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ABSTRACT

Self-healing of asphalt concrete (AC) is highly dependent on temperature, and its healing capacity increases with elevated temperatures. The main objective of this study is to investigate the effect of microwave heating on promotion of self-healing in AC. With this purpose, two types of AC specimens (neat AC without additives and conductive AC containing steel fiber and graphite) were prepared to for use in thermal conductivity, microwave heating speed tests, four-point bending fatigue, and healing tests. In addition, oscillatory frequency sweep tests were carried out to obtain the flow behavior of asphalt binder. Results indicated that AC containing electrically conductive additives had a higher thermal conductivity and microwave heating speed than neat AC. It was also found that the fatigue resistance and healing capacity of conductive AC after microwave heating were higher than that of neat AC. Moreover, there exists a critical temperature (corresponding to near-Newtonian behavior temperature of asphalt binder) above which healing of AC starts and an optimum heating time (temperature) to maximize the healing effect. Finally, it was found that an intermittent heating mode with a cooling process is more effective than the consecutive heating mode to enhance the healing capacity of AC. Based on these findings, it is concluded that self-healing efficiency of AC can be enhanced via microwave heating.

Keywords

asphalt concrete, microwave heating, healing, fatigue damage, flow behavior

Introduction

Asphalt concrete (AC) is a viscoelastic paving material composed of aggregates, fillers, and asphalt, and it is widely used to pave roads and streets (more than 90 % of pavements around the world are built with asphalt-related materials) [1]. AC suffers damage by daily traffic loads and climate changes (especially temperature and moisture effects). Miniature cracking in AC may lead to major forms of pavement distress if not properly and timely maintained [2]. This is the reason why preventive maintenance must be applied: to extend the service life of asphalt pavements. Pavement rehabilitation can be handled in many ways, ranging from various sealing techniques, patching, microsurfacing, and resurfacing. But these treatments are both economically and technically unsound in certain conditions [3]. The current challenges are to increase the lifetime of asphalt pavements and make the pavements apt for immediate and local repair of the generated damage without stopping traffic circulation.

It is well known that AC has a self-healing capability that allows for repair of existing damage and restoration of original properties to some extent [4]. However, the healing properties of asphalt have not been fully considered in the design and maintenance of asphalt pavements [5]. Fundamental research regarding healing asphalt in the past have (a) provided evidence of asphalt healing in both laboratory samples and in pavements [6,7], (b) established mechanisms of healing [8,9], (c) reconciled differences in fatigue cracking performance in the laboratory versus field performance [7,10,11], and (d) proposed novel technologies to enhance the healing capacity [12,13]. A number of studies have demonstrated that the healing rate of AC increases with temperature in certain ranges [14,15]. This temperature-dependent nature of healing offers the potential to heal the damage in asphalt pavement through asphalt diffusion and flow at high temperatures. Asphalt starts to behave like a Newtonian fluid at temperatures ranging from 30°C to 70°C, depending on the type of asphalt binder [16]. Above that temperature, asphalt may start to flow through microcracks in asphalt pavements and heal them, which can be explained by the capillary flow theory [17]. To this end, novel technologies, such as electromagnetic induction heating and microwave heating, have been proposed to elevate the temperature of AC to accelerate healing or reverse accumulated microcrack damage in asphalt pavements and, finally, to extend the pavement life [18,19].

Both induction heating and microwave heating are very promising thermomechanical treatments to enhance the healing capacity of asphalt pavement. To use the former method, electrically conductive and magnetically susceptible particles must be added to the asphalt mixture [20]. Induction heat is generated because of the induction current, and Joule effects are generated through the conductive components in the electromagnetic field. For the latter, conductive additives are not necessities. Microwave heating is achieved through internal friction of polar molecules by changing their orientations in the alternating magnetic field. However, the addition of these thermoelectrical particles can significantly increase the microwave heating speed of AC [21,22]. The technique of induction heating has been extensively studied in recent years. The induction heating rate is not homogenous over the thickness of the sample because of the decreasing magnetic field intensity from top to bottom [20]. Under induction heating, the surface of the specimen is easily burned or overheated because of the skin effect, whereas the inside temperature may still not reach the necessary healing temperature. By contrast, microwave heating can provide rapid and uniform heating without overheating the surface layer of the asphalt pavement [23]. Microwave heating can also provide deep heating without a significant difference in the temperatures of the surface and the bottom of the pavement with relatively lower power [24,25]. In addition, the device needed in the laboratory is much simpler in the case of microwave heating. The efficiency of a material in absorbing microwave energy can be described by its dielectric properties. The dielectric properties of asphalt at microwave frequencies are quite low because the viscosity of the asphalt hinders the orientation of polar molecules. The temperature rise of asphalt pavement under microwaves primarily depends on the aggregates and moisture inside to absorb the energy and transfer it to the asphalt binders [26]. Therefore, research has been carried out to improve the microwave-energy–absorbing efficiency of AC by adding different fillers and fibers. Microwave heating has been used for asphalt conditioning and pavement distress repair for many years [23,27,28]. The economic advantages of microwaves to heat paving materials were reported to have savings of 30 to 40 % over conventional heating methods. However, a more defined economic benefit of using microwaves to heat asphalt pavement, taking the healing effect into consideration, needs a systematic life-cycle cost analysis. Recent studies [29] showed that though longer microwave heating times can produce higher asphalt mixture temperatures, that does not necessarily mean higher healing ratios since overheating may melt and age the bitumen, thus damaging the composite material. Norambuena-Contreras and Gonzalez-Torre determined that the optimum microwave heating time for asphalt mixtures with 4 % fiber was 40 s using a 700-W microwave heating oven. The corresponding surface temperature of the specimen after 40 s of heating was 87°C. It was also concluded that the temperature achieved as a result of the heating time is the most influential variable on the self-healing properties of asphalt mixtures [29].

Therefore, the main objective of this study was to investigate the effects of microwave heating on the thermal and healing properties of fatigue-damaged AC samples on a laboratory scale. With this purpose, (1) the effect of conductive additives on the microwave heating properties of asphalt mixtures was investigated, (2) the fatigue performance of different asphalt mixtures was evaluated through four-point bending tests, (3) the rheological tests of asphalt binder were carried out to determine the critical temperature for asphalt healing, and (4) the optimum microwave heating conditions (temperature, time, and mode) for asphalt healing were determined through an established healing evaluation index.

Experimental Investigation

MATERIALS

In this study, conventional asphalt binder (Shell-70), basalt aggregates, and limestone fillers were used to produce asphalt mixtures. The basic properties of the asphalt binder are listed in **Table 1**. To prepare electrically conductive AC (CAC) samples, certain amounts of steel fiber and graphite (as shown in **Fig. 1**) were added to the mixture. The physical parameters of steel fiber and crystalline flake graphite are presented in **Table 2**. The mean length of steel fibers was 10 ± 1 mm according to previous studies. Longer fibers are prone to curl and become tangled during the mixing process, while shorter fibers cannot perform bridging and reinforcing effects in the asphalt mixture. Dense AC gradation (AC-13) with a 13.2-mm nominal maximum aggregate size was used.

Two types of asphalt mixtures, conventional asphalt mixture and conductive asphalt mixture, were prepared. The same asphalt content of 4.8 % was used for both mixtures. The respective contents of steel fiber and graphite were determined as 1.14 and 4.86 %,

TABLE 1
Basic properties of asphalt binder.

Properties	Value
Penetration (25°C, 100 g, 5 s, 0.1 mm)	71
Ductility (5 cm/min, 5°C, cm)	32.2
Softening point (R&B, °C)	47.5
Flash point (°C)	272
Rotational viscosity (60°C, Pa.s)	203
Wax content (%)	1.6
Density (15°C, g/cm^3)	1.032

FIG. 1
Appearance of (a) steel fiber and (b) graphite powder.

TABLE 2
Physical properties of conductive additives.

Conductive Additive	Density (g/cm^3)	Particle Size /Diameter (μm)	Carbon Content (%)	Specific Surface Area (m^2/g)	Electrical Resistivity (Ω·m)	Thermal Conductivity [W/(m·K)]
Graphite	2.2	75	96.1	7.12	10^{-6}	151
Steel fiber	7.5	100 ± 20	0.25	–	7×10^{-9}	36~54

respectively, by volume of asphalt to obtain a mixture resistivity of around 10^3 Ω·m. Detailed information about material selection, mass percentage, and mix design process can be found in Ref. [30].

RHEOLOGICAL TEST OF ASPHALT BINDER

There are two types of asphalt mixtures (neat AC and CAC) used in this study. It was assumed that the addition of steel fiber does not change the viscoelastic properties of asphalt binder. The rheological properties of the two types of asphalt binder, neat binder and graphite modified binder (corresponding to conventional AC and CAC), were measured using a dynamic shear rheometer to estimate the flow behavior of asphalt when healing happens at a high temperature. To determine the temperature at which the near-Newtonian behavior of asphalt binder occurs, frequency sweep tests of asphalt binder were carried out over a range of 0.01–10 Hz at different temperatures under a constant strain of 1 % within the linear viscoelastic region. All the asphalt binder samples were aged in a rolling thin-film oven at 163°C for 85 min to simulate the short-term aging process. An 8-mm-diameter parallel plate configuration with a 2-mm gap was used to obtain the complex viscosity (η^*) of asphalt binder at various temperatures and frequencies.

THERMAL CONDUCTIVITY MEASUREMENT

The energy transfer between heat energy and cracking surface energy was involved during the healing process of asphalt mixtures under microwave heating [31,32]. Therefore, it was necessary to investigate the thermal properties from macroperspectives. Thermal conductivity is one of the important factors that affect the microwave heating process, which refers to heat transfer. The thermal conductivity measurement was done through a steady-state method using an HFM 436 heat flow meter (NETZSCH Group, Selb, Germany) according to ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*. A plate specimen (15 × 15 × 4 cm) is placed between a hot and a cold plate, and the heat flow created by the well-defined temperature difference is measured with a calibrated heat flux transducer. In this case, the cold plate was kept at a constant temperature of 5°C, and the hot plate was kept at a constant temperature of 45°C. After reaching a thermal equilibrium, the test is done. The thermal conductivity can be obtained directly from the data acquisition system in accordance with Fourier's law of heat conduction.

MICROWAVE HEATING AND TEMPERATURE MEASUREMENT

To heat the cylindrical AC specimens, a household microwave oven with a power rating of 1,200 W was used. The oven can produce microwaves of up to 1,000 W with a frequency of 2.45 GHz, which corresponds to an approximate wavelength of 120 mm. Each type of AC specimen has two duplicates because of the potential variation of test results. The standard Marshall specimen (Φ101.6 × 63.5 mm) was placed in the center of the glass plate in the microwave oven. Both surface and internal temperatures of the test specimens were measured as shown in Fig. 2. The surface temperature was measured every 10 s with an infrared temperature-measured gun, swiftly opening the door at a total heating time of 120 s. Because of the temperature difference between coarse aggregates and asphalt mastic, four temperatures were taken randomly from the surface of the test specimen, and the average was calculated to obtain a "near-uniform temperature." Additionally, because of the hysteresis effect of the inside temperature sensor (thermocouple), only the final internal temperature after 120 s heating was recorded through the intelligent instrument.

FIG. 2
Temperature measurement during microwave heating: (a) surface temperature and (b) internal temperature.

(a) (b)

FOUR-POINT BENDING BEAM FATIGUE TEST

The standard four-point beam-bending fatigue tests were conducted on beam specimens of two types of asphalt mixture. The tests were performed at 20°C with a frequency of 10 Hz under haversine controlled-strain loading mode. The point corresponding to a 50 % reduction of initial stiffness was consistently used as the fatigue failure point because it represents a value that relates to field failure in asphalt pavements [33]. Different microstrain levels (300, 400, 500, 600, and 700 με) under controlled-strain loading mode were applied to have a first sight of the fatigue performance of different asphalt mixtures and to determine a reasonable microstrain level for the following healing tests.

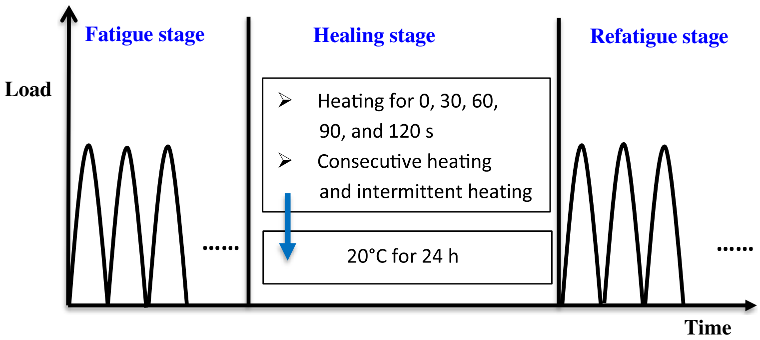
HEALING TEST PROGRAM

The healing test program consisted of three stages as shown in Fig. 3.

- Fatigue stage. The asphalt mixture beam specimens were damaged with four-point bending fatigue tests. The tests were carried out at standard test conditions of 20°C and 10 Hz with haversine controlled-strain loading. The strain level was chosen as 600 με based on the considerations of obtaining stable test data and saving time. The fatigue test was terminated when a 50 % reduction of initial flexural stiffness of the AC specimen was reached.
- Healing stage. The damaged specimens in the fatigue stage were first heated in a microwave oven for different combinations and then put in a temperature chamber for 24 h at 20°C. To avoid the potential dimensional distortion of the beam specimens, all the heated specimens were put on a flat plank [29]. In terms of the heating procedure, fatigue-damaged specimens were heated for 0, 30, 60, 90, and 120 s to quantify the effect of temperature on the healing capacity and to determine the optimal heating temperature (for how long the damaged specimens should be heated). In addition, the effect of consecutive heating and intermittent heating on healing levels were studied for conductive AC specimens. Literally, consecutive heating means heating the specimens for 120 s without shutting down the microwave oven. Intermittent heating has six heating sequences, in which one lasts 20 s, and then there is a 20-s interval between each following heating sequence.
- Refatigue stage. The fatigue test was conducted again on the beam specimens after rest from the healing stage. The same test parameters and conditions of the fatigue stage were used.

FIG. 3

Schematic diagram of healing test program.



Healing Evaluation Index of Asphalt Mixtures

Generally, the existing healing evaluation indexes for asphalt materials can be classified into two categories: phenomenological methods and mechanism-based models [34]. The phenomenological methods have the commonness of quantifying healing by its effect on some material property that is due to healing, such as the change of the modulus or strain energy. The mechanism-based methods describe healing as a combination of a wetting process and a diffusion process. However, it is difficult to evaluate the healing of AC in the mechanism-based methods because of the extra energy supply in this study. In terms of phenomenological methods, the healing indexes are usually dependent on loading mode. Therefore, this study presented a more straightforward method to quantifying the healing effect.

By comparing the fatigue curve after heating and rest (referred to as the healing curve) with the curve before heating and rest (referred to as the initial curve), it is hypothesized that the closer the two curves are to each other, the better the healing performance of the AC, which was verified in healing quantification of asphalt binder [35]. Based on this hypothesis, the ratio of the area between the two curves (A_p) to the area below the initial curve (A_{before}) is used in the healing index, as shown in **Fig. 4**. The healing index is described by Eq 1.

$$HI = \frac{A_p}{A_p + A_{after}} \tag{1}$$

where HI is the healing index; A_{before} (equal to $A_p + A_{after}$) is the area below the initial curve; and A_{after} is the area below the healing curve.

To further validate the applicability of this index, the fatigue life extension ratio (F_{ex}) defined in Eq 2 was also used to quantify the healing rate of AC. The graphical expression is depicted in **Fig. 5**.

$$F_{ex} = \frac{\Delta N_f}{N_f} \tag{2}$$

FIG. 4
Schematic of the healing index calculation.

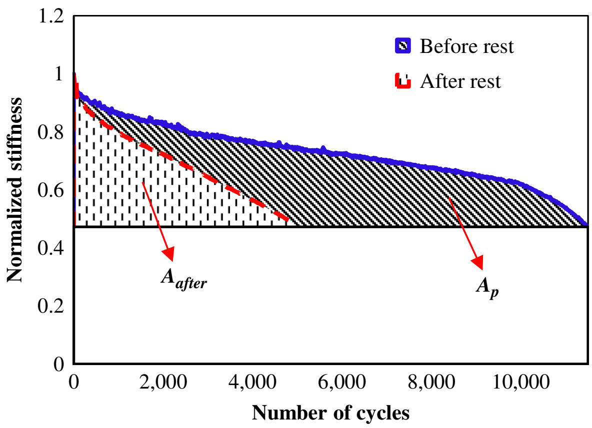
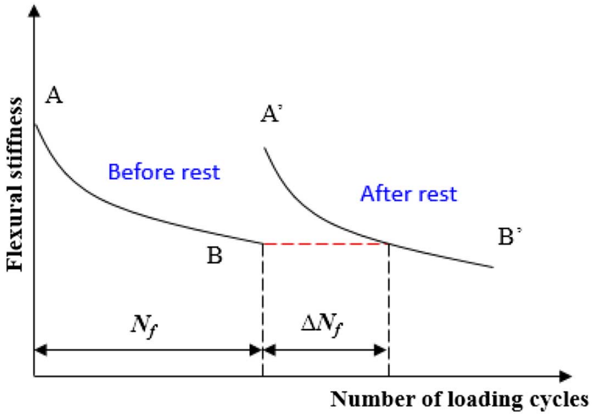


FIG. 5

Fatigue life extension ratio index.



where N_f is the fatigue life of specimens before healing; and ΔN_f is the loading cycles when the stiffness of the healed specimens reaches the 50 % stiffness of unhealed specimens, which means the extended fatigue life.

Results and Discussions

THERMAL CONDUCTIVITY

The steady-state heat flow method was used to measure the thermal conductivity of the asphalt mixture samples. The magnitude of the heat flow through the sample can be described by the Fourier heat flow equation with considerations of different parameters:

$$\dot{Q} = \lambda A \frac{\Delta T}{\Delta x} \tag{3}$$

where $\dot{Q}$ is the heat flow, λ is the thermal conductivity of the sample, A is the area through which the heat flows, ΔT is the temperature difference across the sample, and Δx is the thickness of the sample.

At an average temperature of 25°C, the thermal conductivities of neat AC and CAC were 1.13 W/(m·K) and 1.46 W/(m·K), respectively. As shown in Table 2, both thermal conductivities of graphite and steel fiber at room temperature are much higher than that of AC. According to the general mixing law of composite material, the addition of graphite and steel fiber into asphalt mixture was supposed to increase the thermal conductivity, but the increment of thermal conductivity was not significant, which is generally due to two reasons. First, the dosage of conductive additives was relatively low, only accounting for about 1 % by weight of asphalt mixture. Second, the addition of graphite and steel fiber increased the voids ratio of AC samples by 0.5 % [36]. Since the thermal conductivity of air is only around 0.024 W/(m·K), air that penetrates the voids of asphalt mixtures will generate huge thermal contact resistance, decreasing the thermal conductivity of the asphalt mixture.

MICROWAVE HEATING PROPERTIES OF AC SAMPLES

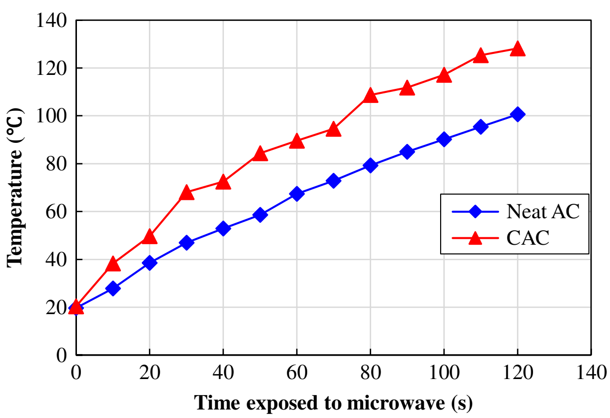
The mechanism of microwave heating is that dielectric material can generate heat in the microwave field because of its dielectric loss, including polarized relaxation loss and conductive loss [37]. As a dielectric material, asphalt mixtures can also be heated with a microwave. Fig. 6 presents the surface temperature evolution of conventional and conductive AC specimens. It can be observed that the surface temperatures of both types of specimen increased significantly after microwave heating for 120 s. The final surface temperatures of the control AC and CAC reached 101°C and 128°C, respectively. The temperature increased faster in the first 40 s, and then the heating speed slowed down. It is reported that the addition of conductive material can increase the microwave absorption capability of the composite material, transferring more microwave energy into heat energy [38]. As shown in Fig. 6, this statement is also applicable to asphalt mixtures.

The dielectric parameters of material are the key factors that influence the absorbed microwave energy. When materials are put in a microwave electromagnetic field, materials have three kinds of reaction: penetration, reflection, and absorption. Under given dissipated power, the dielectric loss constant of a material determines the energy used to heat the material. The dielectric loss constant of graphite is much higher than that of the asphalt mixture, which means graphite can improve the microwave absorption capacity. Specifically, (1) as a conductive powder, graphite can be considered as a dipole in the process of damped vibration and thus attenuate the electromagnetic wave; (2) graphite powders used in this study have high specific surface areas and more dangling bonds that are due to small particle size, so they can attenuate the electromagnetic wave by multi-scattering and reflecting; and (3) the formed conductive net by graphite and steel fibers produces leakage conductance between particles, which can attenuate electromagnetic wave. For steel fiber, as a metal, it will reflect microwaves, but it can produce eddy current in the alternating electromagnetic field and generate heat to increase the temperature of asphalt mixtures. Besides, the reflection of the microwave will result in the second microwave absorption of asphalt mixture. More importantly, the thermal conductivity of CAC is higher than that of neat AC. These factors increased the heating speed of CAC.

After 120 s of microwave heating, a comparison of the surface and internal temperatures of the specimens is shown in Fig. 7. Similarly, CAC specimens have higher internal temperatures than neat AC specimens. The internal temperatures of both types of asphalt

FIG. 6

Surface temperature evolution of AC specimens.



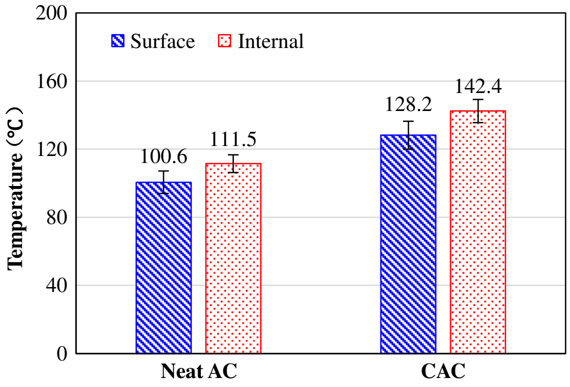


FIG. 7 Surface and internal temperatures of specimens after 120 s of microwave heating.

mixture specimens are about 10°C higher than the surface temperatures. This is possibly due to the fast heat dissipation on the surface. It is notable that binder at this temperature, after 120 s of heating, will be flowable and lose its bonding capability and eventually may even have negative effects on the healing level and cause binder drainage issues.

FATIGUE PERFORMANCE OF DIFFERENT AC

The classical Wöhler curve of strain/stress versus fatigue life has been extensively used as a traditional fatigue data representation approach in pavement design for decades. The fatigue curves of different AC beam specimens were plotted in Fig. 8 according to the following fatigue law:

$$N_f = a\varepsilon^{-b} \tag{4}$$

where N_f is the number of loading cycles to fatigue, ε is the microstrain amplitude (300, 400, 500, 600, and 700 με used in this study), and a and b are the fatigue constants.

In Fig. 8, it can be found that conductive AC has an improved fatigue life as compared to the control AC. This can be explained by the fact that well-distributed steel fibers

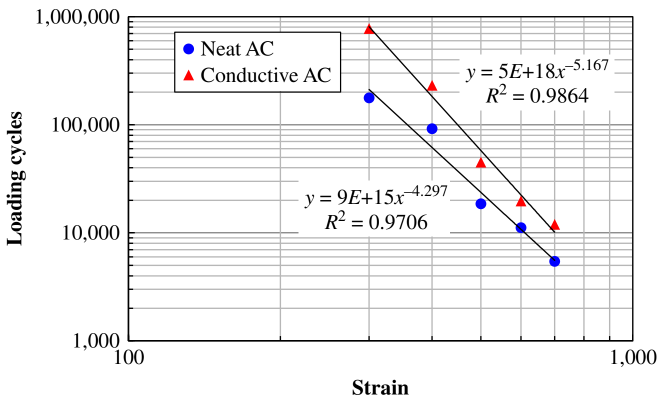


FIG. 8 Fatigue curves of different types of AC.

in AC can form a 3-D reticular structure. The network structure has both a reinforcing and toughening effect on the mixture to improve the cracking resistance. In addition, from the fitted fatigue equation, the fatigue constant *b* increased after the addition of conductive materials. This means the fatigue life of conductive AC is more sensitive to the loading strain level. To save fatigue testing time and obtain stable test data for fatigue analysis, the final microstrain amplitude was 600 με.

APPLICABILITY OF HEALING INDEX AND HEALING EFFICIENCY OF DIFFERENT ACS

To verify the applicability of the proposed healing index, two types of AC sample were tested in light of the healing test program. The microwave heating time was set to 120 s. Fig. 9 depicts the healing index and fatigue life extension ratio of different types of AC. It is noted that the proposed healing index and fatigue life extension ratio have the same ranking of healing efficiency of studied AC. Since fatigue life extension has been verified as a simple and effective index to quantify healing effect [39], the proposed healing index in this study is a reasonable indicator of healing. In addition, the proposed healing index is higher than the fatigue life extension ratio, which probably means that the extension of fatigue life is not only influenced by the healing effect but also by the viscoelastic recovery that is due to the relaxation effect of the asphalt mixture. However, this finding needs to be further studied to verify it.

In terms of healing efficiency, CAC samples have higher healing rates than control AC samples. This is possibly because of the relatively higher microwave heating speed of CAC. With more absorbed energy to increase the temperature of the asphalt binder, it would accelerate the wetting process on the cracking interface and molecular diffusion, and eventually increase the healing level.

CRITICAL TEMPERATURE FOR ASPHALT HEALING

Asphalt is a viscoelastic material and acts like a Newtonian fluid when its temperature reaches a certain high level. Based on different asphalt types, the critical temperature for the near-Newtonian behavior of asphalt ranges from 30°C to 70°C. When the temperature exceeds this critical value, asphalt will flow through the cracks in the form of capillary flow and heal the cracks [40,41]. As shown in the previous section, AC samples can be rapidly heated by a microwave to a temperature of more than 100°C, but the process of

FIG. 9

Healing index and fatigue life extension index of AC.

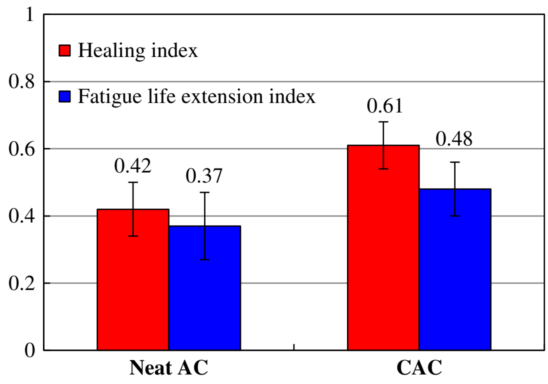
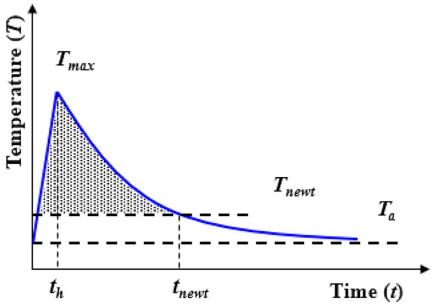


FIG. 10

Schematic of temperature changes during the heating and cooling process.



cooling to room temperature takes several hours. Therefore, asphalt flow healing is not only happening in the heating process but also happening in the following cooling process as long as the temperature of the asphalt is higher than the Newtonian transition temperature (T_{newt}). As shown in Fig. 10, the shaded area below the curve shows the time and temperature range when healing happens. In Fig. 10, T_{max} denotes the sample temperature after heating, T_a denotes the environment temperature, and t_{newt} represents the time when healing stops, which can be calculated by Newton's law of cooling. A detailed derivation process can be found in Ref. [40].

Based on this analysis, it is of great importance to determine when the asphalt reaches a near-Newtonian behavior through rheological tests. For a generalized Newtonian fluid, it can be described by the Ostwald-de Waele power law [42] as shown in Eq 5:

$$\eta^* = m \cdot |\omega|^{n-1} \tag{5}$$

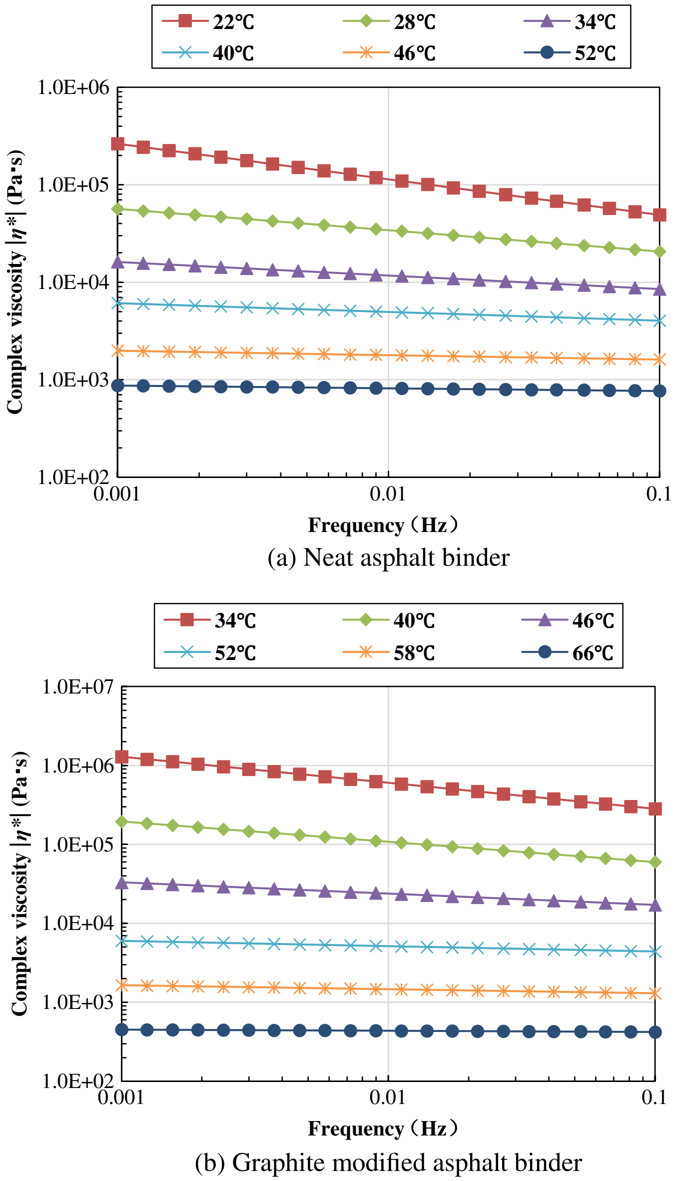
where η^* is the complex viscosity, ω is the shear rate or angular frequency, and m and n denote the fitting parameters, while m also represents the flow consistency index, and dimensionless n is the flow behavior index. The power-law fluid can be subdivided into three different types of fluids based on the value of flow behavior index. $n = 1$ corresponds to a Newtonian fluid and $n < 1$ reflects more pseudoplastic properties of the fluid. $n > 1$ represents a dilatant or shear thickening fluid. Based on previous studies [40], the transition from pseudoplastic to Newtonian behavior of asphalt was defined as the flow behavior index and is higher than 0.9. This transition from $0.9 \leq n < 1$ is also known as near-Newtonian behavior [43].

Fig. 11 shows the complex viscosity of asphalt binder at various temperatures and frequencies. From Fig. 11, at relatively high temperatures, the complex viscosity of asphalt is relatively independent of frequency, exhibiting a near-Newtonian behavior. In contrast, at relatively low temperatures, the complex viscosity of the asphalt binder decreases with increasing frequency, and asphalt presents a shear-thinning (pseudoplastic) behavior. Comparing Fig. 11a with b, the temperature for the different behavior's transition varied with the type of asphalt. Graphite powders have the properties of high oil absorption and surface area, which leads graphite to absorb most of the lightweight fraction of asphalt and stiffens it. This explains why the complex viscosity of graphite-modified asphalt binder was significantly higher than that of neat binder at a certain temperature.

To find the exact transition temperature (temperature above which the near-Newtonian behavior happens), the relationship between flow behavior index and the

FIG. 11

Complex viscosity of two types of asphalt binder.



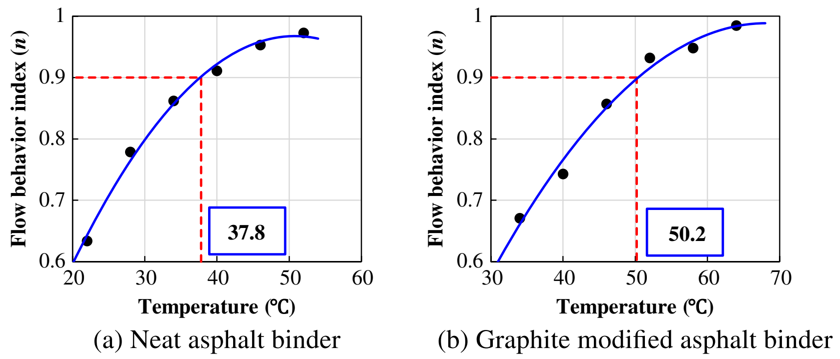
temperature was fitted in Fig. 12. The near-Newtonian transition temperatures for neat asphalt binder and graphite-modified binder is 38°C and 50°C, respectively. Based on the capillary theory to explain heating to heal in asphalt mixtures proposed in this study, the critical temperatures for neat AC and CAC to start healing are 38°C and 50°C, respectively.

OPTIMUM HEATING TIME/TEMPERATURE FOR ASPHALT HEALING

To investigate the effect of different heating times on the healing level of AC, fatigue-damaged samples were microwave heated for 0, 30, 60, 90, and 120 s. The healing index of AC test samples after applying microwave heating for different fixed times

FIG. 12

Flow behavior index of asphalt binder.



(corresponding to different temperatures) is shown in Fig. 13. The optimum heating temperature is defined as the maximum temperature that should be achieved during a microwave heating process in order to obtain the highest healing level. It is obvious that the healing level of damaged AC is very temperature dependent. If microwave heating is not applied, the natural healing index of AC is relatively low, ranging from 0.12 to 0.18. In addition, the error limits of the healing index at natural healing were lower because of less uncertainty compared to heat specimens.

As the heating time increases, the healing level gradually also increases with the increase of heating time and decreases after reaching a peak value. The reason for the decrease of healing level may be attributed to the internal structure damage and asphalt aging caused by overheating. In this study, it is estimated that the optimum heating times to achieve the highest healing levels for neat AC and CAC are 75 and 60 s, respectively. At this moment, the equivalent surface temperatures of neat AC and CA are 76°C and 90°C, respectively. The reason for this temperature difference is due to the different near-Newtonian transition temperatures of asphalt binder to start healing. CAC needed higher transition temperatures to heal the cracks. Above the optimum temperatures, damaged AC samples should not be heated. However, one should note that the optimum heating time is highly dependent on the input power of the microwave and energy conversion efficiency.

FIG. 13

Effect of heating time on the healing level.

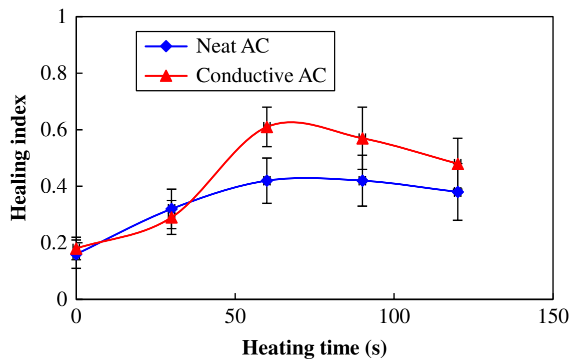
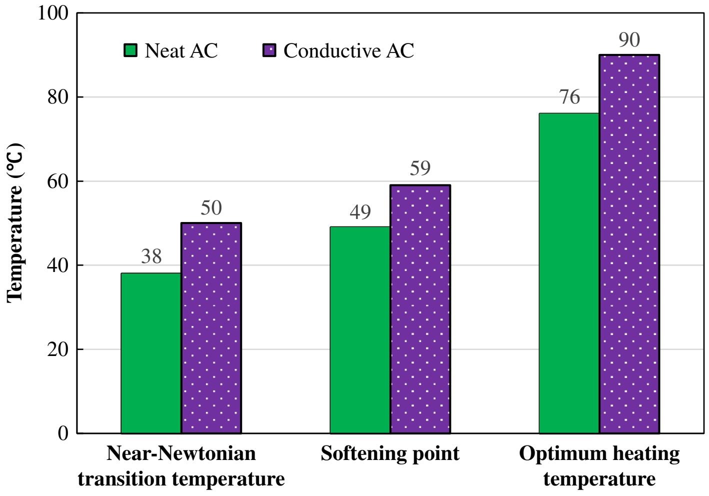


FIG. 14

Comparison of different characteristic temperatures.



Associating the optimum heating temperature with the softening point and near-Newtonian transition temperature, a comparison of the different characteristic temperatures is shown in Fig. 14. There is a strong correlation between these temperatures for asphalt used in both types of AC. The softening point is about 10°C higher than the near-Newtonian transition temperature and about 30°C lower than the optimum heating temperature. This finding is very useful for the practical project application when limited data can be obtained in the field. The potential relationship among these featured temperatures needs validation through further research.

EFFECT OF HEATING MODE ON HEALING EFFICIENCY

Consecutive heating and intermittent heating were applied on conductive AC samples to evaluate the effect of heating mode on healing efficiency. Fig. 15 depicts the temperature evolution of asphalt mixture under different heating modes. As expected, from Table 3, the final surface temperature of the test sample using a consecutive heating mode is higher than that under an intermittent heating mode because of the cooling process in intermittent heating.

FIG. 15

Schematic of temperature changes of asphalt mixture under different heating modes.

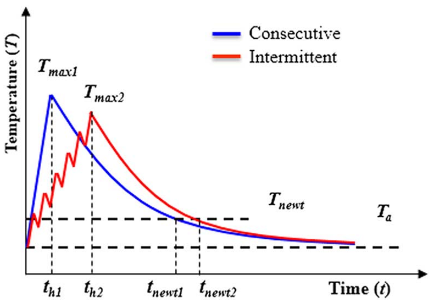


TABLE 3
Effect of heating mode on healing efficiency.

	Final Surface Temperature (°C)		Healing Index	
Heating Mode	Value	Standard Deviation	Value	Standard Deviation
Consecutive heating	120	4.32	0.48	0.012
Intermittent heating	103	6.45	0.56	0.025

It is also noticed that intermittent heating is more effective than consecutive heating in improving the healing efficiency of test samples. This phenomenon can be explained by two reasons in terms of healing temperature and time shown in Fig. 15. Firstly, the heating speed of test samples at a relatively low temperature is higher, as shown in Fig. 6. This means that the average heating speed of intermittent heating with the cooling process is higher than that of consecutive heating. Therefore, intermittent heating offers test samples the potential to absorb more heat energy to enhance the healing behavior. Secondly, self-healing of AC does not only happen during the microwave heating period (approximately 2 min) but mainly during the cooling time (dozens of minutes) [29] as long as the temperature of the AC is above the near-Newtonian temperature of asphalt (50°C for CAC). The existence of the cooling process during the intermittent heating period increases the total healing time at a relatively elevated temperature. These two factors contribute to the different effects of heating mode on healing efficiency.

Conclusions and Recommendations

In this study, microwave heating was used to accelerate healing in AC during rest periods. To this end, thermal conductivity and microwave heating properties of conventional asphalt mixtures and conductive asphalt mixtures were measured. The flow behavior of asphalt was also studied through frequency sweep testing to determine when the healing happens. The proposed healing test program and healing index were applied to quantify the effect of microwave heating on healing level and to determine the optimal heating procedure. Based on the laboratory test results, the following conclusions can be drawn:

(1) The addition of conductive materials can effectively increase the thermal conductivity and microwave heating rate of asphalt mixture. Conductive additives significantly changed the electro-magneto-thermal properties of AC.
(2) CAC containing graphite and steel fibers has better fatigue performance and healing efficiency than neat AC.
(3) The minimum temperatures for flow healing to happen in AC is 38°C and 50°C for neat asphalt and graphite-modified asphalt, respectively, which corresponds to the near-Newtonian behavior temperatures.
(4) The optimum heating time for neat AC and conductive AC are 75 s (equivalent to 76°C) and 60 s (equivalent to 90°C), respectively. If temperatures are increased further, the healing level decreases.
(5) With the same heating time, an intermittent heating mode with the added cooling process is more effective than a consecutive heating mode to enhance healing in AC.

Based on the above findings, microwave heating is an effective method that can be used to heat AC to accelerate its healing behavior. One should note that the optimum heating time and temperature determined from this study are specific to the materials used and the output power and volume of the microwave. For future work, the healing behavior during the cooling process should be more deeply explored with fundamental equations. Numerical simulation is recommended to investigate the electro-magneto-thermo-mechanical properties of asphalt mixture to minimize the uncertainty of laboratory tests. In addition, both localized and overall aging problems of asphalt mixture during the microwave heating process, as well as its effects on healing, should be studied. Furthermore, more accurate and industrial microwave heating equipment needs to be developed to investigate its effect on healing performance for engineering applications.

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