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Healing Performance of Granite and Steel Slag Asphalt Mixtures Modified with Steel Wool Fibers

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Abstract

This paper evaluates the induction healing performance of granite and steel slag asphalt mixtures modified with Steel Wool Fibers (SWF). A computerized tomography scan (CT-scan) was conducted to analyze microstructure and distribution of steel wool fibers in the mixture. Thermal conductivity was examined and heating rate was investigated with induction heating system. The healing performance was investigated by crack-heal cycles with three-point bending test. Dynamic modulus and repeated indirect tensile test were carried out to characterize the mechanical properties of asphalt mixtures modified with SWF. The results showed that the conductive properties and induction heating rate of asphalt mixture was enhanced by adding steel wool fibers and steel slag. The microanalysis results showed the agglomeration and uneven distribution of fibers in the mixtures when the mixed conductive additives exceed a certain dosage. It was found that heating rate of steel slag mixture was higher than that of granite mixture; however, its healing performance was slightly lower because of the cracking of weak steel slag. Finally, the mechanical test results demonstrated that the rutting resistance of asphalt mixtures was enhanced by adding steel wool fibers.

Keywords: *induction heating, steel wool fibers, self-healing, steel slag, repeated indirect tensile*

1. Introduction

Cracking is one of the typical damages of asphalt pavement. There are many causes of cracking such as fatigue cracking, low-temperature cracking, reflection cracking, etc. Normally, cracks usually form from micro-cracks, then develop into large cracks. In this case, asphalt pavement needs rehabilitation or reconstruction to maintain the required level of performance. These works are not only costly and time-consuming but also cause a traffic jam and environmental pollution. The preventive maintenance of the pavement is, therefore, necessary to extend the life of the road and prevent the future major damage. Fortunately, asphalt pavement deterioration can be healed by the crack closing ability of softened asphalt binder under high ambient temperature. In recent years, induction heating method has been studied to increase the temperature of the pavement in order to increase its healing capacity. This method is generally used to heat the metal placed in a magnetic field (Rudnev *et al*., 2003). Hence, to apply the induction heating technology to healing asphalt pavement purpose, the conductive additives (such as SWF, steel powder, and steel fibers) were added to the mixture to enhance its conductivity, heating capacity as well as healing performance. Liu *et al.* (2011) investigated the induction healing of asphalt mastic and porous asphalt mixture modified with steel wool. The mechanical properties of porous asphalt concrete containing steel wool were also examined. The results indicated that the healing performance of both asphalt mastic and porous asphalt mixture was enhanced by using induction heating method. Besides, the fatigue life of porous asphalt mixture was prolonged significantly by adding steel wool. In another study, they concluded that a heating temperature of 85°C was the optimum temperature for self-healing with induction heating method. Dai *et al*. (2013) tried to improve the healing capacity of SWF modified asphalt mastic and asphalt concrete beam using induction heating generator. The result indicated asphalt concrete beams can be recovered more than 50% of the initial strength that asphalt mastic can be completely healed after six cracking-healing cycles. Menozzi *et al.* (2015) evaluated the healing capacity of steel particles modified asphalt mixture. The mixtures were suffered fatigue damage and after that were healed by induction heating. It was concluded that the lifetime of damaged asphalt mixture can be prolonged significantly by using induction healing method. Apostolidis *et al.* (2016) believed that the electrical conductivity, thermal conductivity, and induction heating rate of asphalt mortar were increased by adding iron powder or steel fibers.

Steel slag is a by-product of the steel production. Every year, there are billions of tons of steel slag produced around the world. With the durability and high strength, steel slag can be used as

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aggregate in many applications such as hot metal dephosphorization, road and hydraulic construction, production of cement and concrete. In the field of road and pavement, steel slag is widely researched and applied to both base and surface layer. Ahmedzade *et al.* (2008) examined the effect of steel slag coarse aggregate on properties of hot mix asphalt mixture. The results demonstrated that both mechanical and conductive properties of mixtures were improved by using steel slag to replace coarse aggregate. Chen *et al.* (2016) investigated the engineering properties and performance of steel slag asphalt mixtures. They found that the steel slag mixture had better moisture resistance, skid resistance, and rutting resistance when compared with the conventional mixture. Besides, steel slag was also used as a conductive material for deicing asphalt pavement with microwave (Gao *et al.*, 2017). It was concluded that the utilization of steel slag not only enhanced the heating performance of asphalt mixture but also benefited the economy and environment.

The main purpose of this research is to investigate the healing performance of steel slag aggregate asphalt mixture with induction heating method. Other purposes are to examine the effect of SWF on healing performance and mechanical properties of the asphalt mixture. Different asphalt mixtures were developed with two kinds of aggregate (granite and steel slag) and different content of SWF. The thermal conductivity and heating performance of asphalt mixtures containing SWF and steel slag were examined. The CT-scan test was carried out and the obtained images were then analyzed by image analysis program to observe the dispersion of SWF in the mixture. The healing performance of asphalt mixtures was evaluated through eight crack-heal cycles using induction heating system and three-point bending test procedure. Finally, the mechanical properties of asphalt mixtures modified with SWF were investigated by dynamic modulus and repeated the indirect tensile test.

2. Materials and Testing Method

2.1 Material

The asphalt binder used in this study was PG 64-22 grade with a density of 1.023 g/cm^3, a penetration of 7.0 mm at 25ºC and a softening point of 48.5ºC. The aggregates used were granite and steel slag with the particle size distribution shown in Table 1. The soil pollution environment test results and the basic parameters of steel slag were presented in Table 2. The additive for induction heating used was steel wool fibers (SWF). The SWF with an average diameter ranging from 70-130 μm, the density of 7.18 g/cm^3, length varied from 3-5.5 mm, and thermal conductivity of 80 W/m.K.

2.2 Specimens Preparation

The asphalt mixtures were designed according to the Superpave Mix Design Method with the target air voids of 4 ± 0.5 percent and a dimension of 100 mm in diameter and 110 mm in height. After 24 hrs curing at room condition, the compacted specimens

Table 1. Particle Size Distribution of Granite and Steel Slag

Sieve size (mm)		19	12.5	9.5	4.75	2.36	0.6	0.3	0.15	0.075
Percent passing (%)	Granite aggregate	100	98	86	60	45	23	14	8	3
	Steel slag	100	99	85	52	35	13	3	1	0

Table 2. Parameters of Steel Slag

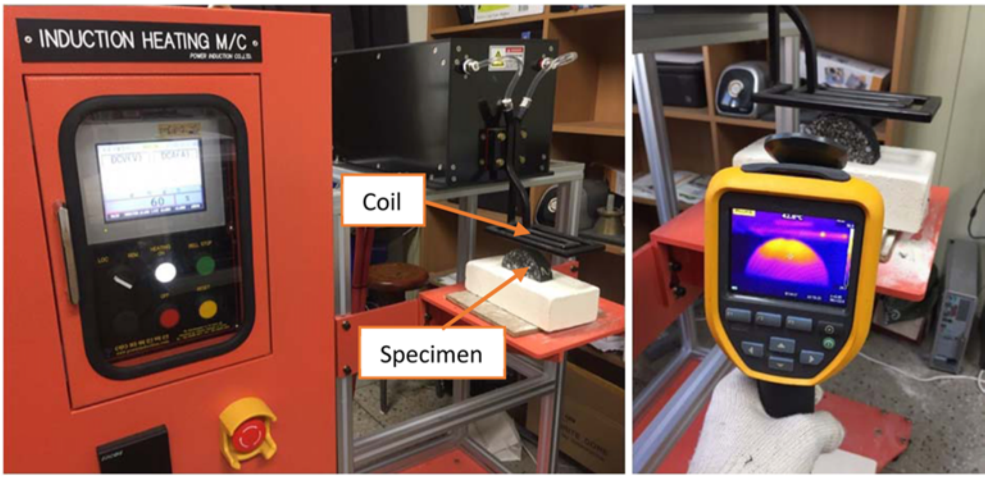
Soil pollution environment test		
Ingredient	Standard (mg/kg)	Content (mg/kg)
Cd	≤ 60	2.13
Cu	≤ 2000	5.23
As	≤ 200	None
Hg	≤ 20	0.05
Zn	≤ 2000	295
Ni	≤ 500	5.33

Chemical component									
Name	Fe_2O_3	CaO	Free CaO	MgO	SiO_2	Al_2O_3	P_2O_5	MnO	Others
Content (%)	24	48	5	2	13	2	1	1	4
Density: 2.933g/cm^3									

Table 3. Combination of Asphalt Mixtures

Name	Mixture type	SWF content (%*)	Steel slag content (%**)	Granite aggregate content (%**)
N	Granite asphalt mixture	0	0	100
S	Steel slag asphalt mixture	0	30	70
NF	SWF modified granite asphalt mixture	4, 6, 8	0	100
SF	SWF modified steel slag asphalt mixture	4, 6, 8	30	70

*by volume of asphalt binder
**by volume of total aggregate



(a) (b)

Fig. 1. (a) Induction Heating Heater, (b) Infrared Camera

then were slice into 3 equals for thermal conductivity measurement and cut into 6 semi-circular for healing measurement. Four kinds of asphalt mixtures were fabricated in this study, including granite mix (N), steel slag mix (S), steel wool fibers modified granite mix (NF), steel wool fibers modified steel slag mix (SF). The contents of SWF, granite, and steel slag aggregate were presented in Table 3.

2.3 Thermal Conductivity Measurement

The thermal test was conducted to evaluate the effect of SWF and steel slag on thermal properties of asphalt mixtures with a Thermal Constants Analyser system. The test system included a Hot Disk TPS 1500 model connected to a Kapton-insulated sensor by cable. The measurement process met ISO Standard 22007-2 (ISO standard 2008) with a measurement range of 0.01-400 W/mK and the accuracy of measurement was better than 5%. The sensor was placed between two specimens and was then heated by a constant electrical current for a short period time of approximately 20 seconds. To ensure reliability for the test, a total of 12 measurements were conducted for each mixture type.

2.4 CT-Scan Test

The dispersion of the SWF in the mixture was observed using a micro-CT scanner (SkyScan-1076 model). The scanner image can display the object with a small size of up to 0.35 μm, the visualization up to 4000 × 2300 pixels and three offset positions. The test specimens with SWF content of 4%, 6%, and 8% were cut from Superpave specimens with the dimension of approximately 30 × 20 × 20 mm. Before testing, all specimens were heated at 40ºC degrees for 8hrs to completely remove the moisture. The specimen was scanned from the bottom up and there were about 1,000 cross-sectional images taken for each specimen.

2.5 Induction Heating Test

To investigate the effect of SWF and steel slag on the heating performance of asphalt mixture, the induction heating test was conducted by using an induction heating generator with a capacity of 50 kW and a maximum frequency of 35 kHz (Fig. 1(a)). The test specimen was placed under the coil with a distance of 2cm and then was heated until the specimen reached the target temperature. An infrared camera (FlukeTiS20 model) was employed to measure the surface temperature of the specimen with a period of 10 seconds (Fig. 1(b)).

2.6 Healing Measurement

The healing performance of each mixture type was evaluated through eight crack-heal cycles. Firstly, the semi-circular bending test was conducted to create the hairline crack and determine the initial strength of specimens (see Fig. 2). Before the test, the specimens were placed in freezing chamber at -18ºC for 4hrs to acquire the brittleness condition. The semi-circular bending testing machine used in this experiment had a capacity of 100 kN and a loading rate of 0.2 mm/min. After that, specimens were kept in ambient condition for 3 hrs to ensure that the moisture caused by the condensation was totally dried out. Secondly, the damaged specimens were placed under induction heater coil and

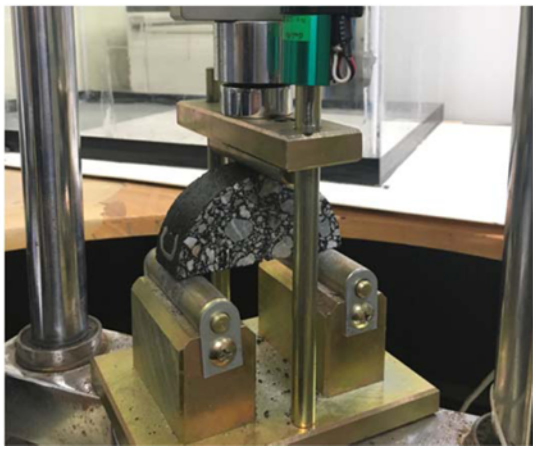
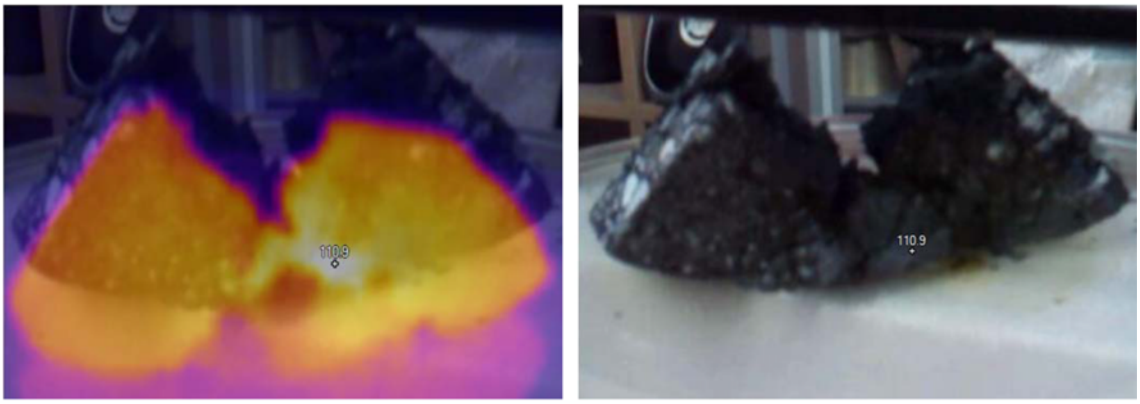


Fig. 2. Semi-circular Bending Tester



(a) (b)

Fig. 3. (a) Infrared Image, (b) The Loose of Asphalt Mixture at 110ºC

heated to a desired healing temperature. In this study, the specimens were heated at three different temperatures of 70, 90 and 110ºC. However, all the test specimens presented a very low healing performance after several cracking-healing cycles under a heating temperature of 70ºC. Besides, with the heating temperature of 110ºC, the specimen was deformed and loosed by its own gravity as seen in Fig. 3; hence, the healing evaluation was done at the heating temperature of 90ºC. The heated specimens were let to rest for approximately 3hrs at 20ºC to help its cool down to room temperature. Finally, the healed specimens were re-tested under Semi-circular bending procedure to finish a healing cycle. The healing level of asphalt mixture sample at the i^{th} cycle, HL_i, was calculated by Eq. (1) below:

$$HL_i = \frac{F_0}{F_i} \qquad (1)$$

where F_0 = The maximum force of the initially tested specimen, and

F_i = The maximum force of the specimen at i^{th} the healing process.

2.7 Dynamic Modulus

Dynamic modulus testing was conducted at -4, 20, and 40ºC and 0.1, 0.5, 1.0, 5, 10 and 25 Hz (AASHTO 2007). Compacted samples of 100 mm in diameter and 150 mm in height at air voids of 7 ± 0.5% were used to perform the test. The modulus of asphalt mixes at all levels of temperature and time rate of the load is determined using a master curve constructed at a reference temperature (NCHRP, 2004). Master curves were constructed, and the master curve was established according to Christensen *et al.* (2003) using the following equation:

$$\log(E^*) = \delta + \frac{(Max - \delta)}{1 + e^{\beta + \gamma\left[\log(t) - \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{295.25}\right)\right]}} \qquad (2)$$

where: E^* = Dynamic modulus,

Max = Limiting maximum modulus, and

t = Loading time,

T = Temperature (ºK),

β, δ, γ and ΔE_a = Fitting parameters from experimental data.

2.8 Repeated-Load Indirect Tensile Test

The test is to quantify the resistance to fatigue cracking of asphalt mixes. The disk-shape specimens were tested at 20ºC in an environmental-control chamber. The loading pattern includes a 2 kN peak and 0.2 kN seating load with a duration of 0.1 and 0.9 sec, respectively, applying along the diametral direction of the specimen. The vertical deformation was recorded throughout the experiment and the fatigue life was determined by the total number of cycles at failure (N_f). The higher the N_f, the better resistance to fatigue cracking.

3. Results and Discussion

3.1 Effects of Steel Slag and SWF on the Thermal Conductivity

The results of the thermal conductivity test of asphalt mixtures are shown in Fig. 4. The SF mix has slightly higher thermal conductivity than NF mix. Higher content of SWF provides greater thermal conductivity; however, as the SWF reaches 8%, it has a decrease sign. This might be caused by uneven distribution of fibers in the mixture which would be demonstrated in the CT-

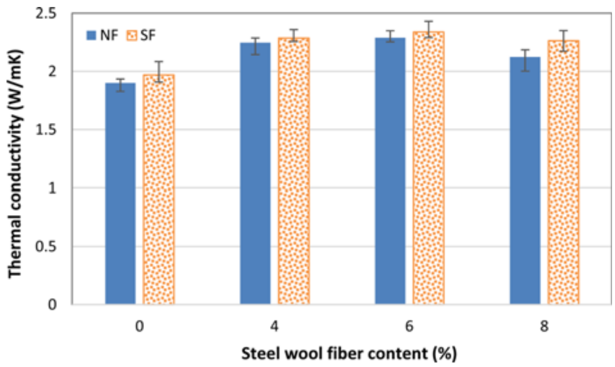
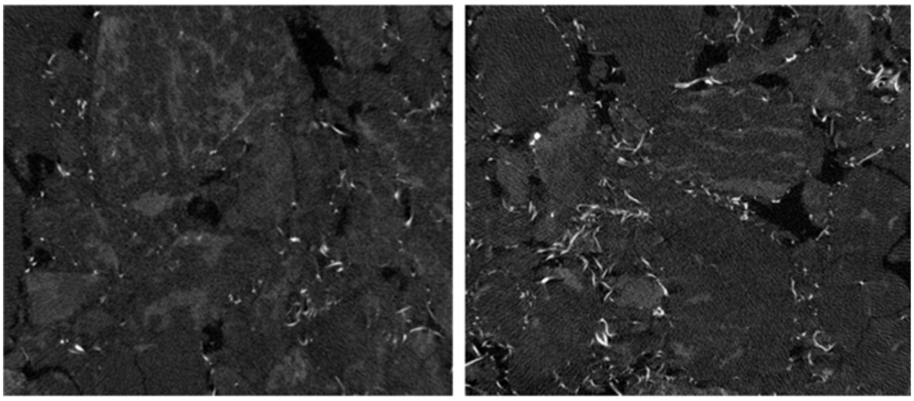
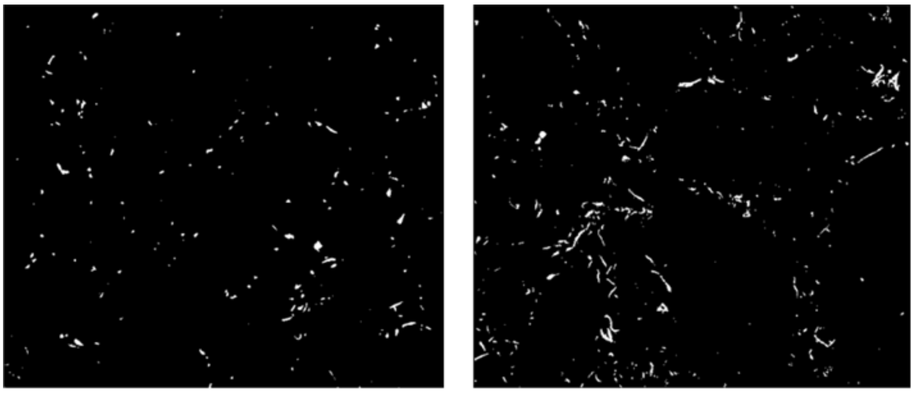


Fig. 4. Thermal Conductivity Results



(a) (b)

Fig. 5. CT – scan Images at a Cross-section of Mixes: (a) SWF4, (b) SWF8



(a) (b)

Fig. 6. Analysis Results of the CT-scan Images of Mixes: (a) SWF4, (b) SWF8

scan test.

3.2 CT-scan Test Result

An image analysis program was developed based on MATLAB (2015) as a new method to evaluate the dispersion of the SWF in the asphalt mixture. The cross-sectional images obtained from CT-scan test were grayscale images with the BPM format. Along the 30 mm height of the specimen, a total of 200 cross-sectional images were selected as the input data for analysis and computation. Firstly, the grayscale images (Fig. 5) were converted to binary images (Fig. 6) by global threshold method. The global threshold method was described as follows: Suppose the threshold value is T, if the pixel intensity value is lower than T, the pixel will become black; otherwise, the pixel will be white. According to the observation, the high-intensity areas should be considered the SWF area; therefore, different global threshold levels were applied to images, and finally the value of 0.55 was shown as the best value for visual solution. In this study, the program identifies the fibers areas as white pixels. After that, the SWF area percentage was calculated by the ratio of white pixels to the total.

Figure 7 shows the variation of SWF area percentage through the height of the specimens. The higher fibers content presents the larger range of fibers area percentage value. As seen in Fig. 8, the fibers area percentage variation of the specimen with 8% SWF was significantly higher than that of specimens modified with 4% and 6%. In detail, when the test specimens are scanned from bottom to top (0-30 mm), the fibers area percentage values of specimens contenting 4% and 6% SWF vary from 0.17% to 0.26% and 0.29% to 0.44% respectively, while it is from 0.28% to 0.82% with 8% SWF specimens. It indicates the fibers in this

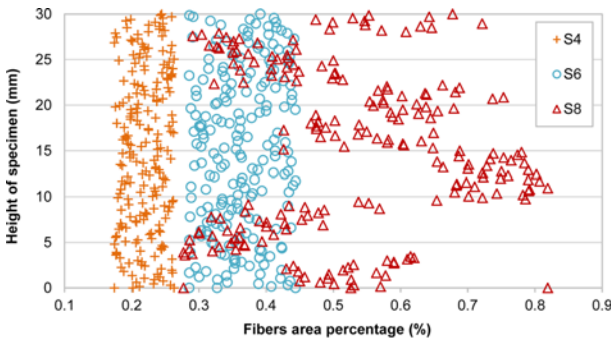


Fig. 7. The Fibers Area Percentage of Sample Surface from the Bottom to the Top of the Specimen

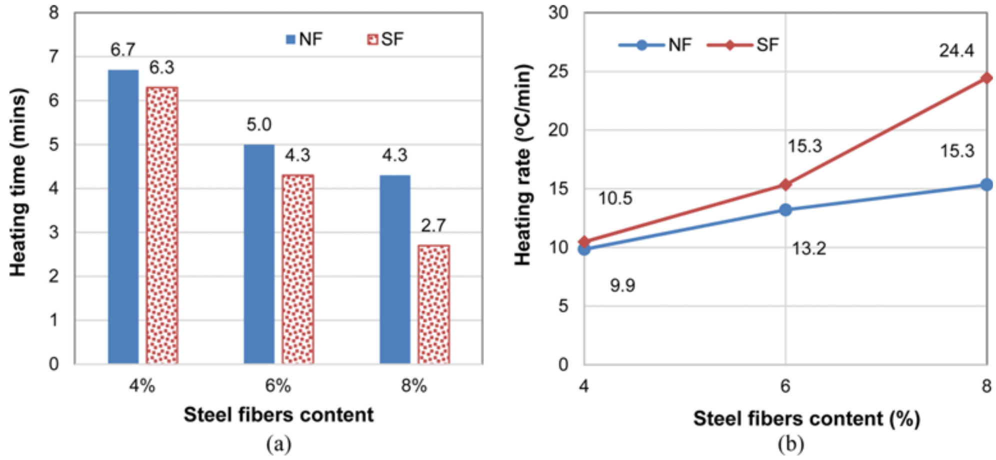


Fig. 8. Heating Performance of NF and SF Mixtures: (a) The Heating Time to Reach 90°C, (b) the Heating Rate

mixture disperses unevenly. At high fibers content, the fibers tend to be entangled in the mixing process and therefore the bundles are formed. This result also demonstrates the decrease in thermal conductivity of mixture modified with 8% SWF as shown in Fig. 4.

3.3 Induction Heating Performance of Asphalt Mixtures

Figure 8 shows the heating time to reach 90°C and the heating rate of NF and SF mixtures. As seen in Fig. 8(a), the SF mix takes less time to reach a target temperature than the NF mix. For mixtures containing 4% SWF, the difference in heating time is not significant. However, with SWF content of 6% and 8%, the heating time of SF mix is reduced by 15% and 40%, respectively compared to NF mix; therefore, it concludes that mixture with steel slag has less heating time which can reduce the time of road closure and construction cost. From Fig. 8(b), the heating rate of NF and SF mixtures increases with an increase in SWF content. In addition, the heating rate of SF was higher than NF; namely, the maximum heating rate of mixtures were 15.3 and 24.4°C/min for NF and SF respectively.

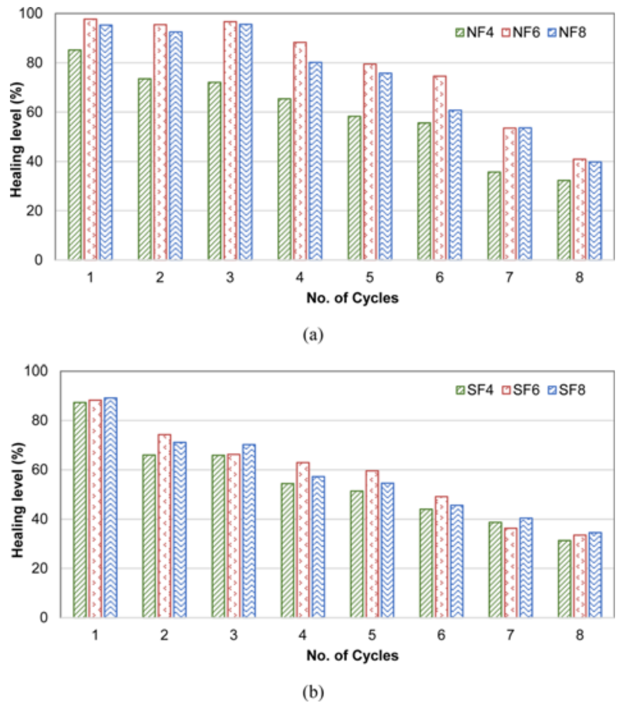


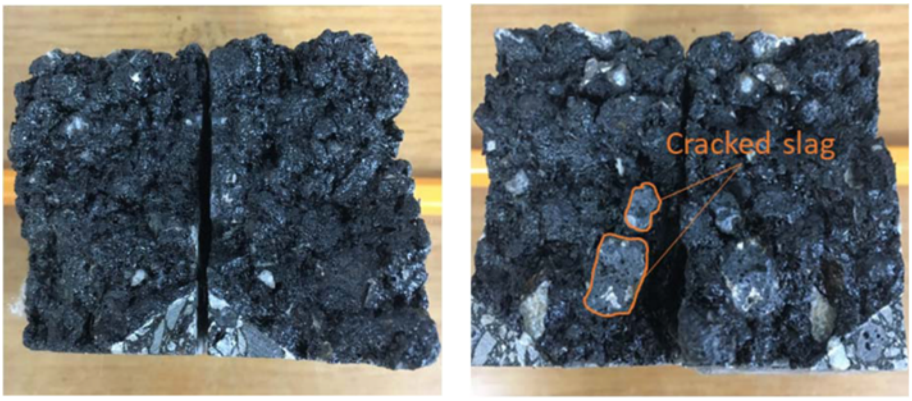
Fig. 9. Healing Performance of: (a) NF, (b) SF Mixtures

3.4 Healing Measurement Result

Figure 9 shows the healing performance of NF and SF mixtures. In general, the NF mixes have a good healing performance and its healing level decreases with the increase in the number of crack-heal cycles. In Fig. 9(a), the healing level of NF mixes with 6% and 8% SWF are relatively similar and obviously higher than that of NF mix with 4% SWF. For example, at the second cycle, the healing level of NF mix with 4% SWF is 73.5%, while the maximum load of NF mix with 6% and 8% of SWF can recover 95.5% and 92.5% respectively. Accordingly, 6% SWF by volume of asphalt binder is a reasonable content for induction heating method.

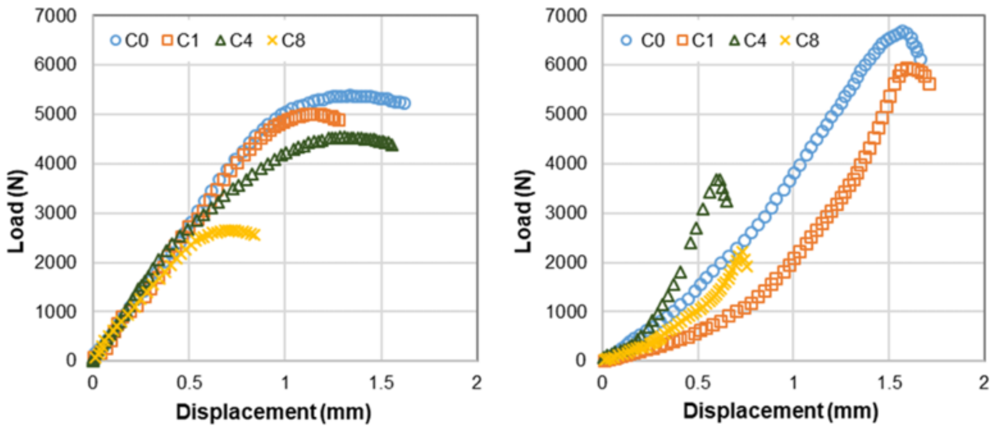
The SF mixtures with different SWF content demonstrate almost the same healing performance (Fig. 9(b)). The SF mixtures were heated with induction heating by both steel fibers and steel slag, which helped temperature of SF to disperse evidently into the mixtures; therefore, using steel slag can reduce the steel fibers content and the SF with 4% content by volume of asphalt binder was reasonable for induction heating method. In addition, it is clear that granite asphalt mixture shows the higher healing level than steel slag aggregate asphalt mixtures because it has some steel slag particles contained many voids, which are fragile and have the low strength (Fig. 10). Once the aggregate is cracked or broken, the healing areas would be reduced because the asphalt cannot flow into those areas to fill the crack; hence, the healing level of SF mix decreases.

The load-displacement curves of NF mix and SF mix are presented in Fig. 11. As seen in Fig. 12(a), the load of NF mix



(a) (b)

Fig. 10. The Cracking Surface of: (a) NF Specimen, (b) SF Specimen



(a) (b)

Note: C0, C1, C4, and C8 are the initial state, first, fourth, and eighth heating cycle

Fig. 11. Load-displacement Curves of Mixes: (a) NF, (b) SF

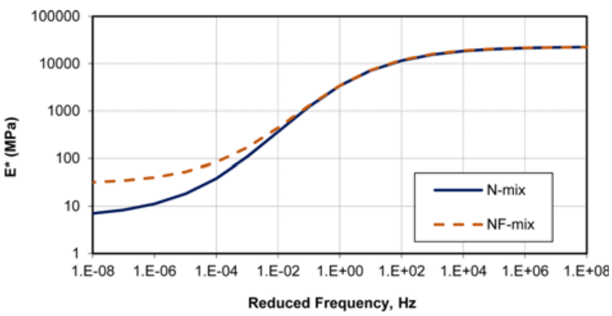


Fig. 12. Dynamic Modulus Master Curves at Reference Temperature of 20°C

increases rapidly and then it increases slowly to reach the maximum load value; after that, the load decreases slowly with the ductility behavior until failure. The initial maximum load value of SF mix was higher than that of NF mix. However, the load-displacement curves of SF mix do not behave as those of NF mix. The SF mix decreases suddenly after reach the peak even at the first cracking-healing cycle. The SF mix seems more brittle compared to the NF mix due to the cracking of some steel slag particles as shown in Fig. 10.

3.5 Dynamic Modulus Test Result

The dynamic modulus master curves of the two mixes are presented in Fig. 12. There are two replicates for each mixture. The coefficient of variation (COV) is 10.2 and 8.7% for mixes N and NF, respectively which is generally acceptable. The two mixes show a modulus around 22,000 MPa at high frequency; and a distinct change at the low frequency. Dynamic modulus master curves for mixes N and NF are primarily similar across frequency greater than 0.1 Hz. At low frequency (or high temperature), mix F reflects greater dynamic modulus than mix N.

Rutting is characterized using the rutting factor, $|E^*|/\sin\varphi$ (Bhasin *et al.*, 2004). Since rutting usually occurs at high temperature condition, the modulus values were obtained at 40ºC and the frequency of 10 Hz and 25 Hz. Fig. 13 illustrate the rutting factor of mixes N and NF. Higher rutting factor shows better rut resistance. As seen in Fig. 13, asphalt mixture with fibers shows better resistance to rutting with higher $|E^*|/\sin\varphi$ at the two frequency levels 10 Hz and 25 Hz.

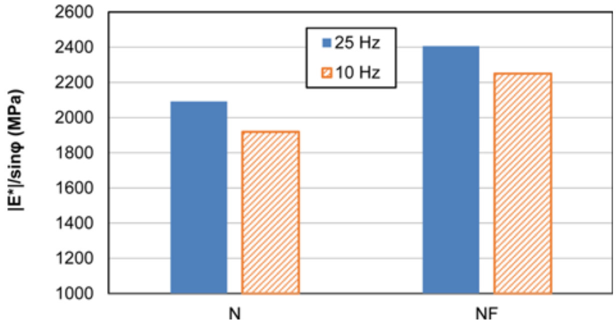


Fig. 13. Rutting Factor Comparison at 40ºC, 10 and 25 Hz

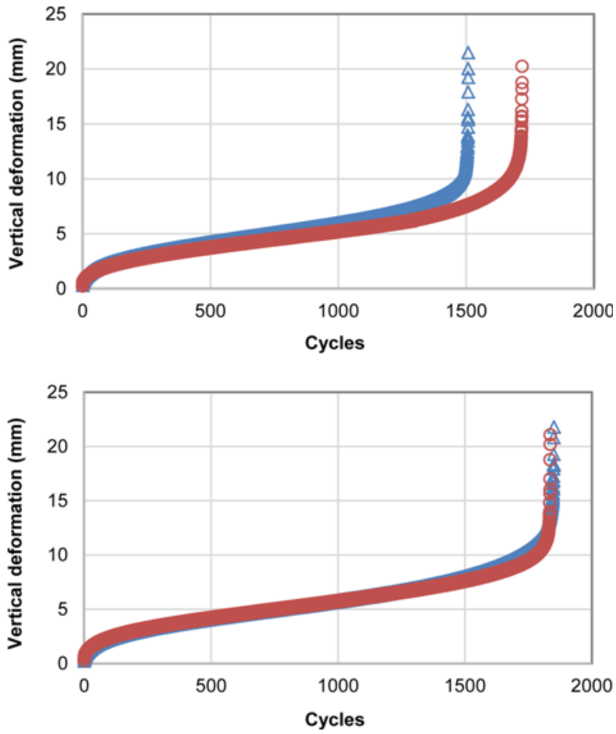


Fig. 14. Repeated IDT Test for Mixes N (above) and NF (below)

3.6 Repeated Indirect Tensile Test

The testing results of mixes N and NF are shown in Fig. 14. Measurements reflected an average of two replicates with the coefficient of variation less than 17% which is considered generally acceptable for asphalt mixtures. The results suggested that mix NF has the fatigue life about 15% higher than mix N. Summary of testing results is shown in Table 4. It is evident that the fatigue resistance of asphalt mixture could be improved by adding SWF. Besides, as a result from Fig. 12, at a corresponding temperature and a frequency of 1 Hz, mixes N and NF had almost same stiffness value; hence, it is concluded that the fatigue life of asphalt mixtures was not in agreement with its stiffness value.

Table 4. Summary of Repeated IDT Tests

Mix	N_f	Avg. N_f	COV (%) N_f	Failure strain, ε_f	Avg. ε_f	COV (%)ε_f
N	1507	1612	14.0	23.71	24.90	10.0
	1718			26.08		
NF	1849	1841	0.8	27.84	25.87	16.4
	1834			23.91		

4. Conclusions

In this study, the effect of steel slag and SWF on induction heating and healing performance of asphalt mixtures were examined by induction heating system and cracking-healing cycles. Some mechanical tests were also carried out to identify the difference between a conventional mixture and SWF modified mixture. The uneven dispersion of fibers in the mixture with SWF content of 8% was observed by image analysis program. The thermal conductivity, heating rate and healing performance of granite asphalt mixture were enhanced by adding a certain content of SWF. The mix with 8% SWF showed the higher induction heating rate; however, the uneven dispersion of fibers caused the decrease in both thermal conductivity and healing performance compared to the mix with 6% SWF. Therefore, it is concluded that 6% SWF is an optimum content for induction healing granite asphalt mixture. The steel slag improves thermal conductivity and induction heating rate of the asphalt mixture. The healing performance of steel slag asphalt mixtures modified with different content of SWF was almost similar. The maximum load of mix contenting steel slag was higher than that of granite asphalt mixture; however, the steel slag mix had a lower healing performance than granite mix due to the crack of weak steel slag particles. The steel slag showed a good healing performance, especially reducing the heating time. With the still slag mix, the authors recommend that the content of 4% SWF is reasonable for induction healing purpose. Besides, SWF can increase the dynamic modulus value and prolong the rutting life of asphalt mixture. With the result showing above, the authors believe that SWF and steel slag have promise in healing asphalt pavement with induction heating techniques.

Acknowledgements

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