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Investigation of Microwave Healing Performance of Electrically Conductive Carbon Fiber Modified Asphalt Mixture Beams

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ABSTRACT

This presented paper aimed to investigate the physical properties and microwave-healing performance of carbon fiber modified asphalt mixture. Two types of carbon fibers, HexTow® IM8 and AS4 (from HEXCEL Company), were added to asphalt mixture. About 2% and 4% HexTow® IM8 fiber (by mixture weight) were chopped and dry-mixed for the modified asphalt mixture. About 1.5% and 3% of HexTow® AS4 fiber (by binder weight) were pre-cut and wet-mixed with asphalt binder then the modified asphalt mixture was produced. The thermal conductivity of carbon fiber modified asphalt mixture samples increased. The electrical resistivity of them decreased with fiber content. In addition, the cyclic fracture-microwave healing tests were conducted to evaluate the healing performance of the control and carbon fibers modified asphalt mixture samples. The test results, namely the original strengths and recovered strengths, indicated that the original strength of the carbon fiber modified asphalt mixture decreased slightly. The carbon fiber modified asphalt mixture can achieve superior healing performance with microwave healing approach.

INTRODUCTION

The asphalt mixture is a composite material of air void, asphalt binder and aggregates of various shapes and sizes (You, Adhikari et al. 2009). The binder and mixture present viscoelastic and thermoplastic characteristics (Si, Ma et al. 2014). Due to the sensitivity to temperature and moisture, the performance and serviceability of pavements are prone to deteriorate than other infrastructures (Ma, Si et al. 2014). One main reason is that the microcracks develop in the asphalt mixture (Liu, Schlangen et al. 2010). Therefore, the pavement surface layer needs to be maintained frequently.

Asphalt mixture has the ability to repair its damage during the service life called self-healing (García, Schlangen et al. 2012). But the healing process is limited by two factors, temperature and rest periods (Kim, Little et al. 2003, García, Schlangen et al. 2012). When the external energy is input to heat thermoplastic asphalt binder, microcracks generated by the traffic and environmental loadings could be healed (Wang, Dai et al. 2016). This is called the induced healing behavior that can accelerate the self-healing process. The self-healing behavior is a complicated process combined with capillary flow, molecules wetting and intermolecular diffusion studied by Shen et al. (Shen, Chiu et al. 2010).

Carbon fiber, as a type of modifier, was added to asphalt material to investigate the performance by many researchers. Yang et al. (Yang, Yang et al. 2011) utilized carbon fiber into the transportation system to improve the deicing technology. Liu et al. (Liu, Wu et al. 2008) proposed that the conductive asphalt concrete within graphite and carbon fiber was valid for the self-monitoring of strain and stress. In addition, after measuring the mechanical and electrical properties of graphite and carbon fiber modified asphalt concrete, Liu and Wu (Liu and Wu 2011) found the carbon fiber could increase the Marshall stability, residual stability and rutting dynamic stability. Some scientists studied the relationship between the carbon fiber and microwave. For instance, Qing et al. (Qing, Zhou et al. 2010) investigated the microwave electromagnetic properties of carbon fiber as conductive absorber filled insulating epoxy/silicone resin coatings and the complex permittivity of the coatings increased when the content of carbon fiber increased. The microwave absorbing properties of the composites containing inductive activated carbon fiber screens (IACFFSs) were affected by the element configurations of IACFFSs, found by Zhao et al. (Zhao, Zou et al. 2006).

The objective of this research is to investigate the thermal property, electrical property and microwave healing performance of the carbon fiber modified asphalt mixture. First, HexTow® IM8 was blended with asphalt and aggregates by dry process. HexTow® AS4 were added to the asphalt at first, then mixed with aggregates to produce the beam samples, namely the wet process. Afterwards, the thermal conductivity and electrical resistivity of the samples were measured and calculated, respectively. Finally, the cyclic fracture-microwave healing tests were implemented to evaluate the healing performance of the samples.

MIXTURE DESIGN AND SAMPLE PREPARATION

In this research, five types of asphalt mixture samples were prepared as the tested samples, including control, IM8 carbon fiber (2% and 4% by weight of asphalt mixture) modified and AS4 carbon fiber (1.5% and 3% by weight of asphalt binder) modified asphalt mixture, respectively.

Control and carbon fiber modified mixture design

The asphalt binder used in the mixture was PG 58-28 with a density of 1.024 g/cm³. The aggregates consisting of mixture were from Hancock, Michigan with an average density of 2.72 g/cm³. The amount of asphalt used for the mixture samples was 5.7% by weight of the mixture determined by the test of the optimum asphalt content based on Superpave 5E1 mix design. The aggregate gradation of the asphalt mixture is shown in Table 1.

Table 1. Aggregate gradation of asphalt mixture

Sieve Number	Sieve Size (mm)	% Retained	Mass (g)
1/2 inch	12.5	1.3	720.0
3/8 inch	9.5	12.2	924.0
No. 4	4.75	14.7	2172.0
No. 8	2.36	20.4	2280.0
No. 16	1.18	15.3	1296.0
No. 30	0.6	10.6	1272.0
No. 50	0.3	10.8	1536.0
No. 100	0.15	7	996.0
No. 200	0.075	2.3	264.0
Pan	<0.075	5.4	540.0

The carbon fibers used were HexTow IM8 and AS4, from Hexcel Co.. IM8 carbon fiber is a continuous, polyacrylonitrile (PAN) based fiber in 12,000 filament count tows. The tensile strength is 6,067 MPa. The

tensile modulus (Chord 6000-1000) is 310 GPa. The ultimate elongation at failure is 1.8%. The density is 1.78 g/cm³. The filament diameter is 5.2 microns. All the IM8 carbon fibers were first chopped to 6.35 mm then dry mixed with the asphalt mixture. The amount used of IM8 was 2% and 4% based on the asphalt weight. AS4 carbon fiber is a pre-chopped, PAN based fiber in 3000 filament count tows. The tensile strength is 4619 MPa. The tensile modulus (Chord 6000-1000) is 231 GPa. The ultimate elongation at failure is 1.8%. The density is 1.79 g/cm³. The filament diameter is 7.1 microns. All the AS4 carbon fibers were pre-chopped with length about 6.35 mm and also sized to improve fracture strength. The amount of added AS4 was 1.5% and 3% based on asphalt binder weight. These fibers were first mixed with asphalt binder at an elevated temperature to melt the sizing materials. The carbon fiber modified binder was then used to prepare the asphalt mixtures.

Mixture beam sample preparation

In this study, the samples used were beams with a length of 190 mm, width of 50 mm and height of 69 mm. In addition, a 23 mm deep, 3 mm wide notch was sawn in the center of the beams to control the initial cracking position. For each beam sample, two knife edges were glued on the top notch for measuring the crack tip opening displacement by a clip-on gauge. Consequently, 3 beam samples were prepared for each mixture type, control, 2% and 4% IM8 modified, 1.5% and 3% AS4 modified asphalt mixture beam samples. Therefore, 15 beam samples were produced for the whole cyclic fracture-microwave healing tests discussed in the following sections.

THERMAL AND ELECTRICAL PROPERTIES MEASUREMENT OF ASPHALT MIXTURE

Thermal conductivity of asphalt mixture beams

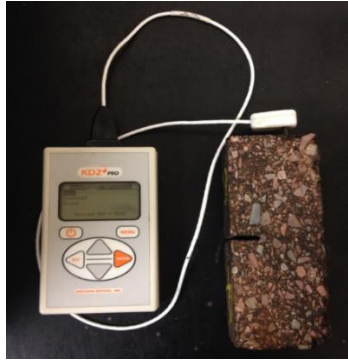
In this study, a KD2 Pro thermal property analyzer from Decagon Devices Inc. was utilized to measure the thermal conductivity of carbon fiber modified asphalt mixture samples based on transient line heat source methods, displayed in Fig. 1(a) (Vacquier 1985, D5334-14 2014). The heat generated by a needle TR-1 sensor (length of 10 cm, diameter of 2.4 mm) inside the sample formed gradient temperature. Then the sensor detected the temperature variation and recorded the data. The thermal conductivity was calculated by Equation (1) and (2):

$$T = m_0 + m_1 t + m_2 \ln t \quad (1)$$

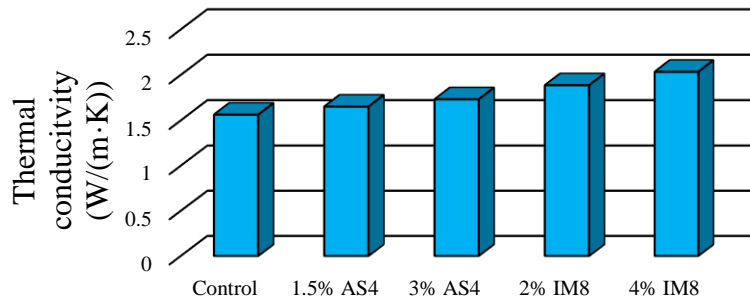
where T is the recorded temperature, m_0 denotes the environmental temperature, m_1 is the varying rate of the background temperature, m_2 indicates the temperature drifting of the tested material, t is the testing time.

$$k = \frac{q}{4\pi m_2} \quad (2)$$

where k is the thermal conductivity (W/(m·K)), q is the heat generated by the device. The thermal conductivity values of five types of asphalt mixture beams were measured, including the control, 2% IM8 modified, 4% IM8 modified, 1.5% AS4 modified and 3% AS4 modified asphalt mixture samples, shown in Fig. 1(b). It is observed that the average thermal conductivity of control asphalt mixture samples is 1.562 W/(m·K). The average thermal conductivities of 1.5% AS4 modified and 3% AS4 modified asphalt mixture samples are 1.651 W/(m·K) and 1.731 W/(m·K), respectively. The average thermal conductivities of 2% IM8 modified and 4% IM8 modified asphalt mixture samples are 1.886 W/(m·K) and 2.033 W/(m·K). Therefore, the carbon fibers could increase the thermal conductivity of asphalt mixture samples. Additionally, the thermal conductivity value of the asphalt mixture sample increases with raising the content of carbon fibers.



(a)



(b)

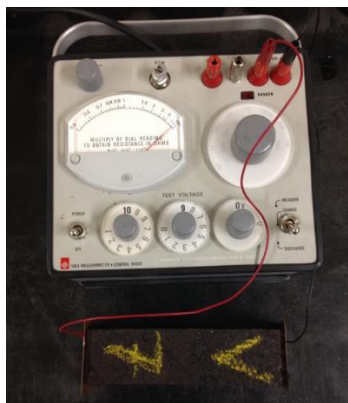
Figure 1. Thermal conductivity measurement of non-fractured asphalt mixture beams: (a) sample and device; (b) thermal conductivity data of tested samples.

Electrical conductivity of asphalt mixture beams

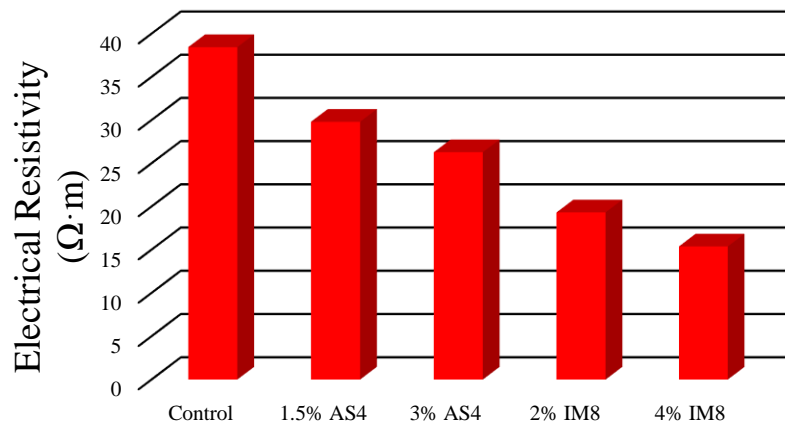
The electrical resistivity measurements were conducted on five different types of prepared beam samples at room temperature, displayed in Fig. 2(a). Two copper electrodes were located on the two sides of the sample to measure the electrical resistance. Then the electrical resistivity of the sample was calculated by Equation (3):

$$\rho = \frac{R \times S}{L} \quad (3)$$

where ρ indicates the electrical resistivity ($\Omega \cdot m$), R denotes the measured electrical resistance (Ω), S is the cross-sectional area and L is the length of the beam samples. The measured electrical resistivity values of prepared samples are plotted in Fig. 2(b). It is observed that the average electrical resistivity of control samples is about $38.5 \Omega \cdot m$. The average electrical resistivity of 1.5% and 3% AS4 modified asphalt mixture samples are approximately 29.8 and $26.3 \Omega \cdot m$. In addition, the average electrical resistivity of 2% and 4% IM8 modified asphalt mixture samples are around 19.3 and $15.4 \Omega \cdot m$. Therefore, both carbon fiber AS4 and IM8 could decrease the electrical resistivity of the asphalt mixture samples.



(a)



(b)

Figure 2. Electrical resistivity measurement of non-fractured asphalt mixture beams: (a) sample and device; (b) electrical resistivity data of tested samples.

Original fracture strength of asphalt mixture beams

The control and carbon fiber modified asphalt mixture beams were used to investigate the original fracture strength (peak load). The sample was placed on a modified bending beam fixture with an elastic foundation instead of three-point bending support. The experimental results showed that the average original peak loads of the 2% IM8 modified asphalt mixture samples reduced by 19.3% compared with the control samples. The average original peak loads of the 4% IM8 modified asphalt mixture samples decreased by 4.7%. The average original peak loads of the 1.5% AS4 modified asphalt mixture samples increased by 2.9%. The average original peak loads of the 3% AS4 modified asphalt mixture samples decreased by 16.8%. Overall, IM8 and AS4 decreased the original strength of asphalt mixture beams. The main reason could be the carbon fibers separated the bonding of binder and aggregates to some degrees.

FRACTURE-MICROWAVE HEALING INVESTIGATION OF ASPHALT MIXTURE SAMPLES WITH ELASTIC FOUNDATION MODIFIED BEAM BENDING TEST

4.1 Mechanism of microwave healing of asphalt mixture

The carbon fibers have the ability to absorb the energy when locating in the microwave field. When absorbing the energy, the temperature of the carbon fibers increase. Then the heat is transferred to the asphalt and aggregate. In this transfer process, the temperature-dependent asphalt behaves as Newtonian flow to fill the cracks in the mixture. In the microscale, the crack healing process could be regarded as a combination of capillary flow induced by surface tension force, gravity of liquid asphalt and friction between aggregate particles and flowing asphalt. Once the binder flow into microcrack space, the molecular diffusion and rebinding process will take place to recover the adhesion strength. The recovered strength was mainly from two aspects. One is the molecules diffusion in asphalt, the other is the rebinding between asphalt and aggregates. Fig. 3 displays the mechanism of microwave healing of asphalt mixture. In this study, the healing effect of carbon fibers modified asphalt mixture was investigated in the following sections.

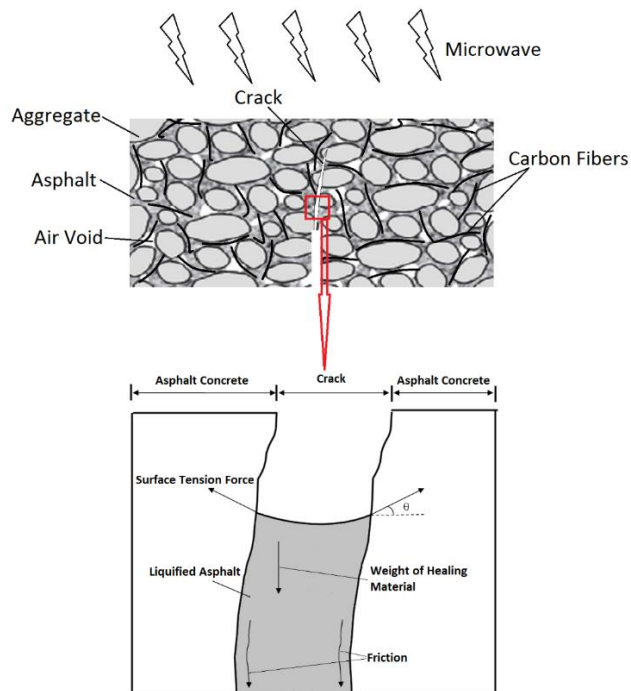


Figure 3. Schematic demonstration of microwave healing mechanism for carbon fibers modified asphalt mixture.

Fracture-microwave healing tests of asphalt mixture samples

In the first place, the induction heater generating electromagnetic (EM) energy with frequency of 120 kHz to 160 kHz was used to heat the carbon fiber modified asphalt mixture before the samples were heated by the microwave. The temperature of the carbon fiber modified samples did not increase. Therefore, it was concluded that the carbon fiber used in this study could not absorb the EM energy with relatively low frequency of 120 kHz to 160 kHz. Then the author attempted to utilize different EM energy with higher frequency. As known, the frequency of the microwave generated by the oven was about 2450 MHz. Hence, the healing performance of carbon fibers in the asphalt mixture was investigated by the cyclic fracture-microwave healing test. Briefly speaking, the test contains two parts, the sample fractured test and sample microwave healed test. In the sample fractured test, the tested sample was first placed in a freezer for 6 hours to assure an internal temperature of -10 °C. Then the beam was located on a modified elastic foundation instead of the regular three-point support, shown in Fig. 4. The crack along the vertical direction of the tested beam was generated by applying a descending load with a speed of 0.5mm/min. During the test, the loading machine was halted manually as long as the applying load increased to the maximum value (peak load). The peak load, crack tip opening displacement (CTOD) and testing time were recorded automatically.

During the sample microwave healing process, the fractured sample was located into a 1100w microwave oven, heating for 2 minutes. The carbon fiber inside the sample absorbed the microwave energy and the surface temperature went up to around 100 °C to heal the crack. Later, the sample was taken out, being healed for another 30 minutes until its temperature decreased to room temperature. Then the healed sample was placed into the freezer for 6 hours and the load was applied on the sample again. This repeated procedure was called cyclic fracture-microwave healing tests. In this research, six cycles of fracture-microwave healing tests were conducted to investigate the healing effect of the control, IM8 and AS4 carbon fiber modified asphalt mixture samples.

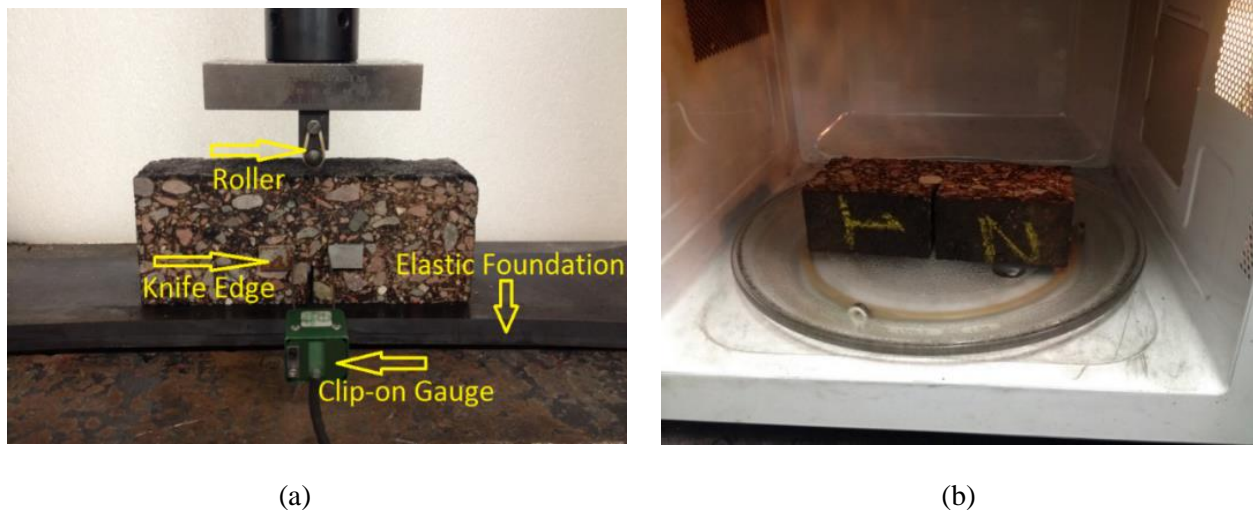


Figure 4 Demonstration of fracture-microwave healing test: (a) Modified bending test of asphalt mixture beam with elastic foundation; (b) Microwave healing of asphalt mixture beam sample.

Fracture-microwave healing test results of asphalt mixture samples

In this study, the recovered strengths (recovered peak loads) were adopted to evaluate the healing effect of the carbon fiber modified asphalt samples. Table 2 exhibits the peak loads of asphalt mixture beam samples by the cyclic fracture-microwave healing tests, including control, 2% and 4% IM8, 1.5% and 3% AS4 carbon fiber modified asphalt mixture beams, respectively. The ratios of recovered peak loads (recovered peak load divided by original peak load) of all the tested beam samples are recorded in Table 3. For the control asphalt mixture samples, it is observed that the range of original peak loads is from 4300 N to 4600 N (average value 4560 N), reducing to the range of 1200 N to 1800 N after five fracture-microwave healing cycles. The average ratio of recovered peak loads after the first cycle remains 55.4%, reducing to 48.9%, 41.8%, 35.0% and 31.9% cycle by cycle. For the 2% IM8 modified asphalt mixture samples, the peak loads are in the range of 3500 N to 3800 N (average value 3678 N) at the first loading, decreasing to the range of 2900 N to 3300 N at the sixth loading. The average ratios of recovered peak loads decrease from 92.0%, 90.8%, 88.8%, 87.6% to 85.7% during five cycles. For the 4% IM8 modified asphalt mixture samples, the scope of original peak loads is from 3700 N to 4400 N (average value 4345 N). After five cycles of loading, the recovered peak loads float from 2200 N to 2400 N. The average ratios of recovered peak loads reduce from 67.2% to 54.4% in the five cycles. For the 1.5% AS4 modified asphalt mixture samples, the range of original peak loads is from 4400 N to 5000 N (4692 N), lowering to about 2200 N at the sixth loading. The average ratios of recovered peak loads are 91.5% after the first cycle and 45.5% after the fifth cycle. For the 3% AS4 modified asphalt mixture samples, the original peak loads are in the scope of 3500 N to 4000 N (average value 3796 N) while the recovered peak loads are between 2800 N and 3200 N at the sixth loading. In addition, the average ratios of recovered peak loads decrease from 90.4% to 78.1% after the fifth cycle. Both the added IM8 and AS4 could improve the microwave healing performance of asphalt mixture. The microwave healing performance of 2% IM8 modified asphalt mixture was much better than the 4% IM8 modified asphalt mixture. It is caused that high content of carbon fibers (more than 2% of mixture weight) may have negative impact on the Newtonian flow of the asphalt during the microwave healing process. This study demonstrates a promising microwave healing technique with carbon fiber modified asphalt mixtures.

Table 2. Peak loads (N) of asphalt mixture beams during cyclic fracture-microwave healing tests.

Sample	1 st loading	2 nd loading	3 rd loading	4 th loading	5 th loading	6 th loading
Control No.1	4349.5	2739.3	2103.7	1978.7	1308.0	1206.9
Control No.2	4799.3	2363.6	2449.7	1724.9	1610.0	1436.1
Control No.3	4529.8	2447.1	2138.8	1990.3	1878.5	1723.5
2% IM8 No.1	3554.4	3285.1	3184.5	3098.0	3068.5	2957.1
2% IM8 No.2	3705.6	3370.3	3397.0	3283.4	3238.0	3234.7
2% IM8 No.3	3773.1	3501.6	3436.7	3421.9	3356.8	3268.4
4% IM8 No.1	4312.3	2728.9	2611.8	2538.2	2428.9	2281.4
4% IM8 No.2	4930.7	2932.4	2746.6	2606.7	2332.1	2311.6
4% IM8 No.3	3792.9	2986.7	2768.8	2754.1	2520.9	2399.7
1.5% AS4 No.1	4934.7	4063.2	3869.7	3319.1	2414.8	2010.8
1.5% AS4 No.2	4688.5	4423.4	4199.0	3784.6	2887.7	2255.8
1.5% AS4 No.3	4452.2	4352.3	3842.77	3649.7	2846.2	2113.2
3% AS4 No.1	3597.6	3106.6	3126.5	3375.1	3121.4	2875.2
3% AS4 No.2	3857.2	3634.0	3462.3	3393.6	3304.3	3188.3

3% AS4 No.3	3931.8	3566.7	3377.6	3171.3	2846.8	2814.0
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Table 3. Ratio (%) of recovered peak loads of asphalt mixture beams during cyclic fracture-microwave healing tests

Sample	2nd loading after 1 cycle	3rd loading after 2 cycles	4th loading after 3 cycles	5th loading after 4 cycles	6th loading after 5 cycle
Control No.1	63.0%	48.4%	45.5%	30.1%	27.7%
Control No.2	49.2%	51.0%	35.9%	33.5%	29.9%
Control No.3	54.0%	47.2%	43.9%	41.5%	38.0%
Average of control samples	55.4%	48.9%	41.8%	35.0%	31.9%
2% IM8 No.1	92.4%	89.6%	87.2%	86.3%	83.2%
2% IM8 No.2	91.0%	91.7%	88.6%	87.4%	87.3%
2% IM8 No.3	92.8%	91.1%	90.7%	89.0%	86.6%
Average of 2% IM8 samples	92.0%	90.8%	88.8%	87.6%	85.7%
4% IM8 No.1	63.3%	60.6%	58.9%	56.3%	52.9%
4% IM8 No.2	59.5%	55.7%	52.9%	47.3%	46.9%
4% IM8 No.3	78.7%	73.0%	72.6%	66.5%	63.3%
Average of 4% IM8 samples	67.2%	63.1%	61.5%	56.7%	54.4%
1.5% AS4 No.1	82.3%	78.4%	67.3%	48.9%	40.7%
1.5% AS4 No.2	94.3%	89.6%	80.7%	61.6%	48.1%
1.5% AS4 No.3	97.8%	86.3%	82.0%	63.9%	47.5%
Average of 1.5% AS4 samples	91.5%	84.8%	76.7%	58.1%	45.4%
3% AS4 No.1	86.4%	86.9%	93.8%	86.8%	79.9%
3% AS4 No.2	94.2%	89.8%	88.0%	85.7%	82.7%
3% AS4 No.3	90.7%	85.9%	80.7%	72.4%	71.6%
Average of 3% AS4 samples	90.4%	87.5%	87.5%	81.6%	78.1%

SUMMARY AND CONCLUSIONS

In this research, carbon fibers IM8 were hand chopped to 0.25 inch, dry-mixed with aggregates and asphalt binder to produce the asphalt mixture. AS4 were pre-chopped to 0.25 inch, wet-mixed with asphalt binder. Then the binder with added AS4 were mixed with aggregates to obtain the mixture. The thermal conductivity and electrical resistivity of the control and carbon fiber modified asphalt mixture samples were measured. In addition, the cyclic fracture-light healing tests were implemented to evaluate the microwave healing effect of samples, including control, 2% and 4% IM modified, 1.5% and 3% AS4 modified asphalt mixture.

The measurement results of the thermal conductivity of the samples indicated that the carbon fiber, as a modifier, could increase the thermal conductivity of the asphalt mixture. Additionally, the carbon fiber has the ability to decrease the electrical resistivity of the mixture. Moreover, the carbon fibers decrease the original strength of the asphalt mixture because of the bonding separation between the asphalt binder and aggregates. Finally, the results of the cyclic fracture-microwave healing test indicated that the carbon fibers, containing IM8 and AS4, both achieved superior microwave healing performance. However, 2% IM8

modified asphalt mixture overperformed than 4% IM8 modified asphalt mixture. Since a higher carbon fiber content (more than 2%) may lead to overcompacted samples with added large fiber volume. The air void may reduce, limiting the binder Newtonian flow in the microwave healing process.

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