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MICROWAVE ABSORBING CHARACTERISTICS OF ASPHALT MIXES WITH CARBONYL IRON POWDER

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Abstract—Power microwave was adopted to heat asphalt mixes with carbonyl iron powder (CIP) by its microwave absorbing characteristics. The Arch reflectivity system was employed for reflectivity tests in the frequency range of $2.0 \sim 4.0$ GHz, and road properties of the asphalt mixes with different heating techniques were studied. The results indicate that 30 mm thickness of the asphalt mixes with the ratio of CIP absorber to asphalt 0.1 : 1.5, can effectively absorb microwave with a -19.1 dB absorbing peak at 2.45 GHz frequency. Microwave heating rate for asphalt mixes with CIP is 16 times higher than that for ordinary asphalt mixes. Microwave heating can enhance road properties of the asphalt mixes, such as Marshall stability, flow value, dynamic stability and splitting strength at low temperature to a certain extant when the ratio of CIP absorber to asphalt is from 0.1 : 1.5 to 0.3 : 1.5.

1. INTRODUCTION

The amount of consumed energy significantly contributes to the total cost in asphalt pavement construction. In addition, fuel gas emission can also pollute the environment. Meanwhile, global awareness and stringent environmental regulations are being actively implemented to prevent the worsening effects of climate change [1]. In many cases, the properties of asphalt mixes, such as Marshall stability and dynamic stability, can be exacerbated since the asphalt mixes experience uneven temperature [2]. Therefore, it is necessary to reduce the total cost of

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pavement construction by using new heating technologies. In addition, environmental friendlier preparations of asphalt mixes materials are welcomed by the concepts of saving resources and reducing pollution by new heating techniques adoption [3, 4].

Microwave techniques with their ability to rapidly heat dielectric or magnetic materials is commonly used as a source of heat and an alternative to conventional conductive heating methods [5]. There have been many studies on the construction and evaluation of asphalt mixes pavement with microwave technology. For example, Li and Soheil [6] used wave propagation techniques to determine the degree of aging of hot-mix asphalt (HMA) and thought that the nondestructive techniques made it attractive to monitor the variation in modulus of an HMA specimen. The multichannel analysis of the surface waves (MASW) method was used to measure pavement depth by measuring the elastic modulus of different layers [7, 8]. In addition, microwave techniques have also been widely used to estimate initial setting time of cement paste and to enhance mechanical properties of cement matrix materials, etc. [9, 10]. On the other hand, CIP as a metallic magnetic material is a conventional microwave absorbent, which can enhance power microwave efficiency and is widely concerned with due to its higher saturation magnetization and Snoke's limit than ferrites [11, 12].

The objective of this study is to investigate wave absorbing characteristics of CIP/asphalt mixes. Therefore, a comprehensive experimental work was performed in which the wave absorbing asphalt materials were prepared, and arch reflectivity system was used to test reflectivity of the asphalt mixes. The heating rate of different asphalt mixes and the influences of microwave heating on road properties of the asphalt mixes with CIP were studied.

2. MATERIALS AND EXPERIMENTAL SETUPS

2.1. Properties of the Materials

The crushed basalt aggregate and limestone filler were used in this study. Their properties were tested according to *Test Methods of Aggregate for Highway Engineering (JTG E42-2005)*, and the results were given in Table 1 and Table 2. AH-90 asphalt was adopted. Its properties tested according to *Standard Test Methods of Asphalt and Asphalt Mixtures for Highway Engineering (JTJ 052–2000)* were shown in Table 3. DT-50 CIP was used, and its density was $1.520\,\mathrm{g\cdot cm^{-3}}$. The SEM morphology in Fig. 1 shows that the particles are spherical like onion bulb, and the diameters are in the range of $1 \sim 6\,\mu\mathrm{m}$. KH-550 silane coupling agent was used, whose chemical formula was $H_2N(CH_2)_3S_i(OC_2H_5)_3$ and density was $0.944\,\mathrm{g\cdot cm^{-3}}$.

2.2. Preparations of CIP Absorber/Asphalt Composites

The mixture of CIP was prepared, coupling agent, asphalt and trichloroethylene according to 1 : 0.01 : 0.01 : 2 in mass to get a

Table 1. Properties of the aggregate.

Properties	**Values**
Apparent specific gravity/$(\mathrm{g} \cdot \mathrm{cm}^{-3})$	2.913
Crushed value/%	12.1
Weared value/%	15.2
Adhesion grade with asphalt	4

Table 2. Properties of the mineral filler.

Properties	**Values**
Apparent specific gravity/$(\mathrm{g} \cdot \mathrm{cm}^{-3})$	2.988
Mean diameter size/μm	15.476
CaO content by weight/%	36.19
SiO_2 content by weight/%	32.12

Table 3. Properties of the asphalt.

Properties	**Values**
Penetration/(25°C, 100 g, 5 s, 0.1 mm)	82
Softening point/$(t_{R\&B}$, °C)	46.1
Ductility/(15°C, cm)	65

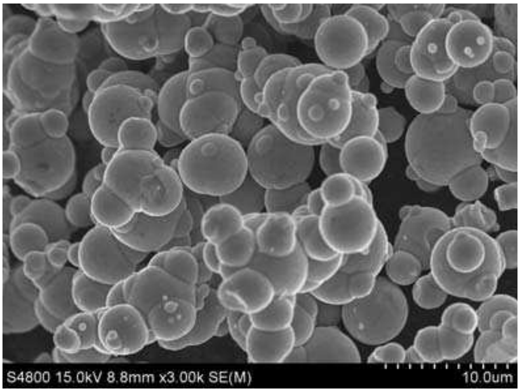

Figure 1. SEM micrograph of CIP.

Table 4. Aggregate gradation of the asphalt mixes.

Sieve size/mm									
16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing percentage/%									
100	95.1	80.4	55.5	34.4	21.8	17.4	12.5	10.1	6.7

CIP absorber; ultrasound cleaner was used to disperse it for 30 min; trichloroethylene was eliminated at 85°C $\sim$ 95°C; and the absorber was obtained. The particles of CIP shown in Fig. 1 could be dispersed uniformly into trichloroethylene due to its smooth surfaces and good sphericity. The absorber and asphalt were mixed evenly by using a shearer according to 0.1 : 1.5, 0.2 : 1.5, 0.3 : 1.5 and 0.4 : 1.5 in mass for 30 min in 160°C and CIP absorber/asphalt composites was obtained.

2.3. Preparations of the Asphalt Mixes

Aggregate gradation of the asphalt mixes was listed in Table 4. The aggregate and CIP absorber/asphalt composites with the ratio of absorber to asphalt, 0.1 : 1.5, were heated for 160°C in experimental microwave oven (800 W power, 2.45 GHz), and the composites and aggregate in 4.9 : 100 were mixed to get asphalt mixes. The specimens for reflectivity and heating rate were prepared. The specimen sizes for reflectivity and heating rate test were 180 mm (length) $\times$ 180 mm (width) $\times$ 30 mm (thickness) and 40 mm (diameter) $\times$ 30 mm (thickness). Finally, road property test specimens with different ratios of CIP absorber to asphalt were provided.

2.4. Reflectivity and Electromagnetic Factor Tests of the Asphalt Mixes

The arch reflectivity system shown in Fig. 2 was employed for reflectivity and electromagnetic factors test [13, 14]. The system was equipped with an E83628B network analyzer made in the United States. The measurement frequency ranged between 2.0 $\sim$ 4.0 GHz. The signal was sent off from the network analyzer by one horn antenna, projected onto the sample, and was reflected. The other horn antenna received the reflected signal through the network analyzer for analysis. The specimen was positioned on an aluminum panel (180 mm $\times$ 180 mm). In this work, the distance between the sample and the horn mouths was about 1.75 m. The floor around the pedestal was

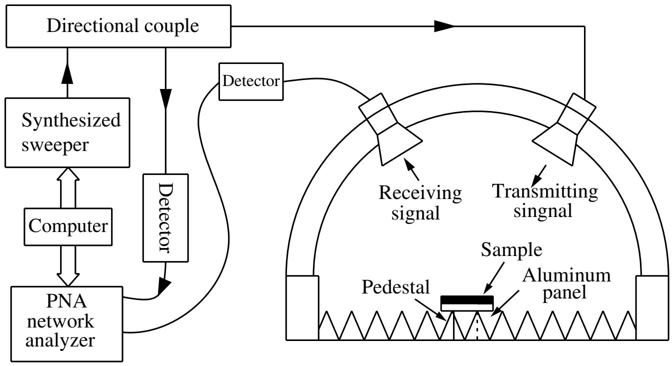

Figure 2. Simplified block diagram setup for reflectivity measurement by the arch reflectivity system (L: 3088 mm; H: 2800 mm).

covered with standard pyramidal absorbers (13 mm × 13 mm × 46 mm), providing a −40 dB background level relative to the 0 dB calibration.

3. RESULTS AND DISCUSSION

3.1. Principle of Microwave Reflectivity

Given the wavelength of microwave, reflectivity is defined as formula (1) when the microwave is incident upon the plane from the same angle in the same power.

$$R = \frac{P_a}{P_m} \tag{1}$$

where R is the reflectivity of the materials; P_a is the reflection power of the materials; P_m is the reflection power of the good conductive plane. Practically, the absolute reflection power is not measured, whereas the ratio of the reflection power of the plane and the materials against the same reference signal is measured in formulas (2) and (3).

$$R_m = \frac{P_m}{P_i}; \tag{2}$$

$$R_a = \frac{P_a}{P_i} \tag{3}$$

where P_i is the power of the reference signal, which is in direct proportion to the transmitting signal. Thus, the reflectivity of the specimens can be expressed as formula (4)

$$R = \frac{P_a}{P_m} = \frac{P_a}{P_i} / \frac{P_m}{P_i} = R_a/R_m \tag{4}$$

When expressed in dB, the following formula (5) is usually used

$$R[\text{dB}] = 10\lg R_a - 10\lg R_m \tag{5}$$

If the materials possess a reflectivity lower than −10.0 dB, they can be used as high effective wave absorbing materials [15].

3.2. Reflectivity of the Asphalt Mixes at Different Frequency

The reflectivity of the asphalt mixes in 2.0 ∼ 4.0 GHz frequency is shown in Fig. 3, which shows that there is an apparent wave absorbing peak with the lowest reflectivity −19.1 dB at a frequency of 2.45 GHz. The specimen was positioned on an aluminum panel in test, so the CIP absorber/asphalt mixes can be seen as a single layer wave absorbing materials. If the depth is kept a constant, the reflectivity changes with the frequency, which is called frequency effect. The reflectivity can also be calculated by formula (6) to formula (9).

$$R = \frac{Z-1}{Z+1} \tag{6}$$

$$Z = \eta \tanh(jkd) \tag{7}$$

$$\eta = \sqrt{\frac{\mu' - j\mu''}{\varepsilon' - j\varepsilon''}} \tag{8}$$

$$k = \frac{2\pi}{\lambda_0}\sqrt{(\varepsilon' - j\varepsilon'')(\mu' - j\mu'')} \tag{9}$$

where Z is microwave impendence; η is characteristic impedance; k is propagation constant; ε' is the real part of relative permittivity; ε'' is the imaginary part of relative permittivity; μ' is the real part of relative magnetic permeability; μ'' is the imaginary part of relative magnetic permeability; d is specimen depth; λ_0 is the wave length in the air. At 2.45 GHz frequency, for the asphalt mixes without CIP, ε' and ε'' are 5.0 and 0.170, respectively; μ' and μ'', 1.0 and 0. For the asphalt mixes with CIP, ε', ε'', μ' and μ'' are 30.1, 3.1, 1.5 and 0.19, respectively. Before the CIP addition, the dielectric loss is the main main factor influencing the reflectivity for the asphalt mixes without CIP, and the ratio of ε'' to ε' is the key factor to determine the microwave absorbing ability. After the CIP addition, the reflectivity depends on the dielectric and magnetic losses, and the ratios of ε'' to ε' and μ'' to μ' can influence the reflectivity together. Especially, the enhanced $\tan\delta$ (dielectric or magnetic loss tangent) is beneficial to improving the microwave absorption properties in 2.0 ∼ 4.0 GHz frequency range.

As to 30 mm thickness of the asphalt mixtures, it is usually used in the upper part of highway asphalt pavement design. Therefore, it can

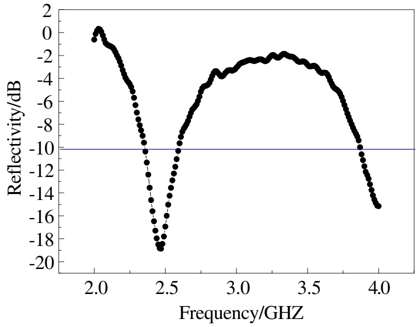

Figure 3. Reflectivity of the asphalt mixes at different frequency.

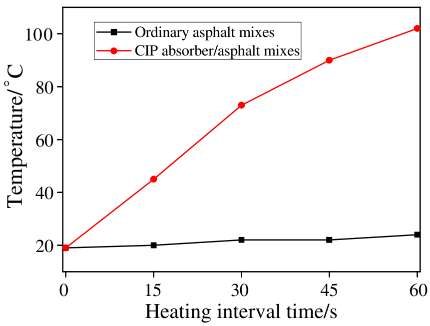

Figure 4. Temperature changes of the different asphalt mixes with heating interval time.

be deduced that the samples with CIP have better absorption efficiency in the lower frequency range as a whole. In addition, 2.45 GHz frequency is the same as the frequency used in microwave maintenance vehicles and microwave radiation heater for asphalt pavements [16], which indicates that the asphalt mixes studied in the paper is suitable for road microwave maintenance. This can put forward a basic theory for asphalt pavement microwave maintenance equipment development.

In view of CIP, Liu et al.'s study suggested that it could be applied as microwave absorbers in 2.0 $\sim$ 4.0 GHz, in which the absorbing properties of the materials were improved [17]. For an asphalt pavement structure, microwave heating depth can be calculated as formula (10)

$$D = \frac{\lambda_0}{2\pi\sqrt{\varepsilon'}\tan\delta} \tag{10}$$

where λ_0 is microwave length, m; ε' is the real part of relative permittivity, 5.0; $\tan\delta$ is loss angel tangent, 0.034. If frequency is 2.45 GHz, the $\lambda_0 \approx 12$ cm. According to formula (10), the microwave heating depth $D \approx 23$ cm for asphalt mixes without CIP. After CIP addition, ε' and $\tan\delta$ increase, which can decrease microwave penetration depth and enhance heating rate on surface or inner of asphalt pavement.

3.3. Heating Rate of Different Asphalt Mixes

The ordinary asphalt mixes and CIP absorber/asphalt mixes were heated in microwave oven for 60 s, and the changes of the temperature with heating interval time were shown in Fig. 4. As shown in Fig. 4, after CIP addition, the surface temperature of the asphalt mixes evidently increases at a different heating interval time, and it is enhanced by 5°C and by 83°C for the ordinary asphalt mixes and CIP absorber/asphalt mixes after 60 s heating interval time, respectively, which suggests that CIP addition is responsible for 16 times of heating rate increase.

In addition, microwave heating power is the other key factor influencing heating rate, which can be calculated as in formula (11)

$$W = 0.5561 f \varepsilon' \tan\delta \cdot E_m^2 \times 10^{-12} \tag{11}$$

where f is microwave frequency, GHz; E_m is electromagnetic intensity, V/m; f, E_m and ε' are not changed easily, but $\tan\delta$ can be changed, which evidently influences microwave heating power. Formula (11) indicates that it is a key measure to enhance the $\tan\delta$, which is effective to transform microwave energy into thermal energy. Addition of CIP improves electromagnetic loss, which is beneficial to enhancing microwave absorbing rate.

3.4. Road Properties of the Asphalt Mixes

Properties of the asphalt mixes with different ratios of CIP absorber to asphalt tested according to *Standard Test Methods of Asphalt and Asphalt Mixtures for Highway Engineering (JTJ 052–2000)* are shown in Fig. 5, which shows that Marshall stability of the asphalt mixes is enhanced by 19.5% after microwave heating. The Marshall stability keeps increasing with the increase of CIP content, in the range from 0 to 0.4 : 1.5. However, the trend of increasing begins to decrease after the ratio is beyond 0.3 : 1.5. Fig. 5(b) indicates that the flow value decreases after the CIP addition and then increases until the ratio is 0.3 : 1.5, which suggests that higher contents of CIP make the asphalt brittle. The dynamic stability shown in Fig. 5(c) indicates that it is enhanced by 31.4% when the ration is 0.2 : 1.5 and then decreases after it. In contrast to splitting strength of the asphalt mixes without CIP at low temperature, the splitting strength evidently increases after the CIP addition, shown in Fig. 5(d). However, when the ratio reaches 0.3 : 1.5, the splitting strength decreases by 50.1%, which indicates that although CIP is the key material for microwave absorbing, excessive amount of it influences the asphalt mixes property at low temperature.

It should be noted that the specimens were heated in closed cavity in which the microwave is resonant to increase the rapid heating [18] and to make the heating in the specimens more even, which is advantageous to asphalt, aggregate adhesion and improve the mechanical properties, such as Marshall stability and dynamic stability. Vallee and Conner [19] reported that the surface temperature increased when using absorbers with higher permittivity. So it is more

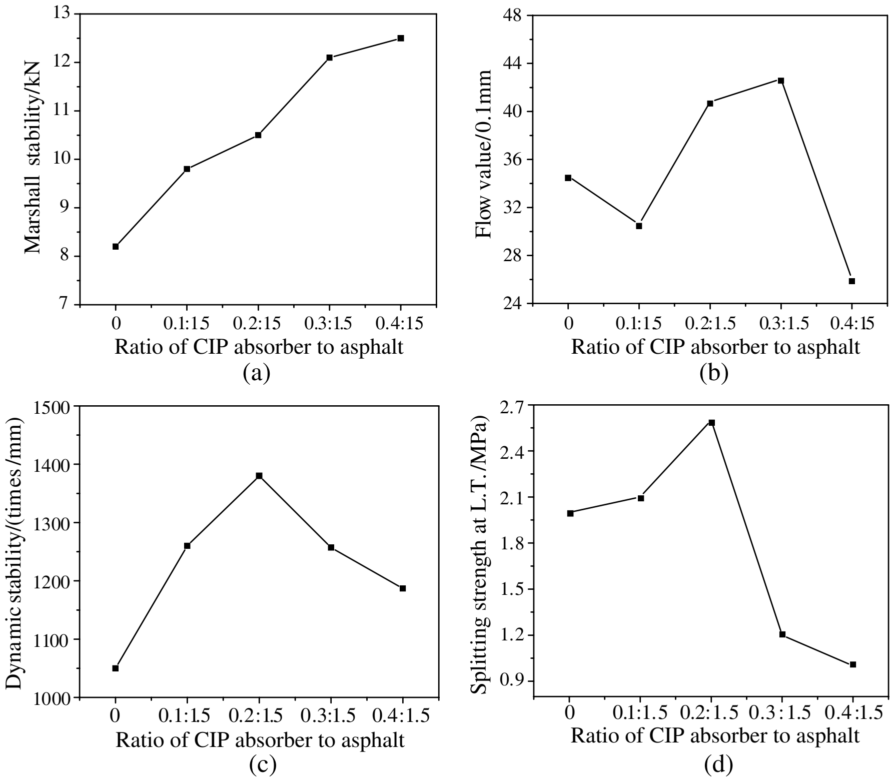

Figure 5. Properties of the asphalt mixes. (a) Marshall stability, (b) flow value, (c) dynamic stability, (d) splitting strength at low temperature.

effective to heat asphalt mixes with CIP by using microwave heating techniques. Unlike conventional heating, where heat flows from the outer surface to the core of the specimen, microwave heat is generated within the specimen, and the heat can propagate in all directions [20], which is also beneficial to exerting binding functions of the asphalt. Therefore, suitable CIP contents improve the Marshall stability, flow value, dynamic stability and splitting strength at low temperature.

4. CONCLUSIONS

1) 30 mm thickness of asphalt mixes with the ratio of CIP absorber to asphalt, 0.1 : 1.5, can effectively absorb microwave with a −19.1 dB reflectivity peak at 2.45 GHz frequency, which is usually used in

asphalt pavement microwave maintenance vehicles and microwave radiation heater.

2) After CIP addition, surface temperature of the asphalt mixes distinctively increases at a different heating interval time, and microwave heating rate for the asphalt mixes with CIP is 16 times higher than that for ordinary asphalt mixes.
3) Significantly, road properties of the asphalt mixes with suitable CIP contents tested are as well as or better than those tested using conventional heating. In contrast to conventional heating method, microwave technique can enhance Marshall stability, flow value, dynamic stability and splitting strength at low temperature if the ratio of the CIP absorber to asphalt in mass is not beyond 0.3 : 1.5.

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