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Research Article

Microwave Heating Characteristics of Emulsified Asphalt Repair Materials Incorporated with Steel Slag

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Emulsified asphalt needs to be cured for a certain age after demulsification to produce strength, which seriously affects the traffic opening time. In this work, microwave heating technology was applied for emulsified asphalt repair materials. Steel slag with high microwave activity was adopted to improve the performance of emulsified asphalt repair materials by microwave heating. Effects of steel slag sizes and contents on the heating rate, temperature distribution, and thermal performance of emulsified asphalt repair materials were analyzed by close microwave heating, open microwave heating, and repair simulation tests. Results show that the temperature of emulsified asphalt repair materials presents three different heating stages under microwave irradiation. The "critical point of phase transition" in the three stages is gradually advanced with the increase in steel slag content. The core temperature and maximum temperature of emulsified asphalt repair materials with different steel slag sizes are basically the same; however, the heat distribution of emulsified asphalt repair materials is significantly different. In contrast to conventional asphalt mixture, there exists a smaller temperature difference. The temperature of repairing materials can reach above 80°C. The interface area can form an embedded interface structure. Incorporation of steel slag and adoption of microwave heating are effective to improve the performance of emulsified asphalt repair materials.

1. Introduction

Emulsified asphalt repair materials are a mixture of emulsified asphalt as a binder and are mixed according to a certain proportion, which is used to treat asphalt pavement potholes and other diseases. They have the advantages of energy saving and environmental protection, low pollution, wide application, simple construction, and less external influence [1–3]. However, as emulsified asphalt is a water-based emulsified material, the internal free water is difficult to volatilize and exists for a long time [4–6]. This results in low interfacial adhesion, low strength, and poor flexibility of the emulsified asphalt mixture [7–9].

In recent years, microwave heating technology has been applied to asphalt and cement pavement engineering [10, 11]. Microwave heating technology has the characteristics of fast heating rate, uniform heating, and environment friendly for asphalt mixture [12]. Microwave heating technology is suitable for the repair of asphalt pavement cracks and depressions. Notably, microwave treatment of metal factory waste (such as steel slag and cooper slag) is very effective in asphalt mixture crack repair [13, 14]. Furthermore, the mixture heated by microwave has better high-temperature rutting resistance, low-temperature crack resistance, and water stability [15]. In addition, microwave heating technology has been applied in the chemical field of crude oil demulsification [16–18]. In contrast to traditional methods, such as thermal demulsification and stable emulsion demulsification, microwave heating technology has a higher demulsification rate, higher dehydration rate, and better demulsification effect [19–22]. Based on the advantages of microwave heating technology, it is feasible to introduce microwave heating technology into an emulsified asphalt mixture.

At present, the influence of microwave heating on the performance of emulsified asphalt mixture has been studied [23, 24]. The results show that microwave heating is beneficial to improve the mechanical properties of emulsified asphalt mixture. Microwave heating can rapidly increase the temperature in a short period of time to quickly destroy the electrical double layer structure of emulsified asphalt. At the same time, the repulsive force between the emulsified asphalt particles decreases, and the water in the emulsion is released quickly to demulsify the asphalt emulsion. However, the microwave heating time of emulsified asphalt mixture without high microwave active materials is relatively long.

In this work, the emulsified asphalt repair materials based on microwave heating were developed. It can be mixed at room temperature on a construction site, produce strength quickly, and has good interface performance. The heating efficiency and temperature distribution of emulsified asphalt repair materials with different steel slag sizes and contents were studied by heating tests. In addition, the effects of steel slag sizes and contents on microwave heating performance of emulsified asphalt repair materials were analyzed through X-ray diffraction (XRD) test and environmental scanning electron microscopy (ESEM) test.

2. Experimental

2.1. Materials. The material selection and experiments are based on the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011). Tables 1 and 2 show properties of cationic emulsified asphalt and steel slag (the tail slag of steelworks), respectively. Figure 1 shows aggregate gradation used for emulsified asphalt repair mixture.

2.2. Mix Proportion Design. In this work, the single grade aggregate was selected for the mix proportion verification test to ensure the stability of the mix proportion. According to the Marshall test result, the optimum asphalt-aggregate ratio was 4.8%, and the volume content of steel slag was 10%. Tables 3 and 4 show the mix proportion of emulsified asphalt mixture with different steel slag contents and emulsified asphalt mixture with different steel slag sizes, respectively.

2.3. Preparation of Specimens. Figure 2 shows the preparation and test flow chart of the emulsified asphalt mixture with steel slag. First, aggregate, water, mineral powder, and emulsified asphalt were weighed. Their total mass is 1250 g. Then, these raw materials were put into the mixture mixer and mixed for 120 s. Second, the mixture was poured into round molds with the diameter of 101.5 mm and the height of 63.5 mm to prepare the specimens. Then, these molds with mixtures were heated in a microwave. Third, the surface temperature and internal temperature of specimens were tested by using an infrared thermal imager.

2.4. Test Methods

2.4.1. Close Microwave Heating Test. In the indoor heating efficiency test, the civil microwave was used to conduct a close microwave heating test on emulsified asphalt repair materials in ceramic containers. The core temperature, overall infrared thermal imaging, and thermal distribution tests were conducted at different test points. The output frequency and output power of the microwave were 2.45 GHz and 0.7 kW, respectively.

2.4.2. Open Microwave Heating Test. In the simulation test of emulsified asphalt repair, self-prepared open microwave heating equipment (Figure 3) was used to conduct field simulation heating test. According to the Industrial Microwave Heating Installations-Test Methods for the Determination of Power Output (IEC 61307-2011) and Safety in Electroheat Installations-Part 6 and Specifications for Safety in Industrial Microwave Heating Equipment (IEC 60519-6-2011), Table 5 shows the specific parameters of self-prepared open microwave heating equipment.

2.4.3. Repair Simulation Test. Figure 4 shows the simulation test process of emulsified asphalt repair. The new-old mixture bonding model was used in the repair simulation test. The rutting plate of ordinary asphalt mixture was used to repair the old mixture. Firstly, the old mixture is drilled with a rotary drilling rig, and then, the core drilling position of the old mixture was filled with emulsified asphalt repair materials. Secondly, the plate was heated to the design temperature of 140°C in self-prepared open microwave heating equipment. Finally, the plate was rolled and formed.

2.4.4. Microstructure Tests of Steel Slag. In this work, an X-ray diffraction (XRD) test and environmental scanning electron microscopy (ESEM) test were conducted. For the XRD test, first, the steel slag aggregate was crushed into small pieces (4-6 mm) and immersed in ethanol absolute for 24 h. Then, the small piece of steel slag aggregate was dried in a vacuum drying oven at 80°C for 12 h to achieve a constant mass. Second, the small piece of steel slag aggregate was ground into powder (<80 μm). Finally, the powder was tested by using X-ray diffractometer at a scanning range of 5°–80°, a scanning speed of 5°/min, and a step size of 0.02°.

For the ESEM test, the steel slag aggregate was crushed into small pieces (about 5 mm). Then, the small piece was tested by S-4800 cold-field ESEM at an applied accelerating voltage of 7.0 kV and temperature of 20°C.

3. Results and Discussion

3.1. XRD Analyses of Steel Slag. Figures 5 and 6 show the XRD and microstructure of steel slag, respectively. Figure 5 shows that the steel slag contains a variety of minerals, especially magnetite. Magnetite has a strong microwave absorption capacity [25, 26]. As can be seen from Figure 6(a), there are tiny pits and cracks on the steel slag surface. These cracks can be used to fill asphalt to increase

Table 1: Properties of emulsified asphalt.

Test items		Unit	Specification	Test results
Residue percentage (1.18 mm sieve)		%	<0.1	0.03
Viscosity	Engra viscosity E25	—	2–30	8.12
	25°C Saybolt viscosity	s	7–100	55
Evaporated residue	Residual content	%	>62	64
	Solubility	%	>97.5	100
	Needle penetration (25°C)	0.1 mm	50–300	65
	Ductility (15°C)	cm	>40	79
Adhesion to coarse aggregate		—	2/3	2/3
Mixing test with aggregate			Even	Even
Storage	1 d	%	<1%	0.3
Stability	5 d		<5%	2.0

Table 2: Properties of steel slag.

Test items	1.18 mm	2.36 mm	4.75 mm	9.5 mm
Apparent relative density	3.420	3.380	3.320	3.310
Water absorption (%)	1.57	1.61	1.58	1.60
Polished value (%)		67		
Los Angeles attrition (%)		13.0		
Crushing value (%)		12.1		
Adhesion		Level 5		

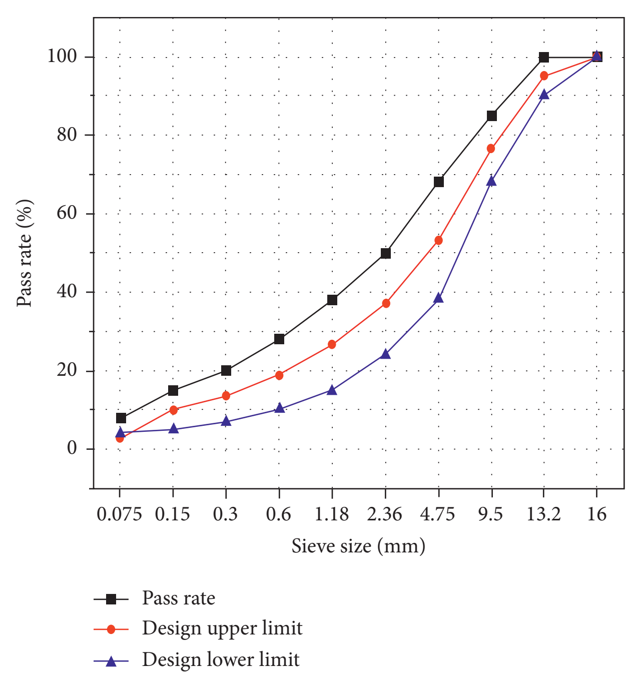


Figure 1: Aggregate gradation chart of emulsified asphalt mixture.

Table 3: Mix proportion of emulsified asphalt mixture with different steel slag contents.

Mix proportion	Aggregate percentage (%)									Mineral powder	Asphalt-aggregate ratio (%)
	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075		
0-0-0	5	18.5	23.5	16	10.5	7.5	5.5	3.5	7	3	4.8
1-2-1	5	18.5	18.5 + 5*	16	10.5	7.5	5.5	3.5	7	3	4.8
1-2-2	5	18.5	13.5 + 10*	16	10.5	7.5	5.5	3.5	7	3	4.8
1-2-3	5	18.5	8.5 + 15*	16	10.5	7.5	5.5	3.5	7	3	4.8

Note: $X + 5^*$ (10^* or 15^*) represents equal substitution of 5% (10% or 15%) ordinary aggregate with steel slag of the same size.

Table 4: Mix proportion of emulsified asphalt mixture with different steel slag sizes.

Mix proportion	Aggregate percentage (%)									Mineral powder	Asphalt-aggregate ratio (%)
	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075		
1-1-2	5	8.5 + 10*	23.5	16	10.5	7.5	5.5	3.5	7	3	4.8
1-2-2	5	18.5	13.5 + 10*	16	10.5	7.5	5.5	3.5	7	3	4.8
1-3-2	5	18.5	23.5	6 + 10*	10.5	7.5	5.5	3.5	7	3	4.8
1-4-2	5	18.5	23.5	16	0.5 + 10*	7.5	5.5	3.5	7	3	4.8

Note: $X + 5^*$ (10^* or 15^*) represents equal substitution of 5% (10% or 15%) ordinary aggregate with steel slag of the same size.

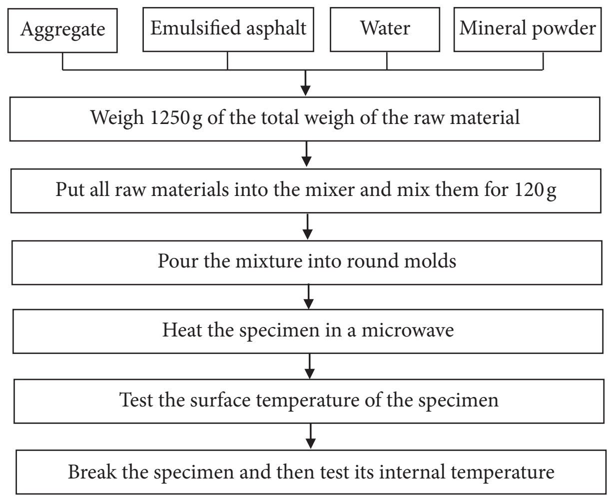


Figure 2: Preparation and test flow of emulsified asphalt mixture with steel slag.

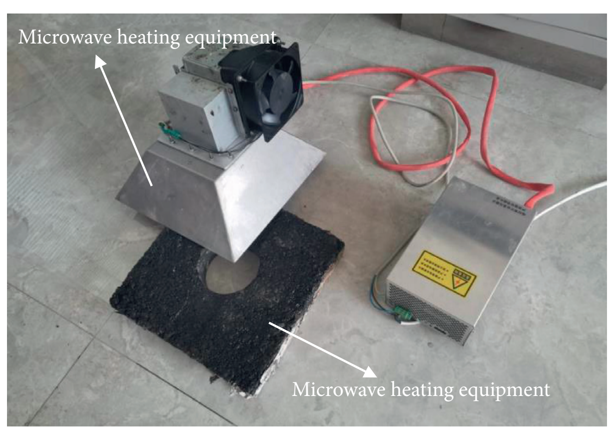


Figure 3: Self-prepared microwave heating equipment.

Table 5: Technical parameters of self-prepared open microwave heating equipment.

Parameters	Size (cm × cm)	Input voltage (V)	Output frequency (GHz)	Output power (kW)
Results	30 × 30	220	2.45	1.5

the depth of embedding on the steel slag surface. The stress area of steel slag can increase, which enhances its resistance to external forces. Therefore, the physical structure characteristics of the steel slag surface provide a skeleton-like effect for the asphalt-aggregate interface [27]. In addition, Figure 6(b) shows that the main elements in the slag are Si (SiO_2), O (SiO_2), Fe (Fe), Mg (MgO), and Ca (wollastonite). It is the presence of Fe element that increases the electromagnetic loss of emulsified asphalt repair materials with steel slag. This can enhance the microwave absorption capacity of emulsified asphalt repair materials to improve its heating efficiency [28].

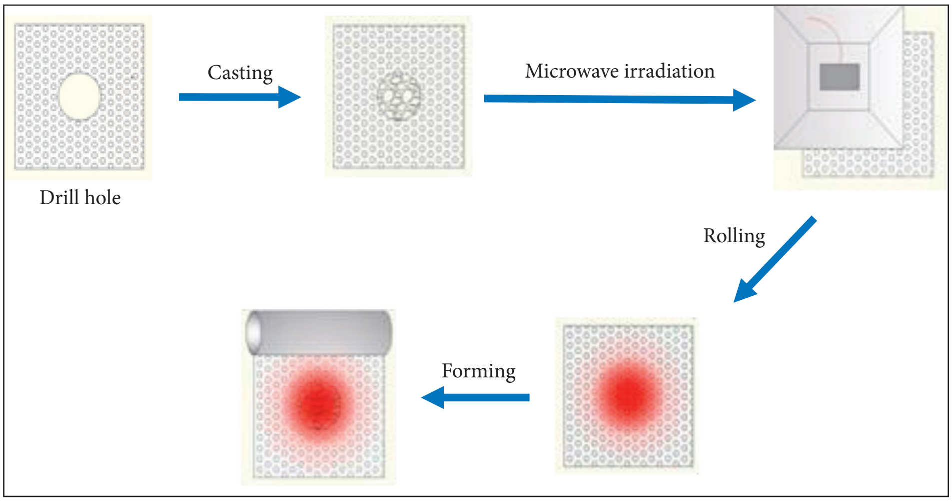


Figure 4: Simulation test process of emulsified asphalt repair.

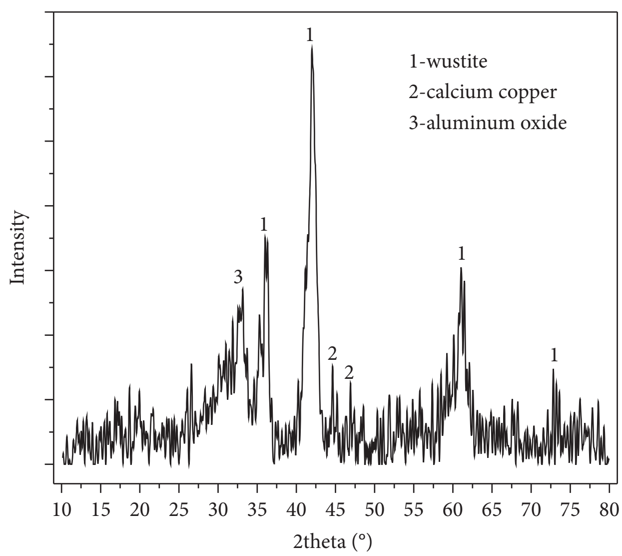


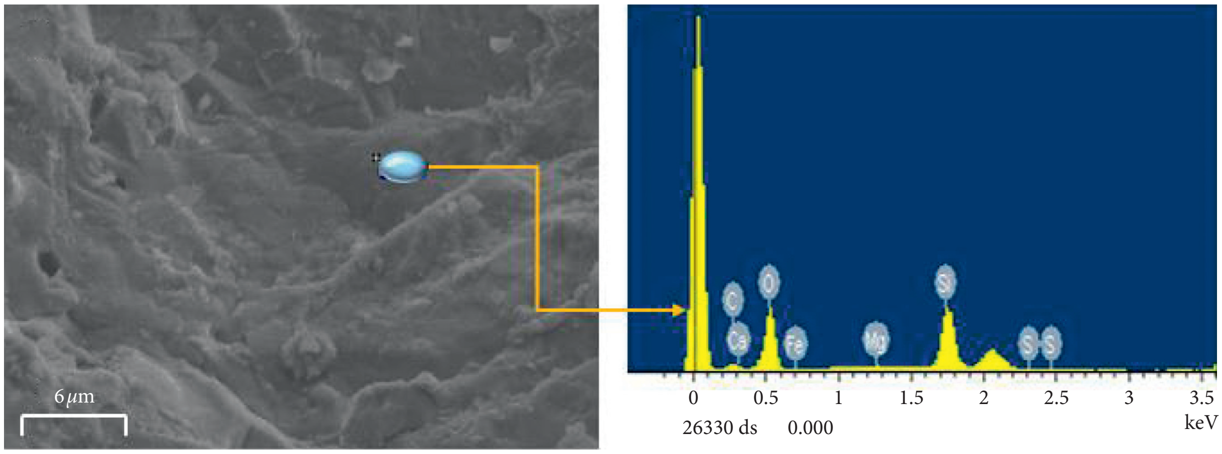
Figure 5: XRD spectrum of steel slag.

3.2. Effects of Steel Slag on Heating Rate of Emulsified Asphalt Repair Materials

3.2.1. Temperature Changes in Emulsified Asphalt Repair Materials. Figure 7 shows the temperature curve of emulsified asphalt repair materials with different steel slag contents under microwave heating (the size of steel slag is 4.75 mm). The heating rate of emulsified asphalt repair materials increases gradually with the increase in steel slag content. This shows that steel slag can greatly shorten microwave heating time. The higher the content, the higher the temperature of emulsified asphalt repair materials. In addition, Figure 7 shows the curve of temperature change (Figure 8). The heating stage can be divided into three stages: initial rapid rising stage (stage I: ≤95°C), medium stable stage (stage II: 95°C–100°C), and late rapid rising stage (stage III: ≥100°C). Figures 7 and 8 show that the heating trend of all samples is roughly the same. However, the transformation points of the three stages are slightly different due to the content of steel slag.

In emulsified asphalt repair materials with steel slag, water and steel slag are the main microwave absorbing materials. They produce a large number of molecular friction and collision under the microwave heating, which makes the temperature of emulsified asphalt repair materials rise rapidly. Thus, it presents an "initial rapid rising stage" (stage I: ≤95°C). The water in emulsified asphalt evaporates, when the internal temperature of emulsified asphalt repair materials increases close to 100°C. In a long period of time, the core temperature of emulsified asphalt repair materials is basically stable, thus forming a "medium stable stage" (stage II: 95°C–100°C). As the microwave heating continues, a large amount of moisture in the emulsified asphalt repair materials evaporates. The main microwave absorbing materials in the emulsified asphalt repair materials change from water and steel slag to steel slag. The core temperature of emulsified asphalt repair materials increased rapidly for the second time, thus forming a "late rapid rising stage" (stage III: ≥100°C). In the emulsified asphalt repair materials without steel slag, water and aggregates are the main microwave absorbing materials. The temperature rise range of emulsified asphalt repair materials without steel slag is less than that of emulsified asphalt repair materials with steel slag.

3.2.2. Temperature Distribution of Emulsified Asphalt Repair Materials. Figure 9 shows the infrared thermograms of the surface temperature of emulsified asphalt repair materials without steel slag and with 5% steel slag heated by microwave for 15 min, respectively. Based on the observation in Figures 9(a) and 9(b), the average surface temperature of emulsified asphalt repair materials with steel slag is 140°C, while emulsified asphalt repair materials without steel slag are 84°C. This shows that steel slag can significantly increase the surface temperature of emulsified asphalt repair materials.



(a)

(b)

Figure 6: The ESEM results of steel slag: (a) microstructures; (b) main elements.

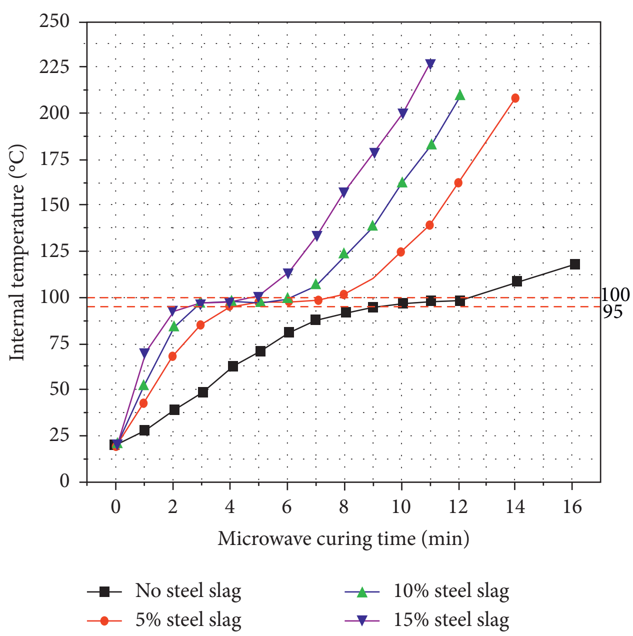


Figure 7: Temperature curve of emulsified asphalt repair materials with different steel slag contents.

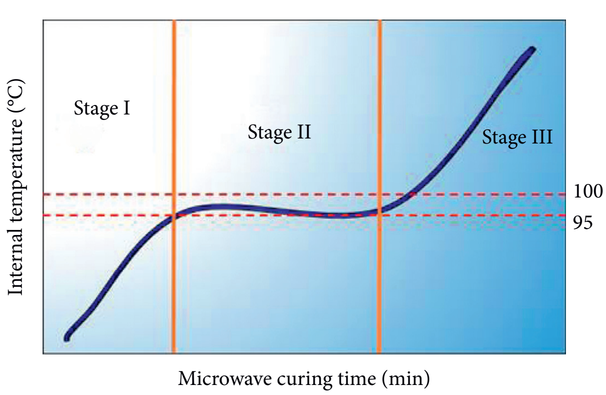


Figure 8: Temperature changes in emulsified asphalt repair materials under microwave heating.

In addition, the temperature distribution of emulsified asphalt without steel slag is uneven, the temperature of the middle part is significantly higher than that of the surrounding, and the temperature difference is about 20°C. The surface temperature distribution of emulsified asphalt repair materials with steel slag is more uniform (Figure 9(b)). This shows that the steel slag is evenly distributed in the emulsified asphalt repair materials, and it is conducive to improve the uniformity of temperature distribution of emulsified asphalt repair materials.

Figure 10 shows the internal temperature of emulsified asphalt repair materials. The average internal temperature of emulsified asphalt repair materials with steel slag is 150°C. The average internal temperature of emulsified asphalt repair materials without steel slag is 113°C. This shows that steel slag can significantly increase the internal temperature of emulsified asphalt repair materials. At the same time, the temperature distribution of emulsified asphalt repair materials with steel slag is approximately uniform, but the temperature at the edge of the mixture is hierarchical. The temperature limit of emulsified asphalt repair materials without steel slag is not obvious. It shows that the internal temperature distribution of emulsified asphalt repair materials without steel slag is more uniform.

In addition, in contrast to the internal temperature and the surface temperature (Figures 9(b) and 10(b)), the internal and external temperature difference in emulsified asphalt repair materials with steel slag is 7°C, while the internal and external temperature difference in emulsified asphalt repair materials without steel slag is 30°C. Therefore, steel slag has a positive effect on reducing the internal and external temperature difference in emulsified asphalt repair materials after microwave heating.

3.3. Effect of Steel Slag Size on Heating Rate of Emulsified Asphalt Repair Materials

3.3.1. Temperature Changes in Emulsified Asphalt Repair Materials. Figure 11 shows the temperature change trend of emulsified asphalt repair materials with different steel slag

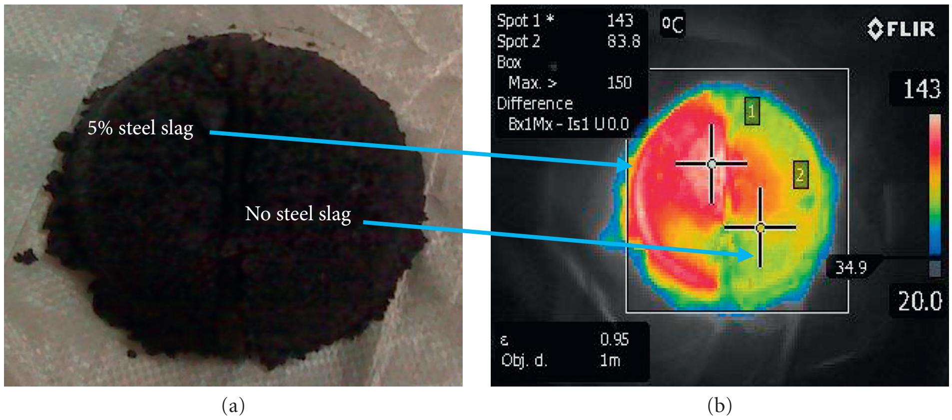


Figure 9: Surface infrared thermogram of emulsified asphalt repair materials: (a) mixture sample; (b) infrared thermogram.

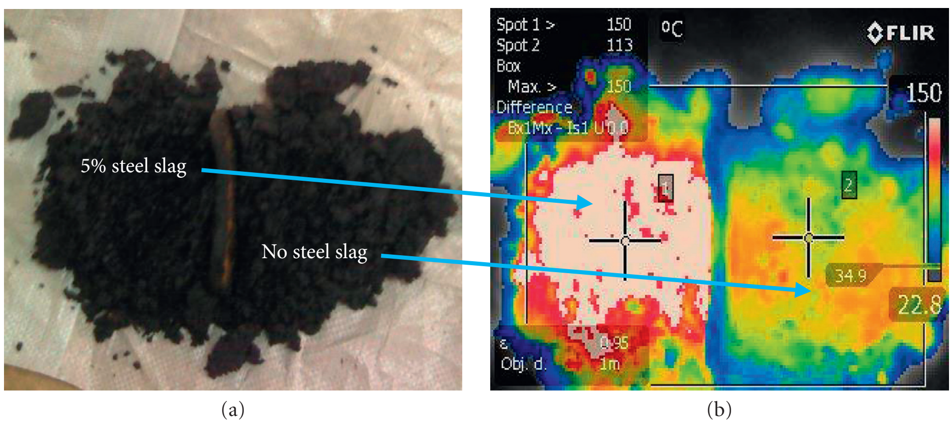


Figure 10: Internal infrared thermogram of emulsified asphalt repair materials: (a) mixture sample; (b) infrared thermogram.

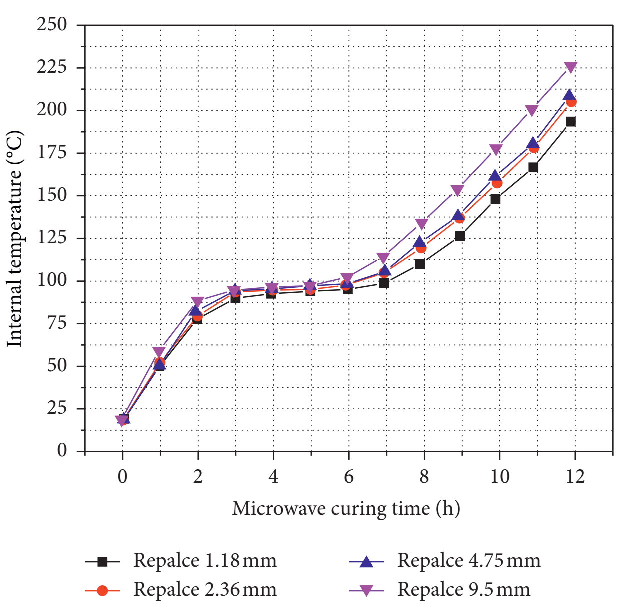


Figure 11: Temperature change trend of emulsified asphalt repair materials with different steel slag sizes under microwave heating.

sizes under microwave heating. The temperature rising rate of emulsified asphalt repair materials with different steel slag sizes is different, but the difference is not significant. According to the size, the order of temperature rising rate of emulsified asphalt repair materials is 9.5 mm > 4.75 mm > 2.36 mm > 1.18 mm. In contrast to Figures 11 and 7, the influence of steel slag sizes on the temperature of emulsified asphalt repair materials is weak. At the same time, the change in the heating curve in Figure 11 is consistent with that of the heating curve in Figure 7, including the initial rapid rising stage (≤95°C), medium stable stage (95°C–100°C), and late rapid rising stage (≥100°C).

Figure 12 shows the distribution results of the main elements in steel slag. The corresponding elements are marked and distinguished with points of different colors. The distribution of Ca, Si, and O in steel slag is uniform, while Fe is uneven and discontinuous. Therefore, the steel slag size has an effect on the heating rate of emulsified asphalt repair materials.

3.3.2. Temperature Distribution of Emulsified Asphalt Repair Materials with Different Steel Slag Sizes. Figure 13 shows the infrared thermogram of emulsified asphalt repair materials with different steel slag sizes. The surface temperature and internal temperature of emulsified asphalt repair materials can be improved rapidly. Compared with the internal temperature, the surface temperature is higher. The maximum surface temperature is 95.4°C, and the maximum internal temperature is 80.3°C. Due to the short microwave heating time, the temperature of emulsified asphalt repair

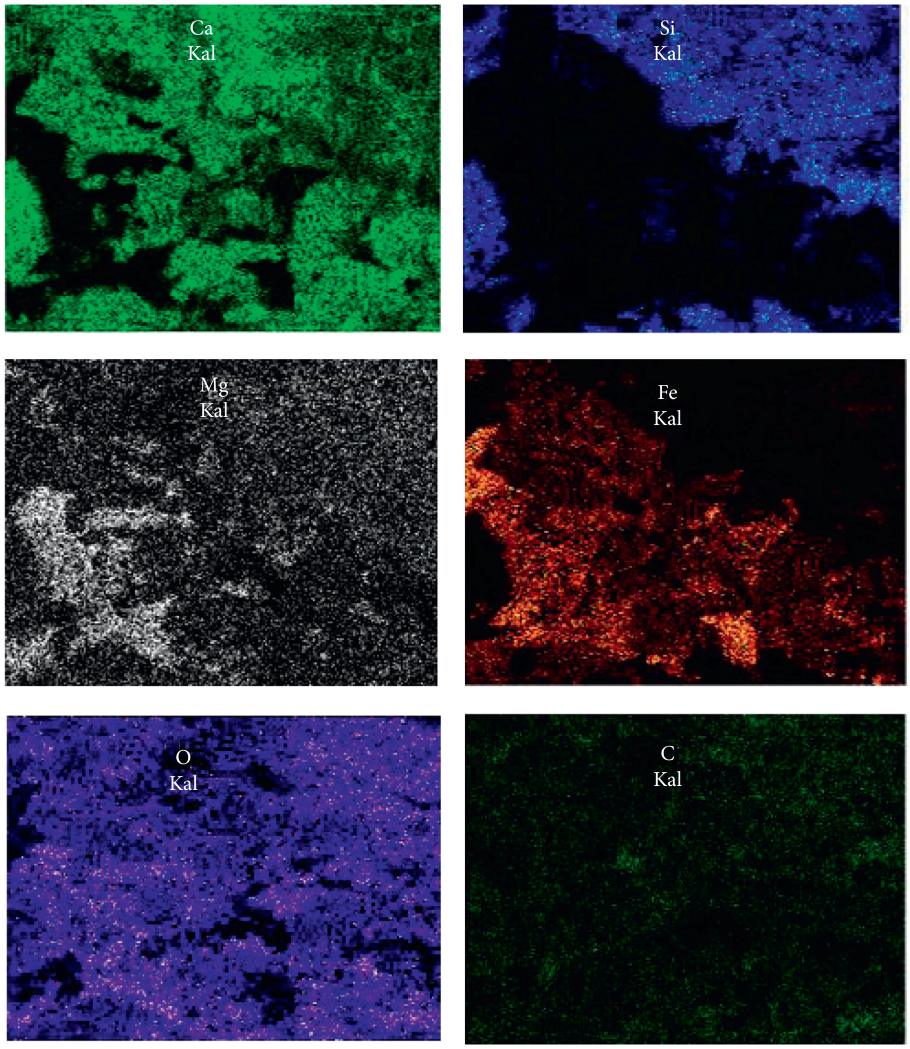


Figure 12: Distribution of main elements in steel slag.

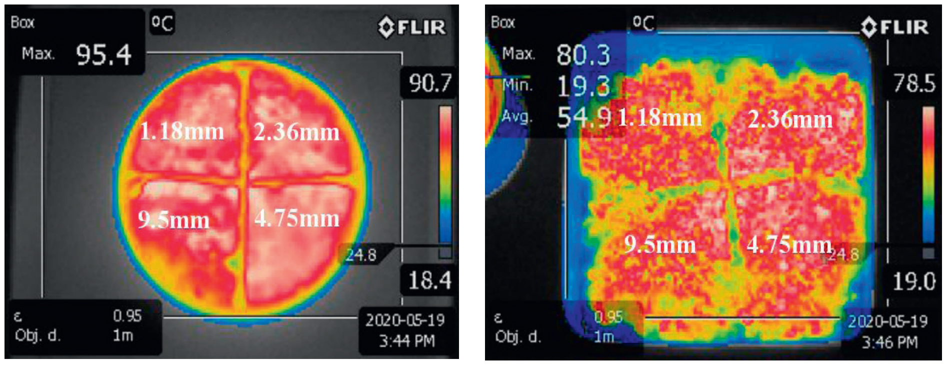
materials is lower. In the process of crushing, emulsified asphalt repair materials dissipate a part of heat, resulting in a large temperature gradient inside and outside. However, the core temperature and maximum temperature of emulsified asphalt repair materials with different steel slag sizes are basically the same, and there is no significant difference. The average surface temperature is about 83°C, and the internal temperature is about 68°C.

In addition, the temperature distribution of emulsified asphalt repair materials is different. The larger the steel slag size, the more uneven the surface temperature and internal temperature. The surface and internal temperature distributions of emulsified asphalt repair materials with a steel slag size of 9.5 mm have a high range of color differences, indicating that the temperature distribution is uneven. However, the surface and internal colors of emulsified asphalt repair materials with 2.36 mm and 1.18 mm steel slags are basically the same, indicating that the temperature distribution is relatively uniform.

Figure 14 shows the simulation diagram of emulsified asphalt repair materials with different steel slag sizes under microwave heating. The distribution of steel slag in emulsified asphalt repair materials is different when the size of steel slag changes (the content of steel slag remains unchanged). The steel slag is distributed in the form of coarse aggregate in the emulsified asphalt repair materials, when the steel slag size is larger. The microwave absorption capacity of large volume steel slag (9.5 mm) is higher than that of small volume steel slag (2.36 mm and 1.18 mm).

Therefore, the heating rate of emulsified asphalt repair materials with large volume steel slag is higher than that of emulsified asphalt repair materials with a small volume steel slag. Notably, the small volume steel slag has the function of fine aggregate. It can fill the gap and disperse evenly in the emulsified asphalt repair materials. Thus, the overall temperature distribution of emulsified asphalt repair materials with small volume steel slag is more uniform under microwave heating [29].

3.4. Analyses of the Effect of Repair Methods. Figure 15 shows the infrared thermogram of the repair model of the



(a) (b)

Figure 13: Infrared thermography of emulsified asphalt repair materials with different steel slag sizes: (a) surface temperature distribution; (b) internal temperature distribution.

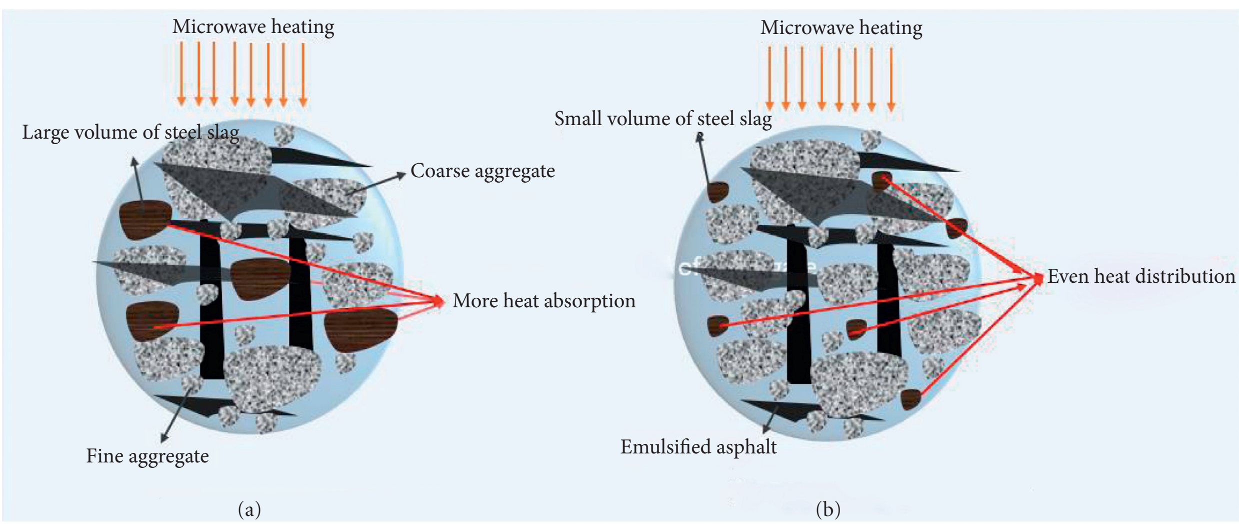


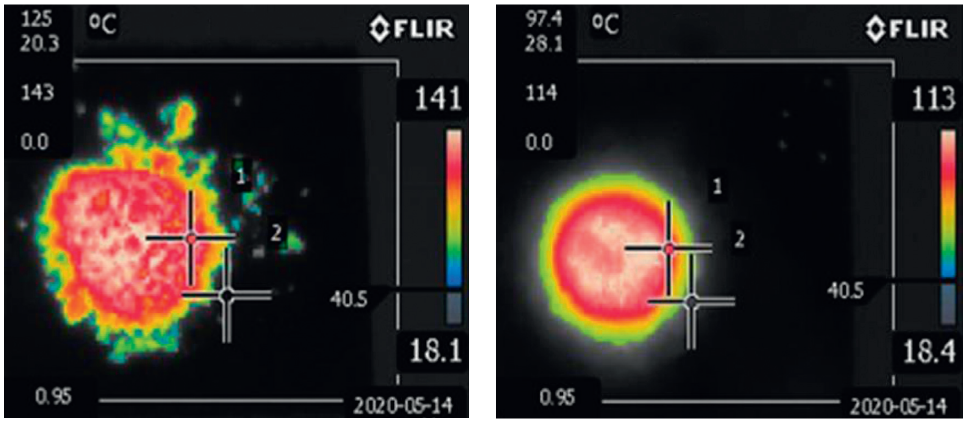
Figure 14: Simulation diagram of emulsified asphalt repair materials with different steel slag sizes under microwave heating: (a) bulk steel slag instead of aggregate; (b) small steel slag instead of aggregate.

conventional asphalt mixture. Based on the observation in Figure 15, the average temperature of the matrix is 20°C, when the conventional asphalt mixture is used to repair the potholes of the asphalt pavement. The average temperature of hot mix asphalt mixture is 125°C. There is a significant temperature difference in the interface transition zone. Excessive temperature difference is not conducive to repair. At the same time, it can be seen from Figure 15(b) that the heat loss in the high temperature zone of the asphalt mixture is large after the mixture is rolled. The temperature difference between after rolling and before rolling is 30°C. However, the temperature of the matrix is not significantly increased, which is only 28.1°C. This shows that the heat loss of conventional asphalt mixture is less absorbed by the matrix. Most of the heat is dissipated, and the energy utilization efficiency is low. Therefore, the temperature difference between the matrix and the hot mix asphalt mixture is high.

Figure 16 shows the infrared thermogram of the repair model based on microwave heating emulsified asphalt mixture. Based on the observation in Figure 16, the average temperature of the matrix and emulsified asphalt mixture is 85°C and 141°C, respectively, when the asphalt pavement potholes are repaired by microwave heating emulsified asphalt mixture. The temperature difference in the transition zone is small (<60°C). At the same time, it can be seen from Figure 16(b) that the heat loss in the high-temperature zone is small after rolling the emulsified asphalt mixture. The temperature difference between after rolling and before rolling is 10°C.

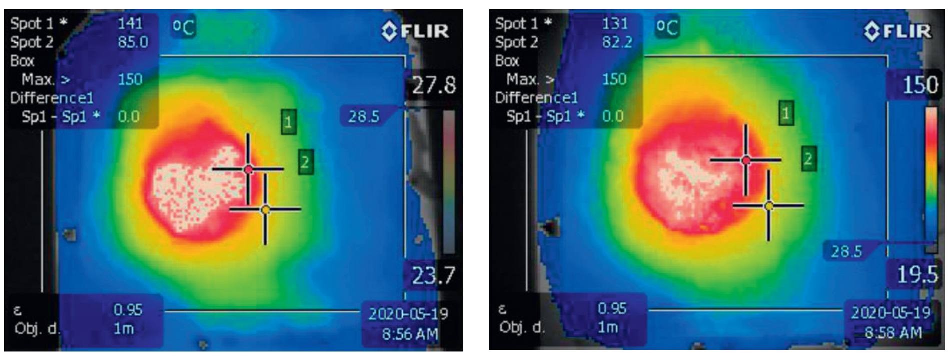
However, the temperature of the matrix has dropped slightly, which indicates that a part of the heat has been lost and has not been fully utilized. In addition, compared with Figures 15 and 16, the heat dissipation part is obviously reduced, and the energy utilization rate is relatively high when microwave heating emulsified asphalt mixture is used to repair asphalt pavement potholes. Thus, microwave heating has a positive effect on reducing the temperature gradient.

Figure 17 shows the mixture repair interface with different repair methods. There are obvious voids and defect areas at



(a) (b)

Figure 15: Infrared thermography of conventional asphalt mixture repair method: (a) temperature distribution before rolling; (b) temperature distribution after rolling.



(a) (b)

Figure 16: Infrared thermography of microwave heating emulsified asphalt mixture repair method: (a) temperature distribution before rolling; (b) temperature distribution after rolling.

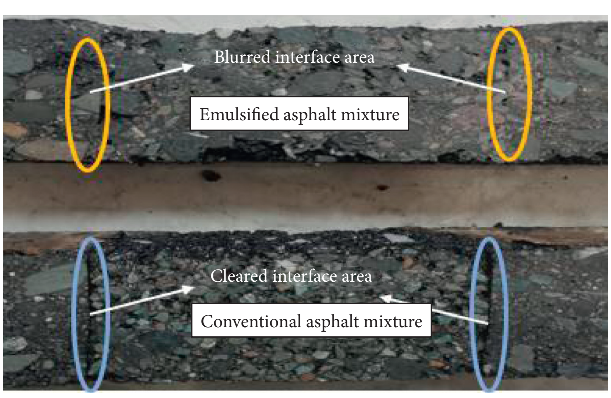


Figure 17: Interface repair with different asphalt mixtures.

the repair interface when the conventional asphalt mixture is used to repair the potholes of the asphalt pavement. The interface zone has a great influence on the fatigue life of mixture, and the interface bonding joint greatly reduces the overall service life of asphalt pavement [30]. The interface transition zone is not obvious when the emulsified asphalt mixture with microwave heating is used to repair asphalt pavement potholes. Therefore, the defect area is reduced, and the combination of repair material and old material is closer, which is beneficial to the service life of asphalt pavement.

4. Conclusions

In this work, the microwave heating efficiency and temperature distribution of emulsified asphalt repair materials with different steel slag sizes and contents were studied by the heating test and simulation test. In addition, the effects of steel slag sizes and contents on microwave heating performance of emulsified asphalt repair materials were analyzed by the X-ray diffraction (XRD) test and environmental scanning electron microscopy (ESEM) test. The following conclusions can be drawn:

(1) Under the microwave heating, the heating stage of emulsified asphalt repair materials can be divided into three stages: initial rapid rising stage (stage I: ≤95°C), medium stable stage (stage II: 95°C–100°C), and late rapid rising stage (stage III: ≥100°C).

(2) With the increase in steel slag content, the “critical point of phase transition” in the three stages of

temperature rise of emulsified asphalt repair material is gradually advanced and the duration of "initial rapid rising stage" and "medium stable stage" is also gradually shortened.

(3) The core temperature of the emulsified asphalt repair materials with different steel slag sizes under the microwave heating has basically the same change trend, showing a typical three-stage change rule. The temperature distribution of emulsified asphalt repair materials with steel slag is obviously different. The larger the steel slag size, the more uneven the surface and the internal temperatures.

(4) In contrast to the conventional asphalt mixture repair method, the temperature difference in the interface zone is smaller. The temperature of repairing materials can reach above 80°C. The temperature loss is small after rolling. The interface area can form an embedded interface structure.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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