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Crack healing performance of hot mix asphalt containing steel slag by microwaves heating

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HIGHLIGHTS

- Steel slag shows better microwave absorption compared to the conventional aggregate.
- Under microwave heating, adding lower than 2% SWF is optimum for healing of HMA.
- Mixtures show ductile behavior at early cycles and brittle characteristics at late times.
- Slag mixture obtain better healing performance compared to the original aggregate.
- The crack formation affects the healing effectiveness.

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ABSTRACT

This study aims to analyze the applicability of steel slag in the asphalt mixtures for the self-healing purpose using microwave heating technique. Hot mix asphalt (HMA) mixtures were developed from four different levels of steel wool fibers (SWF) as a conductive additive and two types of aggregate were used: steel slag aggregate and conventional aggregate. Then, the thermal distribution, as well as the optimum healing time of test samples, were recorded by the infrared camera. 10 damage-healing cycles were applied in all mixtures to evaluate their healing performance under microwave heat. Test results suggested that adding two percent SWF by weight of asphalt mixture provides the best healing level for both types of aggregate mixtures. At this SWF level, the substitution of 30% normal coarse aggregate by steel slag is very promising due to its presence not only provides better healing results but also helps the whole mixture improve the load-displacement relationship with higher ductile behavior. Overall, the application of steel slag in HMA is a prominent solution which contributes toward the sustainable development.

1. Introduction

Steel production industry releases hundreds million tons of steel slag each year in accordance with the World Steel Association report [1]. Due to the landfill disposal solution, this by-product causes many environmental problems, especially concerns on the leaching issues [2–5]. In civil construction such as asphalt pavement, embankment, concrete masonry, and railroad ballast, the application of steel slag aggregate has been increasing in recent years. Road construction has consumed a significant amount of nonrenewable resources from our planet. Hence, the utilization of steel slag as a replacement for conventional aggregate in HMA is a promising key to release environmental pressure and reserve the natural resources.

Based on literature reviews [2–5], steel slag shows feasible characteristics which can be applied in HMA. Steel slag particle has some special properties such as angular shape, broken faces which promote better skid resistance with high moisture stability. HMA with steel slag also acquires lower permanent deformation with higher fatigue life compared to the normal aggregate [2]. However, this special texture otherwise acts as a barrier that prevents the workability of asphalt mixture [3]. It is reported in the related literature that porous particles of steel slag may consume a higher amount of asphalt binder and this excessive absorption may cause a significant increase in the production cost [3,4]. Hence, utilization 100% steel slag as a replacement of conventional aggregate is not recommended. Mansour [3] and Zongwu [4] suggested that the fine part of steel slag should be excluded due to its high binder-consumption. Another issue of steel slag composition is the free lime (f-CaO) which draws critical concern in volume instability [5]. If this chemical is subjected to hydration process,

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Table 1
Particle size distribution of normal aggregate.

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.6	0.3	0.15	0.075
Percent passing (%)	100	98	86	60	45	23	14	8	3

its presence will cause volume expansion and result in cracking. However, this problem can be resolved by six months weather processing method [3,4].

Depended on the type of mixtures, ambient temperature and resting period, the microcracks formed in asphalt pavement can be healed to a different level [6]. Based on the research of Bhasin and Little [7], this phenomenon can be justified by the fact that molecules from the two sides of the crack are diffused together, which will form a new connection and thereby, the continuity of the material can be reconstructed. This explanation agrees with the findings from Kim and Daniel [8]. The authors indicated that the self-healing in asphalt material can be activated from the temperature of 55 °C when samples are free from traffic pressure. In the research of Liu [9], the asphalt samples were pre-cracked, and they were healed at a temperature from 70 to 120 °C. The test results confirmed that test samples can be achieved up to 100% healing performance. To enhance the healing process of asphalt pavement, induction heating and microwave heating are considered to be the best effective methods [6,10].

The induction heating method has been drawn huge attention lately due to its effectiveness in actual applicability. However, when using the electromagnetic induction to promote self-healing of asphalt pavement, conductive additives incorporation is the main requirement. According to Garcia [6], the asphalt material will be more sensitive to electromagnetic induction and the healing capacity would be remarkably increased by adding this additive. In accordance with the Joule law, the SWF particles receive an electrical current from the induction heating machine which increases their temperature [11]. Then, the thermal energy from the SWF will be transmitted to the asphalt mixtures and thereby, bitumen will be heated [11]. Garcia and Schlangen [10] have conducted a series of experiments to quantify the effective SWF content in asphalt mixtures. They concluded that the optimum SWF content can be controlled from two percent to six percent by weight of asphalt mixture. The authors also performed many tests to determine the physical and mechanical properties of asphalt mixtures containing SWF.

Regards to the microwave heating technique for self-healing purpose, researches on this method show some promising signals. Based on the Megahertz principle, the molecules of asphalt materials will change their orientation after exposing to electromagnetic fields [11]. This process will cause an internal friction that increases the temperature of the whole asphalt mixture. Some literature suggests that the increase of temperature can be remarkably accelerated by adding a very small amount of metal particles due to those additives have a high ability of microwave reflection. J. Norambuena and Garcia [11] stated that microwave heating method helps the healing process of the HMA accelerates to a certain value. Adding SWF into mixtures will enhance the healing capacity. However, the required content of this conductive additive is relatively small compared with the induction heating. This statement agrees with the findings from Juan Gallego' research [12,13]. The author concluded that steel wool content used in microwave methods should be controlled at lower than ten times compared to the induction heating method. The author also mentioned that microwave heating method provides a better economical solution due to its low energy consumption, 1.2 kW compared to the 50 kW power supply required from the induction heating machine.

Based on the above discussions, the application of microwave heating to promote the healing performance of asphalt mixtures owns some advantageous. However, the utilization of steel slag as a microwave absorption part in HMA is neglected in related researches. Hence, the main objective of this study is to evaluate the possibility of utilizing steel slag aggregate in HMA to improve the self-healing purpose by microwave heating technique. To achieve this target, 30% steel slag as a replacement of normal coarse-aggregate and four different contents of SWF were used to fabricate asphalt mixtures. Based on the gradation calculation with upper and lower limitation, 30% steel slag was found to be the maximum amount to utilize the use of this by-product material utilized in this study. Then, the infrared camera was employed to determine the thermal transmitting for each mixture in microwave heating. Through this test, the optimum healing time, as well as the effect of cracking formation throughout the whole mixture, was analyzed. Finally, all test samples were subjected to 10 damage-healing cycles to identify their crack healing performance and load-displacement behavior. This number of damage-healing cycles was designed to remain the healing level of samples of higher than 30%. This test concept was only used for laboratories investigation. The previous research results [14] recommend that the microwave heating should be applied for actual road maintenance no higher than four times. This limitation will ensure the acceptable performance of the healing purpose.

2. Materials and methods

2.1. Materials

In this research, HMA mixtures were fabricated to conduct a series of experiments. They were made from the coarse aggregate (4.75–12.5 mm), fine aggregate (0.075–4.75 mm), and filler (<0.075 mm). Table 1 shows its particle size distribution. Bitumen PG 64-22 used in this study has a density of 1.02 g/cm^3 and a penetration value of 70 mm/10 at 25 °C. The general sizes and basic properties of microwave absorption additive applied in this research are shown in Table 2.

The steel slag aggregate was provided by the Korean steel production company with gradation distribution presented in Table 3. The chemical composition of steel slag is illustrated in Table 4. The porous particles of fine steel slag may lead to the very high binder consumption [3,4]. Hence, only coarse steel slag was used as a substitution of normal coarse aggregate in this research. The steel slag aggregate used in this study was subjected to the weathering process in appropriate humid condition. This process was strictly performed by the company that manufactures steel slag aggregate. The treatment will help the aggregate achieve the acceptable

Table 2
Additive properties.

Type	SWF
Average diameter	70–130 (μm)
Density	7.18 (g/cm^3)
Length	4–4.5 (mm)
Thermal conductivity	80 (W/m.K)

Table 3
Particle size distribution of steel slag as coarse aggregate.

Sieve size (mm)	19	12.5	9.5	4.75	2.36	0.6	0.3	0.15	0.075
Percent passing (%)	100	100	78	5	1	1	0	0	0

Table 4
The chemical composition of steel slag.

Compounds	General steel slag composition (%)	Steel slag used in this study (%)
CaO	47–55	50
Free CaO	6.5	6.1
SiO_2	7.5–15	12
Al_2O_3	1.2–1.7	1.5
MgO	1.3–1.5	1.3
FeO and Fe_2O_3	20–26	23.3
MnO	3.5–5.3	3.5
Na_2O	–	–
K_2O	–	–
S	–	–
CaO/SiO_2	3.7–6.25	4.5

hydration [3,4,13]. Hence, the potential of expansion will be reduced.

2.2. Mix design

Based on experience and preliminary researches [14,15], four different percentages of SWF were applied, including 2, 4, 6, and 8% by weight of asphalt mixture. The optimum asphalt binder content used in this test was 5.4%. To obtain this research strategy, 10 different mixture formulations were developed as presented in Table 5.

As shown in Fig. 1, Superpave Mix Design Method was followed to fabricate the HMA samples [16]. Following the compacting process, the samples were developed with a dimension of 100 mm in both height and diameter. After 1 day curing at an ambient temperature of around 23 °C, the cylindrical sample was cut into six equal semi-circular samples with an overall size of 30 mm in thick and 100 mm in diameter to adapt the three-point bending test (TPB) requirement. Hence, from every mixture, three semi-circular samples were used to calculate the average result for the thermal distribution test. The remained three samples were used for the TPB test as three replicates.

Due to the technical requirement of the TPB test, a notch (pre-crack) was prepared in the test specimen from the mid-point of the samples and the loading central axis (Fig. 2). Based on a suggestion from preliminary papers [11] and the author team's experience [14], the notch should obtain 2 mm in thickness and 10 mm in depth. The objective of this pre-crack point is to ensure the crack develops from the middle point of the test samples. However, cutting process wetted the entire samples, this high moisture content may critically affect the precision the microwave heating test. Hence, the samples were let to rest at room temperature for two more days to ensure they were completely dry.

Table 5
Mixture formulation.

Mix	Bitumen	Conventional Coarse Aggregate	Coarse Steel Slag	SWF
C	5.4%	100%	0%	0%
F2		100%	0%	2%
F4		100%	0%	4%
F6		100%	0%	6%
F8		100%	0%	8%
SC		70%	30%	0%
SF2		70%	30%	2%
SF4		70%	30%	4%
SF6		70%	30%	6%
SF8		70%	30%	8%

2.3. Thermal distribution

This experiment aims to identify the surface temperature in HMA samples under microwave heating process. As seen in Fig. 3a, the infrared camera is used to record those values. The testing process comprises of the following steps: the initial temperature of the sample was recorded at room temperature. Then, the infrared camera was employed to measure the surface temperature through the interval of 10 secs until they reach the desired temp of approximately 90 °C. Based on a suggestion from previous research and experiences, at this point, the test sample will yield excellent healing performance without overheating [11,12]. Through the mixing process, the distribution of SWF may affect the thermal properties of HMA sample. In was found from previous researches [10–14] that inhomogeneous distribution of SWF causes overheating phenomenon which critically damages the test sample. From this test, the distribution of SWF in HMA samples will be analyzed.

2.4. Healing process

Before conducting the TPB test, the test specimens were placed in the refrigerator for approximately two hours at -18 °C to obtain the brittle condition (Fig. 4a). Then, the TPB strength of samples was determined through initial TPB test. In this test, the length between the two-supporting roller was fixed at 8 cm and a loading roller was set at the top-central of the semi-circular arch. The capacity of the load device is 100kN with a loading rate of 0.9 mm/min. The whole testing process was conducted at a temperature of approximately 23 °C. After bearing the load to the maximum threshold, the test sample proceeds to failure stage with crack as a failure signal (Fig. 4b). Due to the high moisture from the freezing process, the failure samples were fully covered by napkins and they were let to rest for three hours at 23 °C. After reaching the complete drying condition, the test samples were subjected to the electromagnetic microwave to achieve the healing temperature of 90 °C. The heating time was chosen by the advantages of the trial thermal tests, ranging from 35 to 45 secs. The microwave heating test was performed in a microwave oven with a power capacity of 700 W and a maximum frequency of 2.45 MHz. Every interval of 10 s, the infrared camera was employed to check the surface temperature of the test specimens as well as the thermal transmitting throughout the system. Then, to restore the stable condition as well as the average temperature (23 °C) of the test samples, additional three hours resting period was applied for all samples. Before conducting the later TPB test on the healed samples, they were placed in the refrigerator for two more hours to reach the brittle condition again. Finally, the conditioned samples were subjected to the TPB test one more time and this process ended a damage-healing cycle. Due to preliminary researches recommendations and the author team's experience [14], the healing performance of the test samples was determined throughout 10 damage-healing cycles. Based on findings [6,11,12], the healing

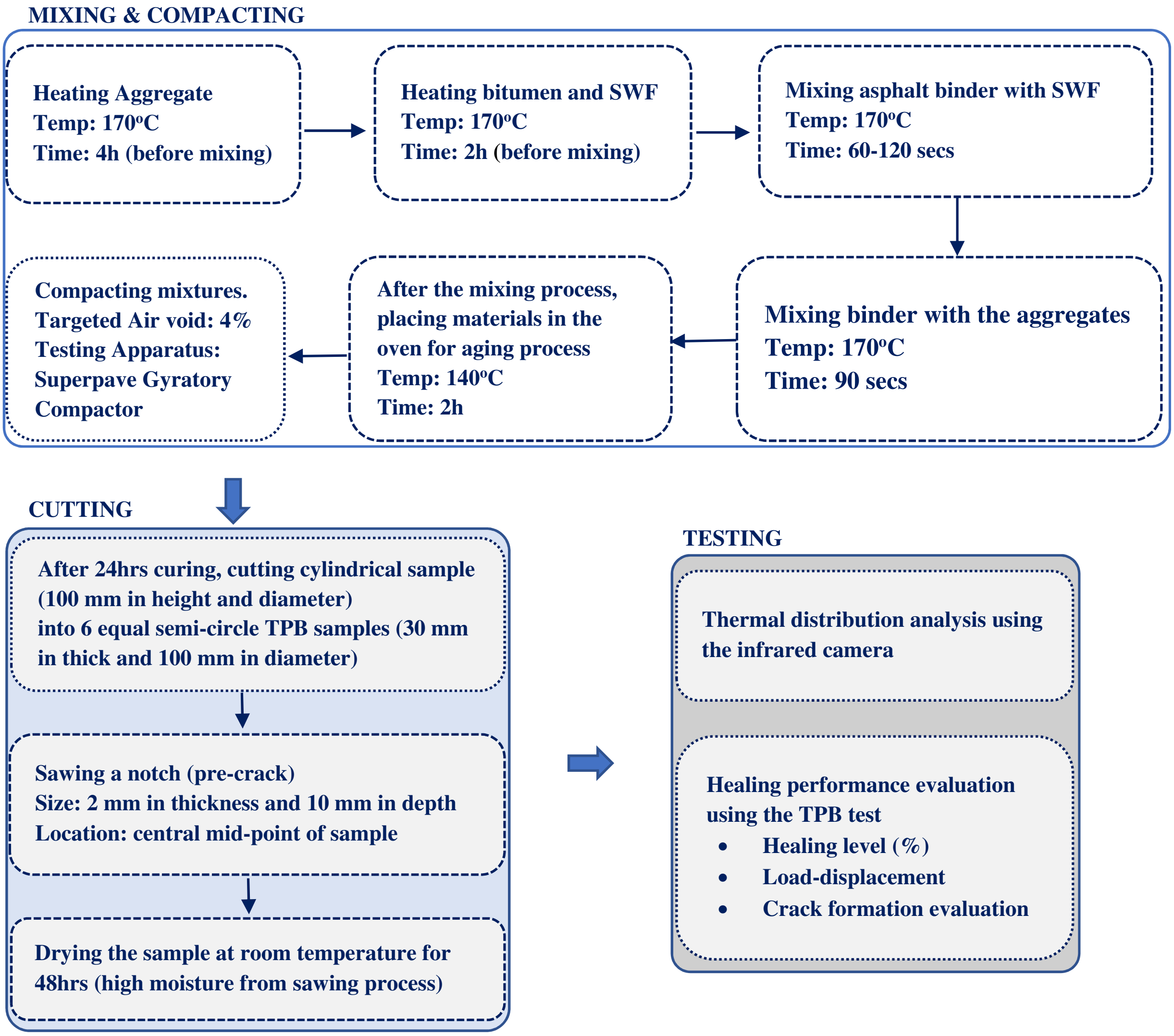

Fig. 1. Experiment diagram.

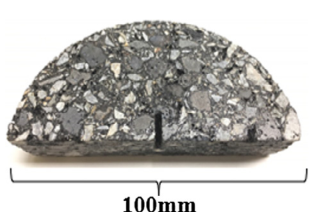

Fig. 2. TPB Test Sample with a notch (pre-crack).

effectiveness of test samples, S_h, was identified by the Eq. (2) below:

$$S_h = \frac{F_a}{F_0} \quad (2)$$

where:

F_0: the maximum force of the test samples before subjecting to the damage-healing cycle.

F_a: the maximum force of the test samples after subjecting to the damage-healing cycle.

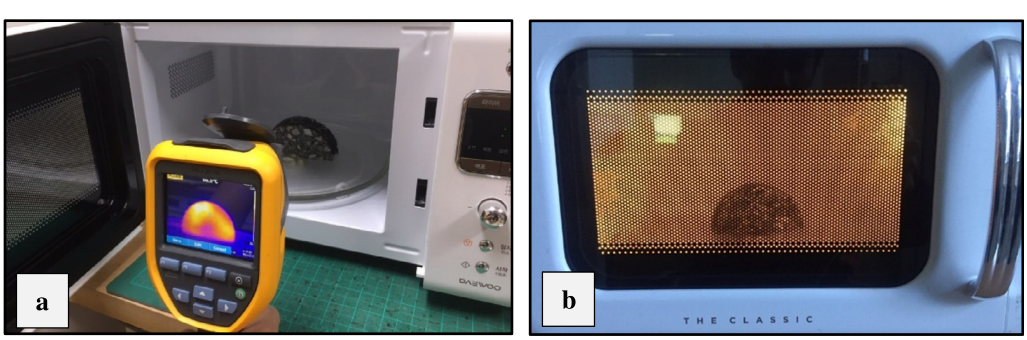

Fig. 3. Thermal transmitting recording: (a) Using an infrared camera to measure the surface temperature of the test specimen; (b) Microwave heating process.

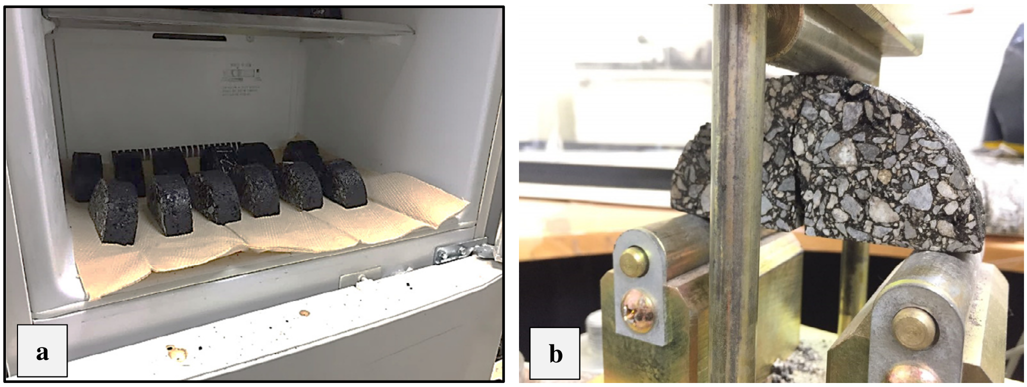

Fig. 4. Damage-healing cycle: (a): brittle condition preparation at −18 °C; (b) TPB test specimen under testing.

3. Test result and discussion

3.1. Thermal distribution evaluation

Fig. 5 presents the relationship between surface temperature and SWF content of mixtures composed with and without 30 percent steel slag after 50 s microwave heating. The result indicates that samples fabricated with 30 percent steel slag reached higher surface temperature than the control samples. Regards to the control sample without SWF, the slag mixtures gained surface temperature of 1.5 times higher than that of the conventional aggregate mixture.

As can be seen from Fig. 6, adding SWF to the asphalt mixture enhanced its surface temperature to a certain value. The higher the amount of SWF, the faster the temperature increases with time. At the same heating time, 30% steel slag mixtures achieved higher surface temperature than that of the mixture with normal aggregate. Based on preliminary research [6,11,12] and the author team's experience [14], the surface temperature should be controlled at approximately 90 °C to achieve the optimum healing performance. This surface temperature not only provides good healing level but also prohibits the overheating phenomenon. Hence, the desired heating time was investigated for each mixture by thermal test with the infrared camera. Table 6 shows the optimal heating time (in seconds) for each mixture with and without 30% steel slag.

Along the 50 mm height of the specimen, a total of 200 cross-sectional average temperature values were used for thermal analysis. The data were extracted from the infrared camera records of samples after undergoing 50 s in microwave heating. The changes of the surface temperature through the height of the samples of mix F2, SF2, F8, and SF8 were shown in Figs. 7 and 8. Overall, steel slag mixture showed a better thermal distribution with

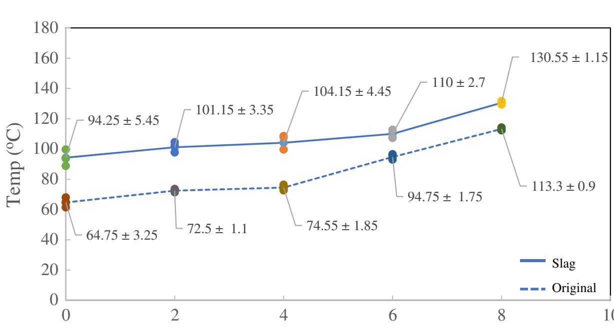

Fig. 5. The surface temperature of HMA mixture with and without 30% steel slag after subjecting to 50 s microwave heating.

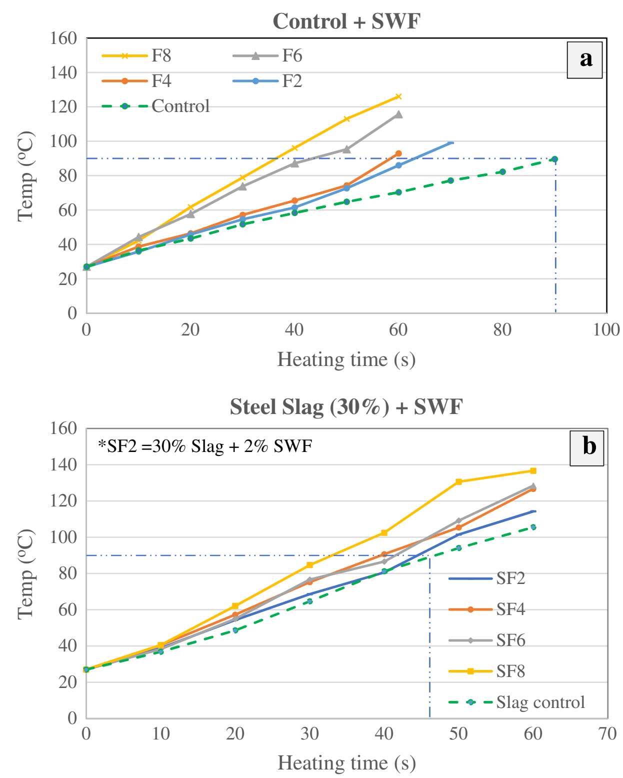

Fig. 6. The surface temperature of SWF mixtures with normal aggregate (a) and with 30% steel slag (b).

homogeneous values compared to that of the original aggregate mixture. For examples, regards to the height between 15 and 50 mm, the gap between the highest and lowest surface temperature of mix SF2 was approximately 25 °C. Meanwhile, this value of mix F2 was about 45 °C. This may be due to the metallic particle of steel slag has better microwave heat absorption which enhances the heat distribution in the whole HMA sample.

However, both types of aggregate samples shared the same trend in surface temperature when the SWF content was increased. It can be seen from both Figs. 7 and 8 that lower SWF content provided much better thermal distribution. For examples, mix F2 and F8 showed a range of variation of 40 °C–90 °C and 50 °C–150 °C, respectively. The test result indicated that the surface temperature of mixtures with 8% SWF varied significantly, especially for mixtures without steel slag [14]. The issue may be attributed to the fibers agglomeration caused by the high fibers content during the mixing process.

Table 6
Optimal heating time for test mixtures.

	0% SWF	2% SWF	4% SWF	6% SWF	8% SWF
Normal Aggregate	90 s	67 s	60 s	45 s	38 s
30% Steel Slag	47 s	44 s	42 s	38 s	33 s

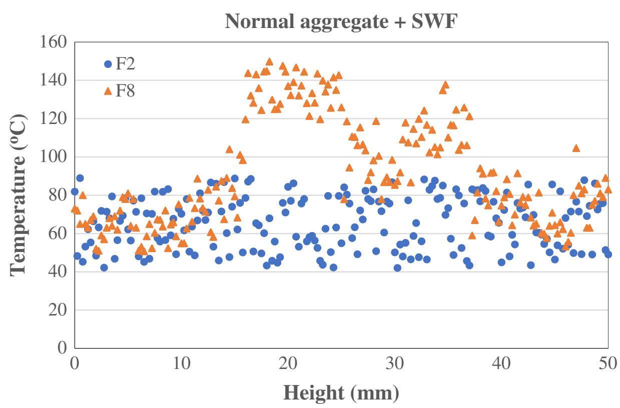

Fig. 7. Thermal distribution of mixtures with normal aggregate.

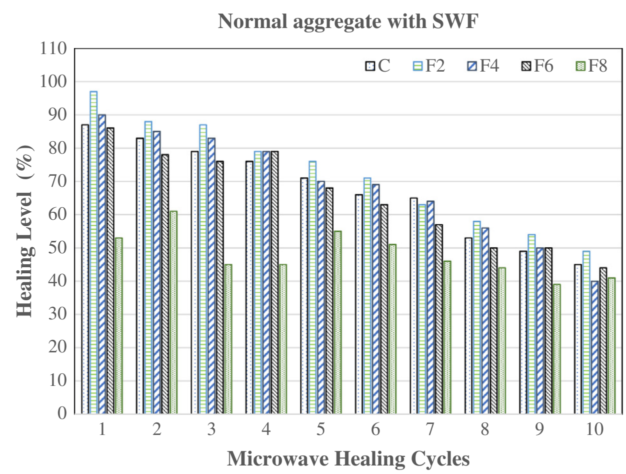

Fig. 9. Healing performance of mixtures with SWF and normal aggregates.

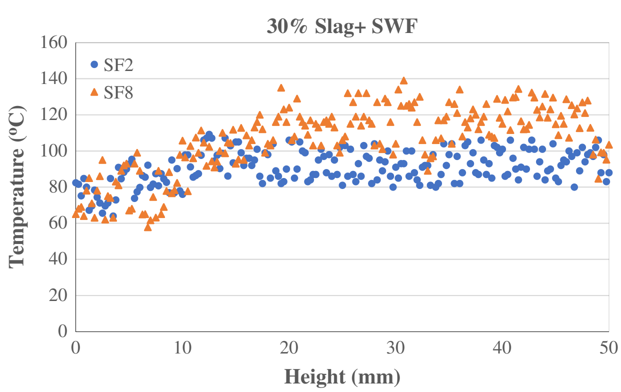

Fig. 8. Thermal distribution of mixtures with 30% steel slag.

3.2. Healing performance

In the following evaluation, the optimal heating time from Table 6 was applied for each mixture to achieve the surface temperature of approximately 90 °C. As mentioned before, this desired temperature will generate acceptable healing performance for HMA samples with low chance of overheating. For each mixture, three semi-circulate samples were used as replicates for average calculation.

Fig. 9 shows the healing effectiveness of convention aggregate samples fabricated with different SWF contents via microwave heating method. In general, the healing performances of SWF mixtures with normal aggregates decreased gradually after 10 cycles and most samples remained healing level higher than 40% at the last cycle. All mixtures obtained a certain healing effectiveness with different improvement results. Among them, mix F2 achieved the highest value which had the healing performance of 76% and 49% after 5 and 10 cycles respectively. This result agrees with the thermal transmitting results recorded by the infrared camera. As mentioned before, mix F2 had the best fiber distribution with the rare sign of fibers agglomeration. The healing performances of mixes F6 and F8 were the lowest. It may be due to the overwhelming use of SWF content created SWF-cluster. This formation not only caused bad thermal distribution but also made overheating phenomenon of asphalt binder.

At late cycles, almost all samples showed brittle behavior since many damaged-healing cycles lead to the degradation of bitumen. Some researches indicate that the internal pressure of the mixture caused by the gases during bitumen heating process may help bitumen to flow into the crack (crack healing). However, asphalt samples with a high percentage of SWF cluster formation may not only cause the internal pressure escaped outside the samples but also critically soften the nearby asphalt binder and thereby, leading to collapse of the whole mixture. This problem appeared at late cycles and damaged the samples (Fig. 10). Interestingly, damaged samples still can be healed with low healing performance. Hence, two percent of SWF or less is recommended in the future research because of the cost-effective objective.

The healing results of SWF mixture made by steel slag aggregate are presented in Fig. 11. It can be concluded that adding 30% steel slag as coarse aggregate to SWF mixture generated better healing performance compared with the normal one. Slag aggregate samples restored the healing performance of higher than 90% until the fourth cycle. Whereas, this value of conventional aggregate dropped below 88% after the second cycle. Slag aggregates with two percent SWF (SF2) had the highest healing performance of 82% after five cycles, which is approximately 6% higher than that of mixes with normal aggregates. This improvement may be due to the higher sensitivity of steel slag particle to microwave radiation.

Mixtures with 8% SWF suffered to the largest drop with healing level lower than 60% after the second cycles. This critical healing reduction can be explained by the inhomogeneous distribution of SWF which may cause overheating phenomenon of the binder. Hence, crack sealing process was significantly slow due to the low flowability of aged asphalt binder with high viscosity. Overall, test data suggests that only mixture with two percent SWF show the desired enhancement, whereas slag mixtures with 4, 6, and 8% SWF have lower healing level compared to the original one. Among four levels of fiber addition (2%, 4%, 6%, 8%), two percent is the recommended to conduct in further study.

Fig. 10. Overheat sample.

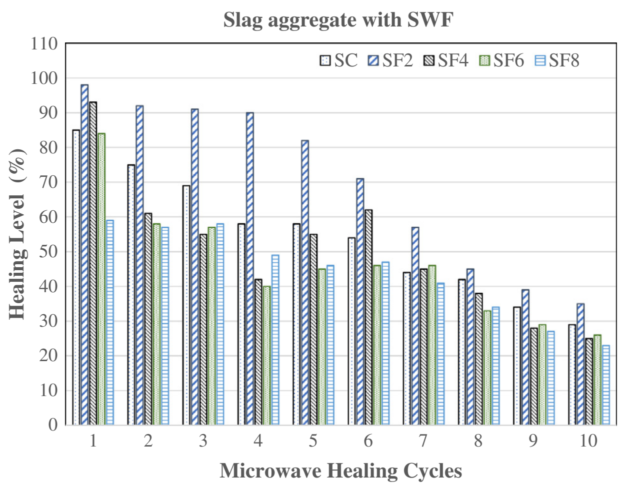

Fig. 11. Healing performance of mixtures with SWF and steel slag aggregates.

3.3. Load-displacement behavior

When using microwave heating technique, mixtures with different SWF contents yielded relatively equivalent load-displacement relationship throughout 10 cycles. Hence, two percent SWF samples from both types of aggregate mixtures were used to represent this link. Due to the vast data collected from the tests, their behaviors were illustrated after 0, 1, 4, and 8 cycles to simplify the trend description.

Fig. 12a shows the load-displacement behavior of mixture containing 100% original aggregate and two percent SWF. At early cycles, ductile behavior was witnessed in all test samples after they reached the maximum load. After this threshold, it is shown that the displacement of mix F2 increases significantly with small load reduction. On the other hand, late cycles-samples showed a much brittle trend with abrupt failure and they achieved remarkably low peak load. This phenomenon can be explained by the oxidization and aging of binder caused by microwave heat throughout many damage-healing tests.

The load-displacement relationship of 30% steel slag mixture with two percent SWF are shown in Fig. 12b. With a substitution of 30% steel slag, this by-product provided the higher ductile behavior for test samples compared to that of original aggregate mixtures, especially at early cycles. It can be explained that metal particles from steel slag has higher ductile characteristics than the conventional aggregate particles and thereby, improving the flexibility of the whole mixture. At late cycles, steel slag mixtures followed the same trend as described in the original aggregate mixtures with very low sign of healing effectiveness, brittle behavior, sudden failure and low peak load.

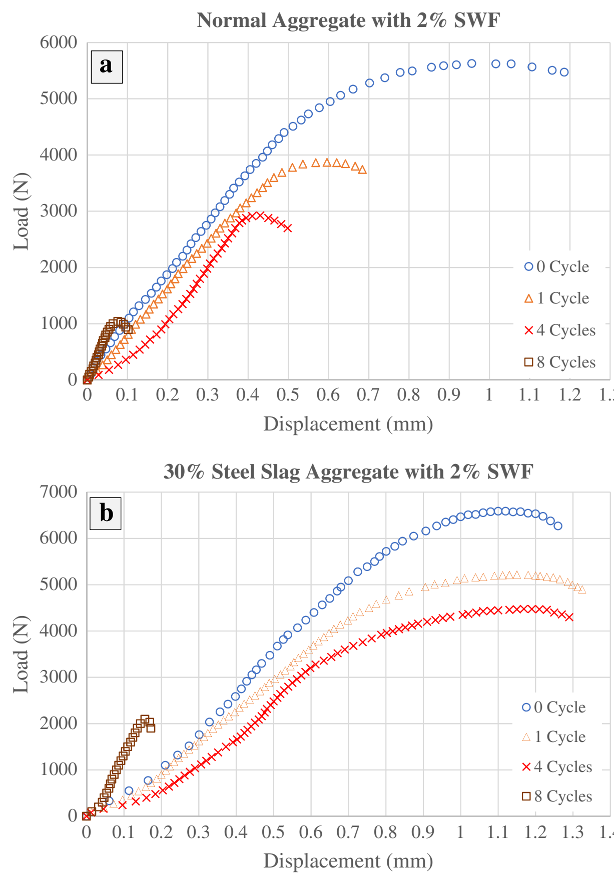

Fig. 12. The load-displacement behavior of two percent SWF mixtures with (a) normal aggregate; (b) 30% coarse slag aggregate.

3.4. Crack formation evaluation

The TPB test machine automatedly released the stress when the failure of sample triggered. Based on the research data, there were three types of crack formation after this process:

- Type one: Hairline crack (Fig. 13a). This crack-type was mostly recorded from early cycles-samples. It can be explained that the test sample remained the high stability and damage resistance. However, if the coarse aggregate of samples was broken, the healing performance would be significantly low as shown in Fig. 13b.
- Type two: Half-way crack (Fig. 13c). The mouth of the crack was widely separate at the notch point, but the sample was still intact in one piece.

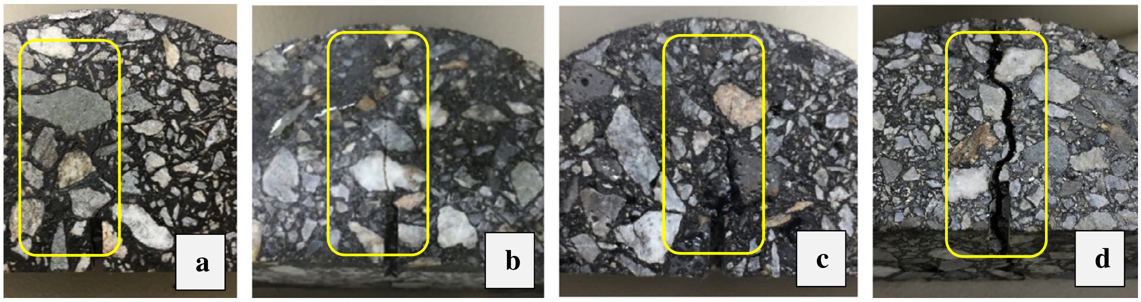

Fig. 13. Sample with broken aggregate.

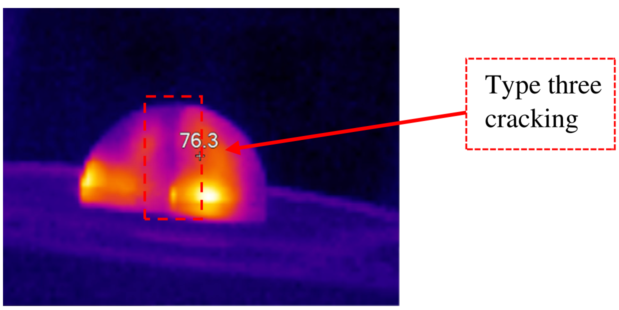

Fig. 14. Thermal transmitting of type three cracking.

- Type three: The sample was cracked into two separate pieces (Fig. 13d). This formation of crack was easily witnessed at late cycles of test specimens. As can be seen from Fig. 14, the thermal transmitting in "type three crack" was prohibited at the vertical mid-point of the sample. There was an empty zone which surrounded the opening crack. This space caused the heat dissipation and lowered the healing effectiveness.

Therefore, the healing performance will vary remarkably depending on the crack formation. Based on the above discussion, microwave heating method will provide the best healing performance for very small crack formation named hairline crack. The effectiveness may be reduced gradually when the gap of the crack increases through time.

4. Conclusion

This research aims to evaluate the healing effectiveness of HMA containing steel slag aggregate and SWF by using microwave heating technique. To obtain the optimum temperature for crack healing, the thermal transmitting was first recorded by an infrared camera to determine the required heating time for each mixture. After this test, 10 damage-healing cycles were conducted to investigate the healing performance of the test samples. To acquire the optimum healing performance, the microwave heating time was modified for each mixture to reach the surface temperature of about 90 °C. A series of test results showed promising signals that steel slag can be utilized for self-healing purpose of HMA. The following results can be drawn from this manuscript:

- Via microwave heating method, it is valid to add coarse steel slag as a replacement of normal aggregate to promote the healing process of HMA.
- At the same heating time, 30% steel slag mixture showed higher surface temperature with homogenous thermal distribution compared to that of the original aggregate mixture at all level of SWF content. It can be explained by the sensitive metallic behavior of the steel slag particle to microwave.
- The healing performances of mixtures with both aggregates types decreased gradually throughout 10 damage-healing cycles to a certain level. Of all level of SWF contents, the test result suggested that two percent SWF mixture produced the best healing effectiveness.
- The healing level of the conventional aggregate mixture was below 88% after the second damage-healing cycle. Meanwhile, this value of steel slag samples remained more than 90% until the fourth cycle. Hence, it can be concluded that the incorporation of 30% steel slag provides better healing effectiveness when the SWF content was controlled at two percent.
- At early healing cycles, steel slag aggregate samples not only yielded the same load-displacement, but it also generates better ductile behavior compared to the conventional mixture due to its particles characteristic. At late cycles, they showed brittle behavior with sudden failure. This phenomenon can be explained by the oxidization and aging of asphalt binder.
- The healing performance of asphalt mixture depends on the crack formation. The effectiveness will reduce gradually when the crack becomes larger.

Conflict of interest

None.

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