Ice melting properties of steel slag asphalt concrete with microwave heating

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Abstract. The ice on the surface of asphalt pavement in winter significantly influences the road transportation safety. This paper aims at the improvement of the ice melting efficiency on the surface of asphalt pavement. The steel slag asphalt concrete was prepared and the high ice melting efficiency was achieved with the microwave heating. A series of experiments were conducted to evaluate the ice melting performance of steel slag asphalt concrete, including the heating test, ice melting test, thermal conductivity test and so on. The results indicated that the microwave heating of steel slag concrete can improve the efficiency of deicing, mainly because the heating rates of steel slag asphalt mixture are much better than traditional limestone asphalt mixture. According to different thickness lever of ice, the final temperatures of each sample were very close to each other at the end of melting test. It is believed the thickness of the ice has a limited impact on the ice melting efficiency. According to the heating tests results, the bonding of ice and asphalt concrete is defined failure at the moment when the surface temperature of the ice reached 3 ºC.

Keywords: ice melting, steel slag, asphalt concrete, microwave heating

1. Introduction
As is known, the ice on the surface of asphalt pavement in winter significantly influenced the road transportation safety. Pervious investigations indicated that 25%-30% of the traffic accidents were caused by the ice on the pavement surface in the cold winters, especially on some sections like bridges and railroad [1]. Several kinds of deicing methods were investigated and recommended, including chemical method, mechanical method, Joule heating method, hydronic method and so on[2]. Nowadays, the chemical method and mechanical method were widely used, such as chemical salt and gritty materials. In China, the annual amount of deicing salt was 100 thousand tons on average and seemed to be increasing in recent years [3].However, chemical salt usually leads to the corrosion of steel and pollution of water [4], while some mechanical methods would surely lead to the surface damages and high maintenance cost for mechanical devices. Another two methods were also popular for removing ice. One is the Joule heating method by electrically conductive asphalt concrete [5]. The other is the hydronic heating with pipe systems interred in the pavement to induce heating [6]. Both the experiences of those two systems confirmed that it was feasible and controllable to melt the ice with heating. But the applications of those two methods were limited due to the practical conditions.
The successful heating of Joule heating method depends on the conductive materials inside the asphalt pavement, and the hydronic heating required the pervious building of pipe systems.

On the other hand, self-healing technology, as a kind of advanced maintenance method of asphalt pavement, has been world-wide researched and applied in recent year [7]. With the temperature increase of asphalt pavement, the asphalt binder will flow autonomously, and the crack would be cured [8-9]. Compared with self-healing method, the deicing technique shared the same temperature control mechanism and performance. However, few researches had been conducted on this field.

The purpose of this paper is to investigate the ice melting performance of self-healing asphalt concrete with microwave heating. Both the ice melting efficiency and properties of the deicing were characterized. A series of steel slag asphalt concrete were prepared, and microwave heating technology was applied to study their ice melting efficiency.

2. Materials
Both limestone and steel slag were used as aggregates in this research. The coarse aggregate of limestone was provided by Keyuan Stone Material Factory from Inner Mongolia Province. The coarse steel slag aggregate was provided by Wuhan Iron and Steel (Group) Company from Hubei Province. The properties of the aggregates were shown in table1. AH-70# base bitumen was also used in this research, which provided by SK Energy Co. Ltd. of South Korea. The properties of the bitumen were shown in table 2.

| Tests                              | Limestone aggregate | steel slag aggregate | Specification | Test method |
|------------------------------------|---------------------|----------------------|---------------|-------------|
| Water absorption%                  | 0.6                 | 1.8                  | ≤3.0          | T0304-2005  |
| Crushed value%                     | 13.2                | 14.5                 | ≤28           | T0316-2005  |
| Los Angeles abrasion value%        | 15.6                | 12.9                 | ≤30           | T0317-2005  |
| Apparent specific gravity %        | 2.901               | 3.413                | ≥2.50         | T0308-2005  |
| Acicular and flat particle%        | 14.4                | 11.3                 | ≤18           | T0312-2005  |

Table 2. Properties of AH-70 asphalt.

| Tests                              | Results | Specification | Test method |
|------------------------------------|---------|---------------|-------------|
| Penetration (25°C, 100g, 5s) [0.1 mm] | 68      | 60-80         | T0604-2011  |
| Softening point (ring & ball) [°C]  | 49      | 44-54         | T0605-2011  |
| Ductility (5cm/min, 15°C) [cm]      | >150    | ≥100          | T0606-2011  |

3. Experiments

3.1. Temperature Raising Characteristic of Mixture
Marshall Specimens of limestone and steel slag asphalt mixtures were prepared in this stage. Temperature raising performances of asphalt mixtures were measured during the heating process. Each Marshall specimen was placed in the microwave oven for heating 20s per time and rest for 10s. Both the flank surface and internal temperatures were measured by an infrared gun and an optical fiber temperature sensor respectively between each two heating periods. The temperature of flank surface were taken in three equally space directions and the average value was defined as the final result. The internal temperatures of optical fiber temperature sensor were taken until the data was stably. This process was repeated six times, and the total heating period reached 120s for each time.

3.2. Thermal Conductivity Tests
In this study, the thermal conductivity of three different kinds of mixtures was tested, including limestone asphalt mixtures, steel slag asphalt mixtures and steel slag asphalt mixtures with moisture. A thermal constant analyzer was applied in this test. The thermal conductivity, thermal diffusivity and specific heat of samples were recorded.

3.3. Ice Melting Experiments
Different thicknesses of ice with Marshall Specimens were prepared (seen in figure 1). The thicknesses of ice were 1.5mm, 3.5mm and 5.5mm respectively. A microwave oven with output power of 700W was applied as the microwave heating equipment. The thickness and mass of the ice was measured before the experiment. Each sample was heating for 30s and rest for 30s alternately. The temperatures of ice surface and Marshall Samples were measured with an infrared gun during each rest period (seen in figure 2). The temperatures were measured in three equally spaced directions. Then the sample was inverted to test if the ice could peel off from the Marshall Sample under its own gravity (seen in figure 3). When the ice peeled off the Marshall Sample, the heating time was recorded as the final melting time. In this study, ice melting experiments were conducted at room temperature of 9 ºC.

4. Results and Discussion

4.1. Heating Rate of Mixtures
The temperature performance of limestone and steel slag asphalt mixtures was shown in figure 4.

Microwave is a kind of wave with frequency in the range from 0.3GHz to 300 GHz, corresponding to the wavelength of 1 mm to 1 m of electromagnetic waves[10]. When the microwave effect on most waves absorbed materials, like metal oxides, semiconductors and polar substances, it can be absorbed, and thus converted into heat to increases the temperature of objects. For non-magnetic materials, the
absorbing capacity related to its dissipation factor \( \tan \delta_E \) of complex permittivity \( \tan \delta \) [11]. As for the magnetic substances, its absorbing capacity is also related to its loss factor \( \tan \delta_M \) of complex permeability. Because of the loss factor \( \tan \delta_M \) and \( \tan \delta_E \) (non-magnetic material can be considered as 0) of each substance is not the same, so the wave absorbed capacity of each kind of material is changed. In general, the greater the loss factor \( \tan \delta \), the stronger absorbing ability of a substance achieved, and more heat was generated as a consequence. From some previous researches [12-13], it is indicated that the microwave would be a good technique to heat asphalt mixtures. The result of this test also agreed with this conclusion.

From figure 4, it is clear that both the steel slag and limestone could be heated by microwave, and the steel slag asphalt mixture is more effective than traditional limestone asphalt mixture. After six times of discontinuous heating, the inner center temperature of steel slag asphalt mixture could reach 102.5 °C, which is approximately two times faster than the heating rate of limestone surface. The flank surface temperature of those two kinds of asphalt mixtures has the same trend. One thing should be pointed out that, the inner center temperature was always higher than the flank surface temperature of each sample. This phenomenon indicated that more heat was absorbed in the middle of the sample, which means that during microwave heating asphalt pavement process. So in practical applications, the inner center temperature should be taken into consideration to avoid the overheating in the center of asphalt pavement while melting process.

4.2. Thermal Conductivity

The result of thermal test of asphalt mixtures were shown in table 3. As is known, the steel slag contains some parts of metallic elements. Some small holes also existed in the steel slag aggregate. Both the metallic elements and small holes may have some influence on the performance of asphalt mixtures thermal conductivity in this test.

**Table 3. Results of thermal conductivity test.**

| Types                      | Limestone Asphalt Mixtures | Steel Slag Asphalt Mixtures | Steel Slag Asphalt Mixtures After Water Damage |
|----------------------------|----------------------------|----------------------------|-----------------------------------------------|
| Thermal Conductivity/[W/mK]| 1.583                      | 1.421                      | 1.514                                         |
| Thermal Diffusivity/[mm²/s]| 1.758                      | 1.213                      | 1.149                                         |
| Specific Heat/[MJ/m³K]     | 0.900                      | 1.171                      | 1.318                                         |

From table 3, it is clear that the thermal conductivity was slightly decreased from 1.583 W/mK to 1.421 W/mK. The thermal diffusivity was also decreased by about 0.5 mm²/s. As a consequence, the specific heat was increased from 0.900 MJ/m³K to 1.171 MJ/m³K. The reasonable explain might be small holes play a more important role in thermal conductivity than metallic elements. As the amount of decrease was limited, and the speed of microwave heating doesn’t depend on the thermal conductivity of materials, it is believed that this difference between steel slag asphalt mixture and limestone asphalt mixture will not influence the heating rate of asphalt mixtures seriously.

It was found that thermal conductivity of steel slag concrete increased from 1.421 W/mK to 1.514 W/mK as the moisture was involved in the thermal properties test. The interpreted might be water contribute to thermal conductivity by reason of water filled in holes. With the water replaced holes, thermal diffusivity decreased from 1.213 mm²/s to 1.149 mm²/s and specific heat raised by 0.147 MJ/m³K. It is indicated that the increased moisture will contribute to the heating of the asphalt pavement and improve the efficiency of the ice melting.

4.3. Analysis of Ice Melting Efficiency

The temperature raising characteristic of mixture with ice was also measured in this paper. The surface temperatures of ice with limestone mixture and steel slag mixture were shown in figure 5.
In figure 5, the samples of limestone mixture and steel slag mixture have the same thickness of 3.5mm. From the figure 5, it is obvious that the ice-melting heating rate of steel slag asphalt mixture was much higher than the limestone. After four times of discontinuous heating, the increase rate of temperature of ice on steel slag asphalt mixture could reach 3.8°C/min, and the heating rate of limestone surface was only 2.6°C/min. Besides, the limestone asphalt mixtures cost six times of discontinuous heating to melting. The ice melting with steel slag asphalt mixture was about one minute quicker than the limestone asphalt mixture. This result shown that, steel slag asphalt concrete had better heating efficiency and ice melting with microwave irradiation compared with traditional concrete.

Figure 5. Ice melting of Limestone and Steel Slag with same thickness.

Figure 6 reflects the ice melting performance of natural melting conditions. It took about 100 minutes for ice to peel off the Marshall sample with its own gravity. However, as shown in figure 5, the microwave heating only needs around 2mins to separate the ice from the Marshall sample. It can be concluded that use the microwave heating can significantly improve the ice melting efficiency compared with natural melting conditions.

As can be seen from figure 7, the ice melting performance of steel slag asphalt mixtures with different thickness was evaluated. The thickness of ice was 1.5mm, 3.5mm and 5.5mm respectively. The final temperatures of each sample were very close (near 3°C) to each other at the end of melting process. It is concluded that the thickness of the ice have a limited impact on the ice melting efficiency. The temperature of 3°C could be used to determine the finish timing of melting.

It could be explained that the heat transfer between the asphalt mixture and the ice would become a state of dynamic equilibrium when the temperature of the interface of those two materials reached at 3°C. The amount of heat absorbed by the ice is equal to the heat absorbed by the concrete with
microwave. This dynamic process ended until interface-bound ice completely melted into water and the ice layer peeled away from the concrete surface.

![Figure 7. Temperature on Ice Surface.](image)

5. Conclusions
- The application of microwave irradiation heating could significantly improve the ice melting efficiency compared with nature conditions.
- Compared with traditional asphalt concrete, steel slag asphalt concrete has better heating efficiency. The heating rates of asphalt mixture are much better than traditional limestone asphalt mixture. Thermal conductivity of steel slag concrete is slightly decreased as there existed some small holes with cold air in steel slag, but the influence is limited.
- The thickness of the ice has a limited impact on the ice melting efficiency. The temperature of 3 ºC could be used to determine the finish timing of heating.
- In practical applications, the inner center temperature should be taken into consideration to avoid the overheating in the center of asphalt pavement while melting process.

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