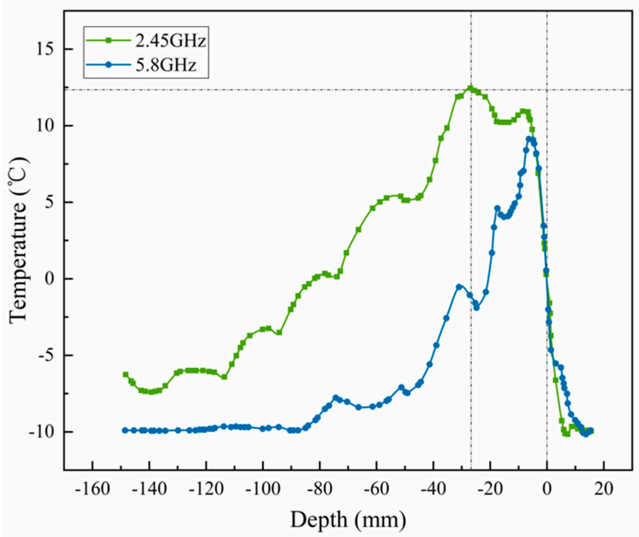


Figure 7. Temperature field distribution along the vertical direction of concrete.

4.1.2. Experimental Research

According to the controlling variable method, the ice thickness of the test piece is controlled to be 50 mm, the microwave emission power is 1000 W, and the distance from the test piece to the waveguide port is 50 mm. The specimens are placed in the test device and tested at microwave frequencies of 2.45 GHz and 5.8 GHz. Place the beaker filled with water on both sides of the specimen to absorb the microwave energy not absorbed by the specimen. A thermocouple between the asphalt concrete and the ice layer records the temperature change of the concrete surface, and the influence of different microwave frequencies on the heating efficiency is obtained, thereby reflecting the effect on the efficiency of the microwave deicing and snow removal.

The ice after microwave irradiation is shown in Figure 8. It can be clearly seen that a large hole appeared in the ice layer, which resembles a bowl-shaped depression, indicating that ice melts first from the part near the concrete surface. The ice layer on the ice surface and the concrete surface melt into water. The water absorbs microwave energy in a large amount, accelerating the melting of the ice layer at the interface, and reducing the bond stress at the joint of the ice surface layer. Therefore, the ice layer is easily removed by mechanical means. This phenomenon also shows that the microwave absorption capacity of the ice layer is weak, and microwaves can penetrate the ice layer to directly heat the concrete.

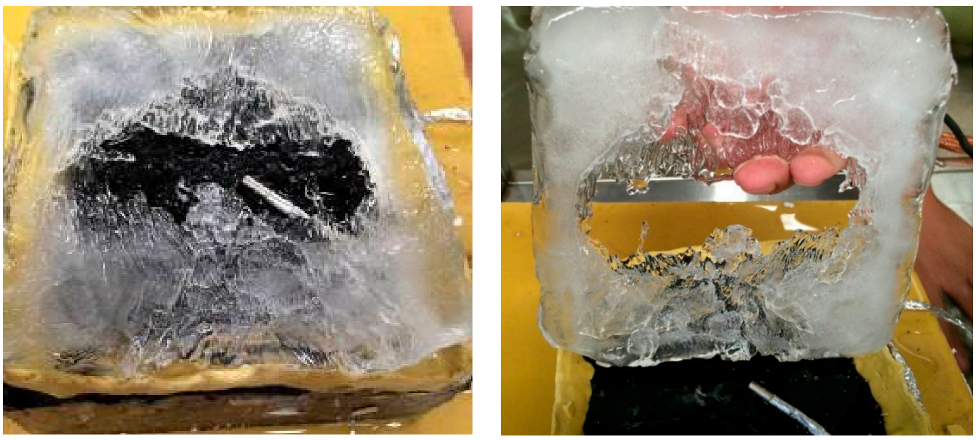


Figure 8. Ice after microwave irradiation.

A thermocouple between the asphalt concrete and the ice layer records changes of the temperature in the concrete surface. The results are shown in Table 7. The average temperature rise rate at 2.45 GHz is 0.032 °C S^{-1}, the average temperature rise rate at 5.8 GHz is 0.0.149 °C S^{-1}, and the average temperature rise rate at 5.8 GHz is 4.6 times that of the 2.45 GHz microwaves.

Table 7. Efficiency of asphalt concrete under different microwave frequencies.

Parameters	2.45 GHz			5.8 GHz		
	1	2	3	1	2	3
Initial temperature/°C	−14.3	−15.8	−13.6	−14.8	−14.5	−13.6
Heating time/S	423	523	413	105	95	89
Temperature-rise rate/(°C S^{-1})	0.034	0.030	0.033	0.141	0.153	0.153

Comparison of deicing rates between indoor tests and simulations of different frequencies is shown in Figure 9. The results also show that there is no correlation between the initial temperature and the temperature rise rate, but it will affect the ice melting time. The higher the initial temperature, the shorter the ice melting time. The test results are very close to the results of the simulation model, demonstrating the reliability of the simulation model. However, the comparison shows that the deicing efficiency obtained by the test is slightly lower than the simulation results. This is because in the simulation model, assuming that the analysis area is insulated on all four sides, the microwave heat loss is all used to melt the ice. In actual experiments, this cannot be completely achieved.

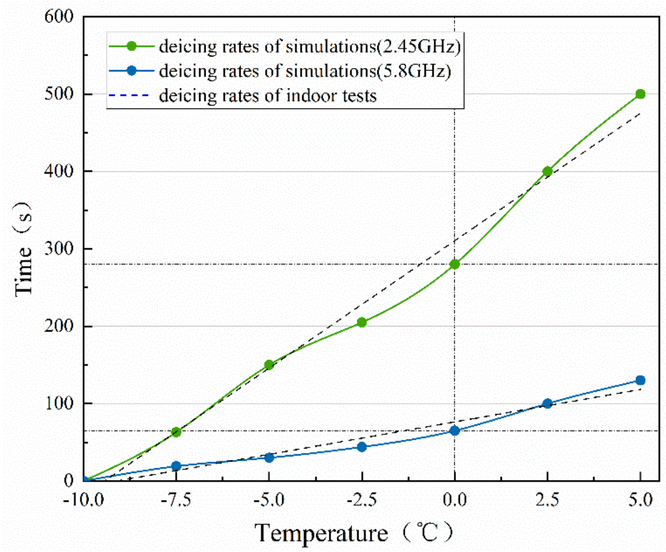


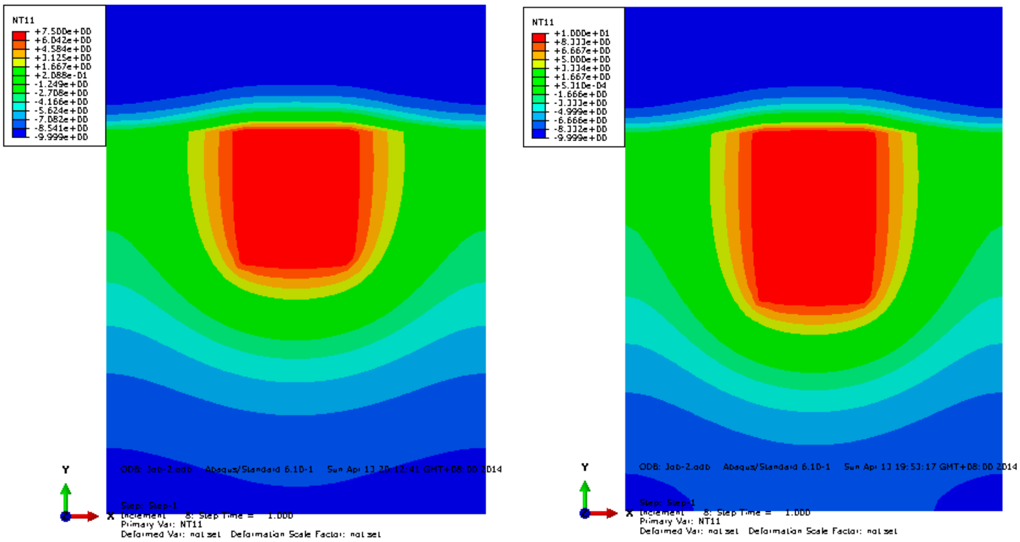
Figure 9. Comparison of deicing rates between indoor tests and simulations of different frequencies.

4.2. Pavement Structural Materials

Road pavement structure materials mainly include cement concrete and asphalt concrete. The characteristic parameters of different pavement materials are different, which in turn leads to different deicing efficiencies. This paper simulates and tests the de-icing efficiency of different road pavement materials at 2.45 GHz and 5.8 GHz.

4.2.1. Simulation Research

It can be seen from Table 1 that the cement concrete parameters are larger than asphalt concrete. According to the principle of microwave deicing, it can be qualitatively concluded that the deicing efficiency of cement concrete pavement is higher than that of asphalt concrete. In the simulation model, the initial temperature of the ice layer and the pavement layer is set to −10 °C, the output power of the microwave is 1000 W, the thickness of the ice layer is 10 mm, and when the emission frequency is 2.45 GHz, the emission port distance from the pavement layer is 50 mm to simulate the de-icing process of different road materials. The de-icing simulation of different pavement materials at 2.45 GHz frequency is shown in Figure 10. The temperature change of concrete G points of different pavement materials at 2.45 GHz and 5.8 GHz is shown in Figure 11.



(**a**) Cement concrete (**b**) Asphalt concrete

Figure 10. Deicing simulation of different pavement materials at 2.45 GHz frequency.

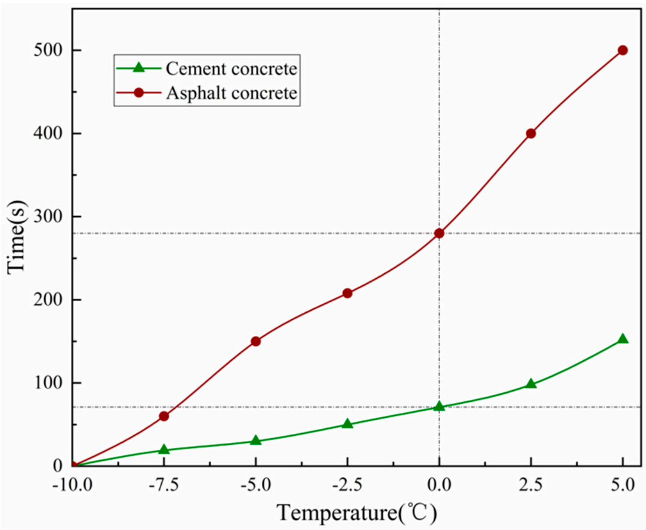


Figure 11. Temperature change chart of concrete G points of different pavement materials at 2.45 GHz frequency.

According to the simulation results, at the frequency of 2.45 GHz, the time for the G point of the cement concrete pavement reaching 0 °C is 71 s, the temperature rise rate is 0.139 °C S^{-1}, and the time for the point, G, of the asphalt concrete pavement reaching 0 °C is 280 s, the temperature rise rate is 0.036 °C^{-1}. The ice-melting efficiency of cement concrete is 3.89 times that of the asphalt concrete. From Table 1, the relative dielectric constant of asphalt concrete is 4.5~6.5, the loss angle constant is 0.015~0.036, and the relative dielectric constant is 8, and the loss angle constant is 0.048. By formula (1)'s calculation, it can be concluded that cement concrete has a stronger ability to absorb microwave heat than asphalt concrete, so under the action of microwave, cement concrete has a higher melting ice efficiency.

It can be seen from Figure 12. that at the frequency of 5.8 GHz, the time for the point, G, to reach 0 °C at the center point of the cement concrete pavement is 13 s, the temperature rise rate is 0.77 °C S^{-1}, and the time for the point, G, to reach 0 °C at the center point of the asphalt concrete pavement is 65 s, the temperature rise rate is 0.15 °C^{-1}, which shows that the ice-melting efficiency of cement concrete is 5.23 times that of asphalt concrete. From Table 1, the relative dielectric constant of asphalt concrete is 4.5~6.5, the loss angle constant is 0.015~0.036, and the relative dielectric constant is 8, and the loss angle constant is 0.048. At 5.8 GHz microwave frequency, f is higher than 2.45 GHz. By formula (1), it can be concluded that cement concrete has a stronger ability to absorb microwave heat than asphalt concrete. The higher the frequency is, the more obvious the gap is. Therefore, under the effect of strong microwaves, the cement concrete ice melting efficiency is higher.

Microwaved ice is a very complicated process, and there are many factors that affect the deicing of microwaves, and they are complicated and cross-influenced. It is not sufficient to analyze the effect of these variable factors on the efficiency of microwave deicing and snow removal by temperature field simulation alone. Therefore, this paper analyzes the test and compares it with the results of temperature field simulation.

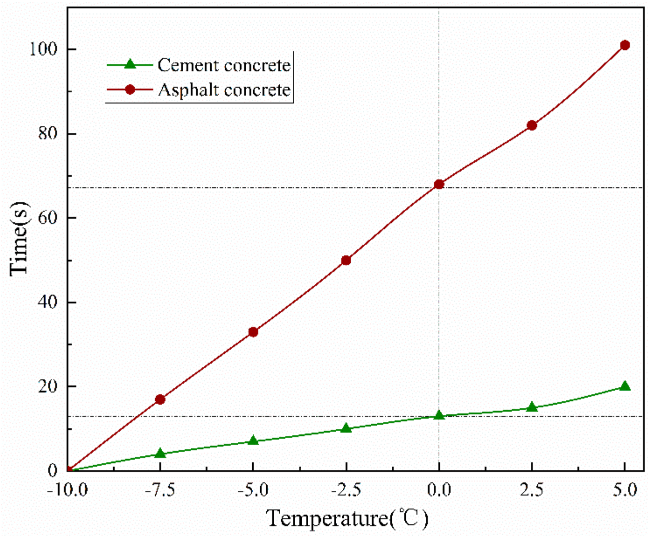


Figure 12. Temperature variation of concrete G points of different pavement materials at 5.8 GHz frequency.

4.2.2. Experimental Research

According to the controlling variable method, the relevant variables are controlled, and the test pieces of different materials are placed in microwave devices and tested at 2.45 GHz and 5.8 GHz, respectively. Thermocouples record the temperature changes on the concrete surface and obtain different road materials' microwave de-icing efficiency at different microwave frequencies, as shown in Tables 8 and 9.

Table 8. Deicing efficiency of concrete with different pavement materials at 2.45 GHz frequency.

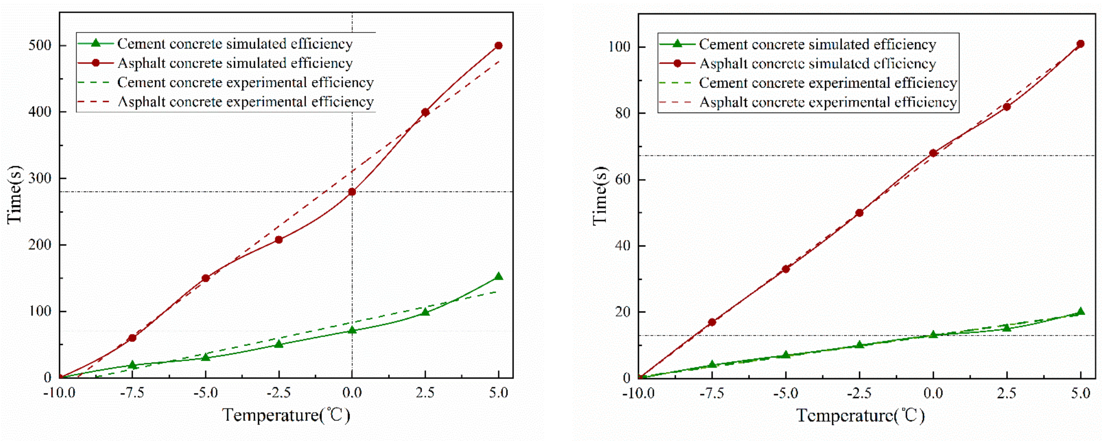
Parameters	Cement Concrete			Asphalt Concrete		
	1	2	3	1	2	3
Initial temperature/°C	−13.8	−14.6	−12.9	−14.5	−15.2	−12.4
Heating time/s	105	116	112	443	475	448
Temperature-rise rate/(°C S^{-1})	0.131	0.126	0.115	0.033	0.032	0.028

Table 9. Deicing efficiency of concrete with different pavement materials at 5.8 GHz frequency.

Parameters	Cement Concrete			Asphalt Concrete		
	1	2	3	1	2	3
Initial temperature/°C	−13.5	−14.3	−14.5	−15.1	−14.6	−14.3
Heating time/s	19	20	20	109	104	110
Temperature-rise rate/(°C S^{-1})	0.711	0.715	0.725	0.139	0.140	0.130

As shown in Tables 5 and 6, at 2.45 GHz, the average temperature rise rate of cement concrete is 0.124 °C S^{-1}, the average temperature rise rate of asphalt concrete is 0.031 °C S^{-1}, and the temperature increase rate of cement concrete is 4.03 times that of asphalt concrete. At 5.8 GHz, the average temperature rise rate of cement concrete is 0.717 °C S^{-1}, the average temperature rise rate of asphalt concrete is 0.136 °C S^{-1}, and the temperature increase rate of cement concrete is 5.26 times that of asphalt concrete.

A comparison of deicing rates between indoor tests and simulations of different road materials is shown in Figure 13. The initial temperature has almost no effect on the temperature rise efficiency. It shows that at the same frequency, cement concrete has a better effect of increasing the temperature of absorbing microwave energy than asphalt concrete, and the de-icing effect of cement concrete pavement with microwaves is better. The higher the frequency, the more pronounced the deicing efficiency difference between the two pavement materials. The result is basically consistent with the simulation result, and the accuracy of the simulation model is verified again.



(**a**) 2.45 GHz frequency (**b**) 5.8 GHz frequency

Figure 13. Comparison of deicing rates between indoor tests and simulations of different road materials.

5. Conclusions

Based on microwave heating and the microwave ice mechanism, a simulation model was established by the finite element method. The influence of microwave frequency and road structural material on microwave deicing efficiency was analyzed. A microwave deicing device was used to perform an indoor verification test. By comparison, the experimental results were basically consistent with the simulation results, verifying the accuracy of the simulation model. Some conclusions can be obtained:

(1) Different microwave frequencies have a great influence on microwave de-icing efficiency. Under the same conditions, the microwave deicing efficiency of 5.8 GHz is 4.31 times that of 2.45 GHz, and microwaves with a frequency of 5.8 GHz are more suitable for pavement deicing.

(2) At the same microwave frequency, the microwave absorption efficiency of different road structure materials is also different. The ice-melting efficiency of cement concrete is 3.89 times (2.45 GHz) and 5.23 times (5.8 GHz) that of asphalt concrete, respectively.

(3) At the same frequency, the effect of a temperature increase of the microwave energy absorbed by cement concrete is better than that of asphalt concrete. The effect of microwave deicing on cement concrete pavement is better. Additionally, the higher the frequency is, the more obvious the difference in the microwave energy absorbed by cement concrete and asphalt concrete is.

(4) As a new type of green deicing method, microwave deicing can overcome the shortcomings of traditional deicing methods, such as mechanical deicing and the chemical method, and it has a good development trend. We should pay more attention to the application of high frequency deicing and microwave deicing in cement concrete pavement. There are many factors that affect the deicing efficiency. If the multi-layer environment, such as air, ice, concrete, etc., and the thickness of each layer can be fully considered, this paper will be more complete. Next, we will further study the output power and different ice thicknesses at the same frequency.

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