Journal of Cleaner Production 152 (2017) 429–442

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Utilization of steel slag as aggregate in asphalt mixtures for microwave deicing

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A R T I C L E I N F O

Article history:
Received 4 December 2016
Received in revised form
6 March 2017
Accepted 17 March 2017
Available online 27 March 2017

Keywords:
Steel slag
Aggregate
Asphalt mixtures
Microwave deicing
Utilization

A B S T R A C T

Under the dilemma of non-renewable natural resources shortage and environmental pollution issues, as a novel aggregate used in asphalt pavement, the application of steel slag is propitious to the improvement of the environment and the enhancement of economics. Meanwhile, steel slag has great potential for microwave heating as an excellent microwave absorbing material, which can contribute to remove the ice layer on the pavement. The primary objective of this work was to explore the feasibility of the usage of steel slag as the aggregate of asphalt mixtures for microwave deicing, and ascertain the most effective volume and particle sizes for partial replacement of conventional aggregate. The deicing mechanism of microwave heating pavement was firstly introduced. Then, the microwave heating capacity of steel slag with different particle sizes was tested and the surface elements distribution of steel slag was measured. In addition, the XRD test was conducted to analyze the material information of steel slag for its microwave heating capacity. Finally, the surface temperature, thermal conductivity and heating uniformity of asphalt mixture containing different steel slag content were tested. Results show that the particle sizes of 9.5 mm, 2.36 mm and 0.6 mm are considered as the most effective sizes. The thermal conductivity and microwave heating uniformity of asphalt mixtures basically decrease with the increase of steel slag content; while the surface temperature presents a contrary trend. Consequently, the suggested steel slag volume content is 40% and 60%; and the particle sizes of steel slag are selected as 9.5 mm, 2.36 mm and 0.6 mm. The comprehensive evaluation results on the supply sources, environmental hazard and cost of steel slag show great feasibility of its utilization in asphalt mixtures for microwave deicing, which is helpful to alleviate the supply shortage of natural aggregates and improve the safety of road traffic in winter.

1. Introduction

In China, more than 90% expressways are constructed with hot-mix asphalt mixtures (HMA) (Chen et al., 2016; MOT, 2015). The increase of road construction imposes considerable pressure on raw building materials, especially on natural aggregates. Substitution for natural aggregates is urgently needed in order to alleviate the supply problem and help to save the dwindling natural resources.

The steel industry has been the important part of the mainstay industries of China in the past decades. As a main solid by-product of iron and steel smelting industry, steel slag is accounting for about 10%–15% of the crude steel production. Currently, China is facing a challenge on more than one billion tons of steel slag accumulations due to its less than 50% recycling rates (Guo and Shi, 2013). Consequently, a series of environmental issues, e.g. land occupation, water pollution and heavy metal pollution are caused. Obviously, recycling of steel slag in asphalt mixture is a promising way to save natural resources and reduce environmental pollution. The literature reviews demonstrate that the asphalt mixtures with steel slag possess not only higher stiffness and lower permanent

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http://dx.doi.org/10.1016/j.jclepro.2017.03.113

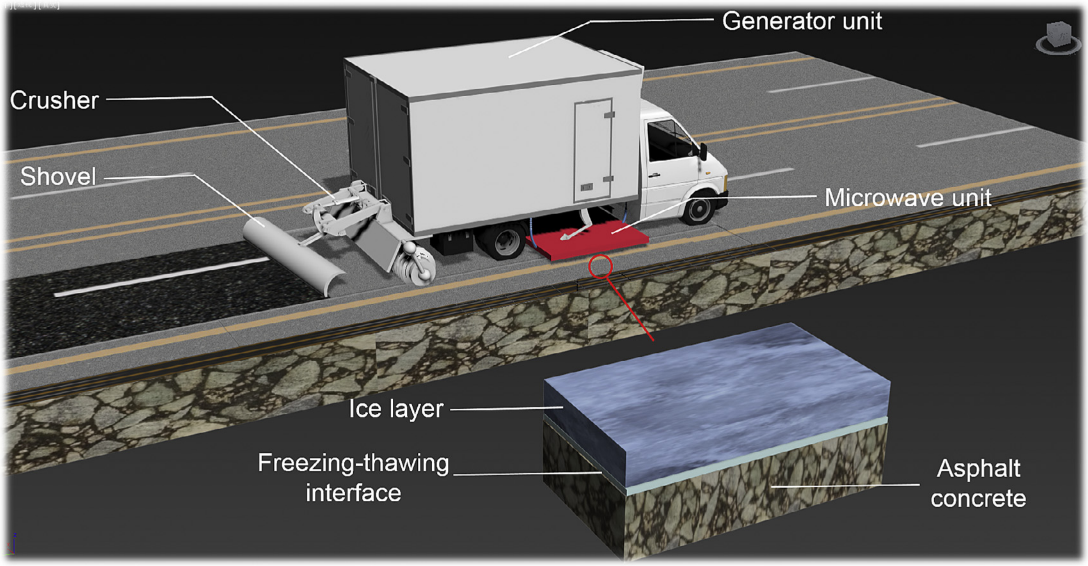


Fig. 1. Working mechanism of the MH vehicle.

Table 1
Basic physical performance of steel slag and limestone.

Aggregate	Apparent specific gravity (g/cm^3)	Soaking swelling ratio (%)	Water absorption (%)	Crushing value (%)	Los Angeles abrasion (%)
steel slag	3.276–3.341	0.9–1.1	1.2–2.6	14.2	12.7
Limestone	2.772	0.4	0.71	20.4	18.4
Criteria in China	≥2.5	<2	≤3	≤22	<26

deformation but also better fatigue, aging and abrasion resistance in contrast to conventional asphalt mixtures (Huang et al., 2012; Xie et al., 2013; Wen et al., 2016; Kanitpong and Bahia, 2003). However, as a kind of magnetic material, the microwave heating function of steel slag is totally neglected in pavement engineering.

Microwave heating (MH) technology has numerous applications in various industrial processes; and it has also been used in the field of highway engineering as a technique of bituminous materials hot-recycling (Benedetto and Calvi, 2013). Nowadays, the traffic safety in winter is becoming a prominent problem because of the pavement was covered with thick ice layer, which is difficult to be

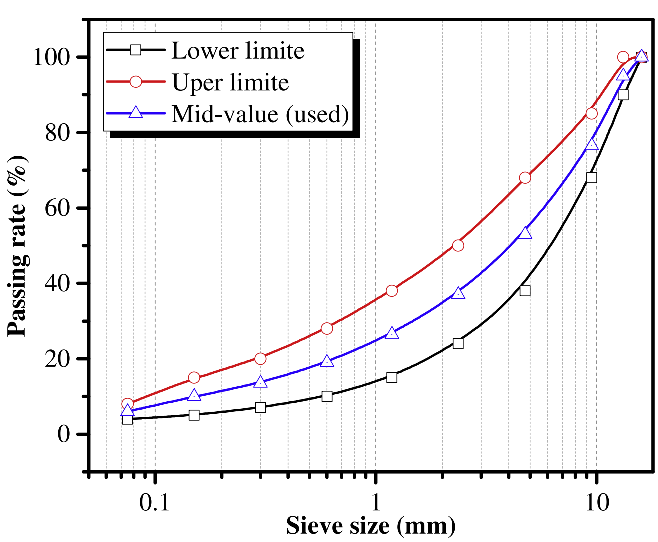


Fig. 2. Gradation curve for AC-13.

removed via the MH technology due to the considerably limited MH efficiency of conventional aggregate used in asphalt mixtures. Therefore, the surface temperature of asphalt mixture containing taconite under microwave radiation was carried out for the first time in 1989 (Osborne and Hutcheson, 1989). Then, the adoption of microwave absorbing materials to pavement materials has become the main methodological in this field. For example, Hopstock (2005) measured the heat capacity, thermal conductivity and microwave absorption coefficient of taconite asphalt mixtures, and established microwave heating model of pavement. Utilization of taconite as aggregate in asphalt mixtures is practical now. (Zanko et al., 2008, 2009; Oreskovich et al., 2008).

In addition, Wang et al. (2014) studied the influence of carbon fiber content on the mechanical properties, microwave reflectivity and microwave deicing function of micro-surfacing asphalt mixtures. Besides, Wang et al. (2011) also conducted a series of experiments to investigate the effect of carbonyl iron powder on the microwave absorbing property of asphalt mixture. Increasing the self-healing rates of asphalt concrete is another application of MH. Gallego et al. (2013) presented the microwave heating test on steel wool asphalt mixtures and indicated that the surface temperature reached 140 °C after 120s microwave radiation. Liu et al. (2014) comparatively studied the MH self-healing rate of asphalt mixtures with different steel wool lengths and contents.

Conventional deicing methods, such as ice-crushing vehicle, snow-blower are failure to perfectly remove the thick ice layer on the pavement resulting from the presence of freezing adhesion action on the interface between ice layer and pavement surface. As is well known (Zou et al., 2011), the freezing adhesion level of material is negatively correlated with atmospheric temperature, which means that the freezing adhesion interface can be efficaciously melted by increasing its temperature.

Table 2
Mix proportion for Marshall specimens.

Replacement	Sieve size (mm)														
	16	13.2	9.5		4.75	2.36		1.18	0.6		0.3	0.15	0.075	filler	Asphalt/Aggregate ratio
			LS	SS		LS	SS		LS	SS					
SS-0	0	59	219	0	279	190	0	124	89	0	65	41	47	71	4.7%
SS-20%	0	59	175.2	51.6	279	152	44.8	124	71.2	21	65	46.2	47	71	4.6%
SS-40%	0	59	131.4	103.2	279	114	89.6	124	53.4	42	65	46.2	47	71	4.5%
SS-60%	0	59	87.6	154.9	279	76	134.4	124	35.6	62.9	65	46.2	47	71	4.5%
SS-80%	0	59	43.8	206.5	279	38	179.2	124	17.8	83.9	65	46.2	47	71	4.4%
SS-100%	0	59	0	258.1	279	0	223.9	124	0	104.9	65	46.2	47	71	4.3%

Note: LS is representing for limestone; SS is representing for steel slag.

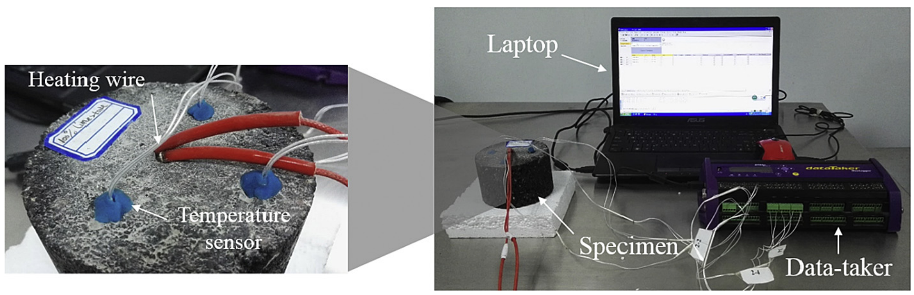


Fig. 3. Thermal conductivity test system.

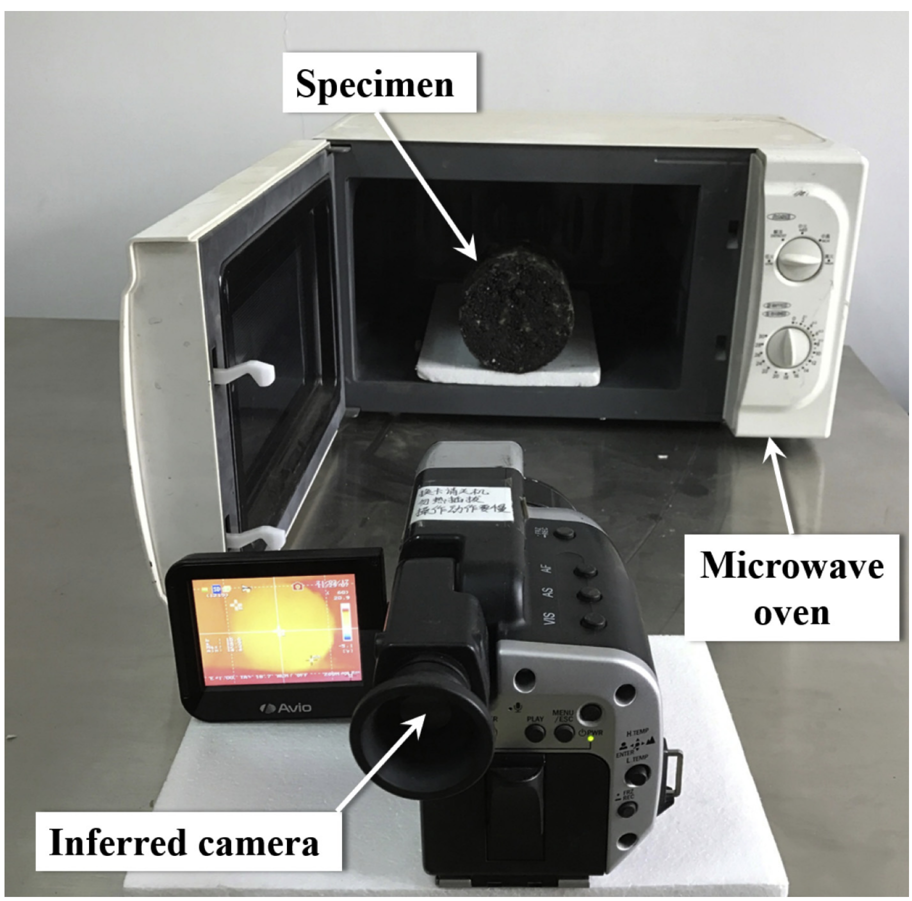


Fig. 4. The setup for capture surface temperature image.

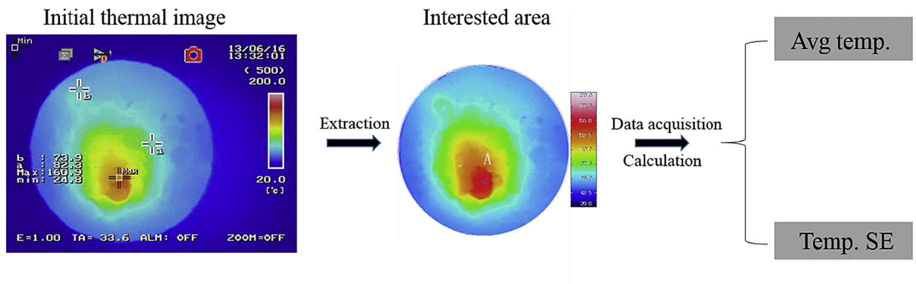


Fig. 5. The process of surface temperature test.

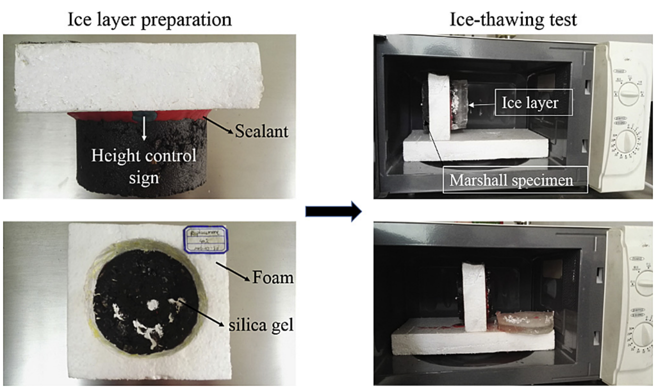


Fig. 6. The process of ice layer preparation and ice-thawing test.

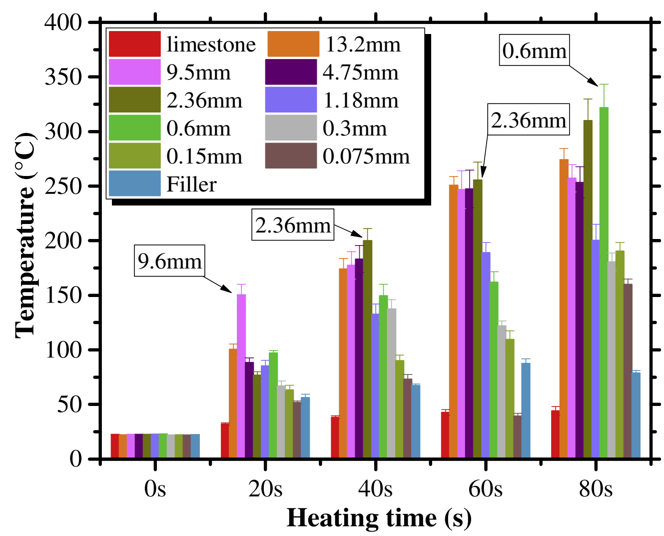


Fig. 8. Surface temperature of 10 particle sizes with different radiation duration.

Generally, two stages are involved in the process of MH dicing. Stage one is that the pavement surface temperature increases from negative temperature to 0 °C under the microwave irradiation, in which the freezing adhesion level is barely existed. In the following, both pavement and the water from melting ice are heated synchronously in the stage two. As a result, more ice layers are melted into water accompanied by the continued microwave irradiation. In conclusion, the best opportunity for deicing is between stage one and stage two. The reason is that the freezing adhesive interface is still having a high strength before the completion of the stage one; and the water melting from ice layer is highly intending to re-freezing under low-temperature atmosphere after the stage two. The pavement MH deicing draws support from external device, including the microwave generator and deicing vehicle. MH vehicles in China have been well developed, and their schematic diagram is shown in Fig. 1. In the process of the vehicle movement, the microwave unit plays the role of heating the pavement. After the melting of the freezing adhesion interface, ice layer is minced by the crusher and is pushed to the road side by the shovel.

Based on the above discussion, utilization of steel slag as aggregate for improving microwave deicing performance of asphalt mixtures has been paid few attentions. Therefore, a novel application of recycling steel slags for microwave deicing asphalt pavement is designed in this work. Specifically, the first purpose is to confirm the validity that the steel slag as the aggregate of asphalt mixtures has the vastly MH ability. On the other hand, as a bitumen-consumption aggregate owing to its porous characteristics (Xie et al., 2012), the second purpose is to ascertain the effective volume and particle sizes for replace conventional aggregate in asphalt pavement, which is helpful to remove the economic barriers of its application. Therefore, the deicing mechanism of MH pavement was illustrated. The MH capacity of steel slags with different particle sizes was measured to determine the most effective particle sizes for replacement. Meanwhile, the surface elements distribution of steel slag was measured to reveal the

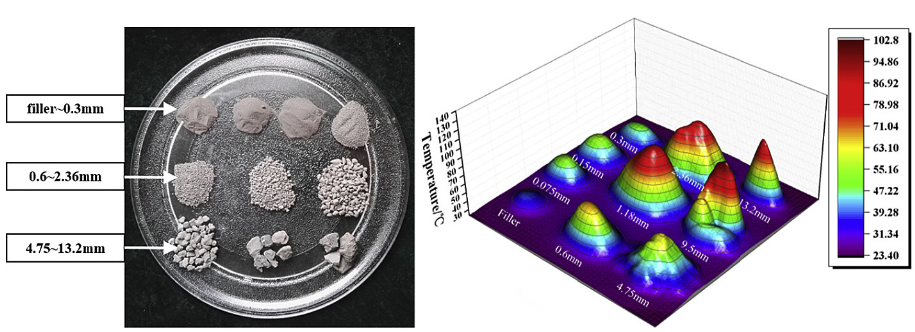


Fig. 7. Thermal image of particles (after 15s radiation).

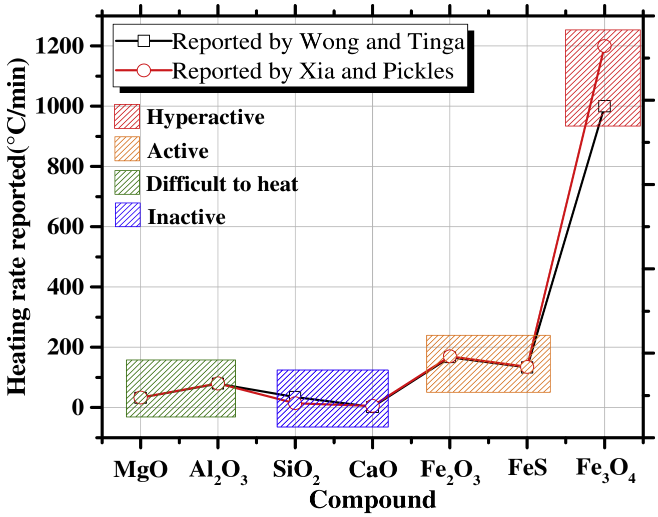


Fig. 9. Microwave heating behavior of common metal oxides.

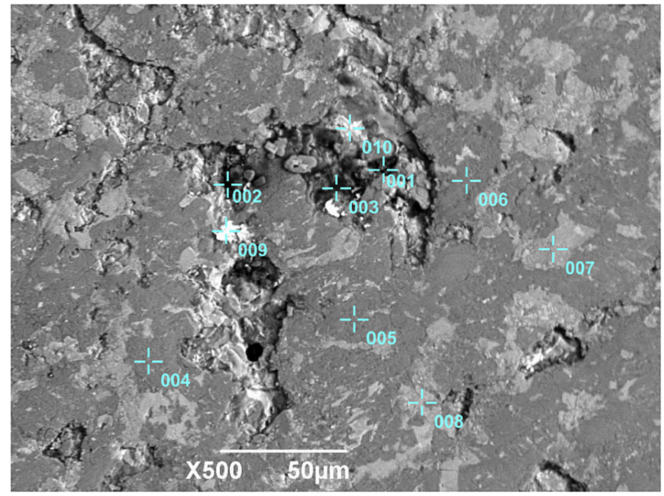


Fig. 10. The micrographs of steel slag.

Table 3
The element distributions on the surface of steel slag.

No.	O	Si	Ca	Fe	Mg
	Mass%	Mass%	Mass%	Mass%	Mass%
Black calcium silicate phase					
01	39.51	9.54	31.66	1.25	0.65
02	15.19	9.10	40.90	4.21	0.64
03	25.86	10.35	35.72	1.88	0.47
Gray calcium-iron phase					
04	32.81	11.71	44.96	2.05	1.98
05	33.34	8.12	42.72	2.75	2.12
06	31.78	11.63	43.07	4.33	2.57
White iron-magnesium phase					
07	24.00	0.24	1.44	46.04	19.70
08	20.22	1.17	5.77	43.60	20.48
09	7.23	0.39	2.51	83.54	4.12
10	17.63	0.35	4.17	59.40	11.62

active ingredient and XRD patterns for steel slag and limestone were obtained to study their mineral component. In addition, the surface temperature, thermal conductivity and heating uniformity of asphalt mixtures containing different steel slags content were tested to recommend the optimal steel slag content. Finally, the comprehensive feasibility of steel slag asphalt mixture was studied via jointly considering its sources distribution, ecological hazardous,cost performance and potential overheating problem.

2. Methods

2.1. Materials

Basic oxygen furnace slag was manufactured by crushing dense slag blocks selected from a Chinese Iron and Steel Group. Conventional aggregate was limestone aggregate. The properties of steel slag and limestone were tested in accordance with the *Testing Procedures of Aggregate for Highway Engineering in China (JTG E42-2005) (Inspection and Quarantine of the People's Republic of China, 2005)*, the results are summarized in Table 1.

2.2. Sample preparations and tests

2.2.1. Preparation of the specimens

Aggregate gradation is shown in Fig. 2. Due to the higher specific density in comparison with limestone, the principle substitution is to replace the limestone by volume with the most effective sizes of steel slags. Six replacement levels were designed from 0 to 100 vol% (20 vol% increment). Marshall tests were conducted to determine the optimal asphalt aggregate ratio for SS-0 (mixture without steel slag), then the asphalt weight for SS-0 was remain unchanged in the rest specimens. The mix proportion for Marshall specimen is presented in Table 2.

2.2.2. Microwave heating capacity and elements distributions test of steel slags

The steel slag was sieved into 10 particle sizes (filler to 13.2 mm) after the crush by using a jaw crusher. Each particle size is selected as a test group; ten groups of MH test samples were selected from steel slags with different particle sizes (filler to 13.2 mm). The mass of each group was 160 g and equivalent quartered for 4 duration of microwave irradiation (20s-80s), 20s increment each time. The MH device was microwave oven, whose power and microwave transmission frequency was 850 W and 2.45 GHz, respectively. To ensure the accuracy of the test, each test was conducted three times. In addition, elements distribution of steel slags was measured by electron probe micro analysis (EPMA). Moreover, the XRD test was conducted to study the mineral components difference between steel slag and limestone thereby provide the material information of steel slag for its microwave heating capacity.

2.2.3. Thermal conductivity test of Marshall specimens

The *standard of determination of thermal conductivity — Parallel hot-wire method (GB/T 5990-2006) (Inspection and Quarantine of the People's Republic of China, 2006)* was referenced in this work. Fig. 3 illustrates the frameworks of the system, which comprising laptop, data-taker, hot wire (HW) and temperature sensors (TS). Ni-Cr alloy hot wire with 4 mm diameter, 50 mm length and 60 W power was used. The specifications of TS are 2 mm diameter, 30 mm length, 0.15 °C error and its working range is within −50 °C to −200 °C. Additionally, to improve the accuracy of test results, three TS were arranged.

The vertical holes in the Marshall specimen for place HW and TS were made by a mini-type drilling machine with corresponding size drills. The hole for HW is located at central position of the upper surface of the Marshall specimen, and three holes for TS are equidistant (r = 2 cm ± 5 mm) to the center hole. The sealant was settled when HW and TS were addressed. In addition, the test begins when ambient temperature fluctuation is below 0.3° within

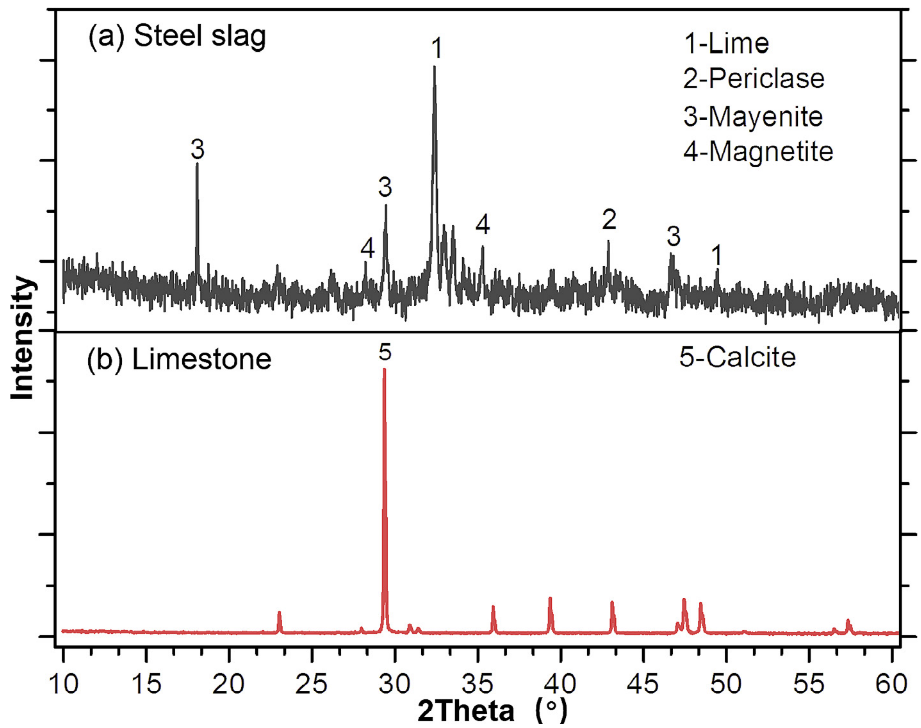


Fig. 11. XRD pattern for steel slag and limestone.

2 min and the data-taker records the data once every 5 s. According to the standard, the time-temperature graph can be drawn to calculate the thermal conductivity (k) by Eq. (1)

$$k = \frac{q}{4\pi l}\frac{E_i\left(\frac{r^2}{4\alpha t}\right)}{\Delta\theta(\mathrm{t})} \tag{1}$$

Where, $\Delta\theta(t)$ is the temperature difference after heating time t (s), °C; q is the heating wire power, W; l is the length of heating wire, m; α is the thermal diffusion coefficient, m^2/s; k is the thermal conductivity, W/(m·K); E_i is the abbreviation of exponential integral; γ is the Euler constant.

When the value of $\frac{\Delta\theta(2\mathrm{t})}{\Delta\theta(\mathrm{t})}$ is determined by acquired time-temperature graph, the value of $E_i\left(\frac{r^2}{4\alpha t}\right)$ can be found in the standard (*GB/T 5990-2006*). Thus, the k value can be calculated by Eq. (1).

2.2.4. Surface temperature test

The R500EX inferred camera was adopted to capture the surface infrared image of specimens. It possesses the properties of 640 × 480 image resolutions, 0.87 mrad spatial resolutions, 0.03 °C sensitivity and ±1 °C error ranges. The temperature capture setup is shown in Fig. 4.

To quantitatively evaluate the heating uniformity, the interested area was extracted from the initial infrared image by software (Inf Rec Analyzer) to export the matrix of temperature data. Then, the average temperature and temperature standard deviation can be acquired. The higher value of standard deviation (SE), the more inferior uniformity it is. The process is illustrated in Fig. 5.

2.2.5. Microwave heating thawing time test

In the preparation process of ice layer, the foam collar was mounted on the specimens, then the interspace between foam collar and specimen was filled with sealant. In addition, the top surface holes were sealed by thermally conductive silica gel to hold the water. Specimens were placed in a freezer after the injection of water to foam collar. In the MH thawing time test, the specimens were putted into the microwave oven, and the thawing time was recorded through observing that the ice layer was totally fell off from the specimen surface. The method of ice layer preparation and ice-thawing test is shown in Fig. 6.

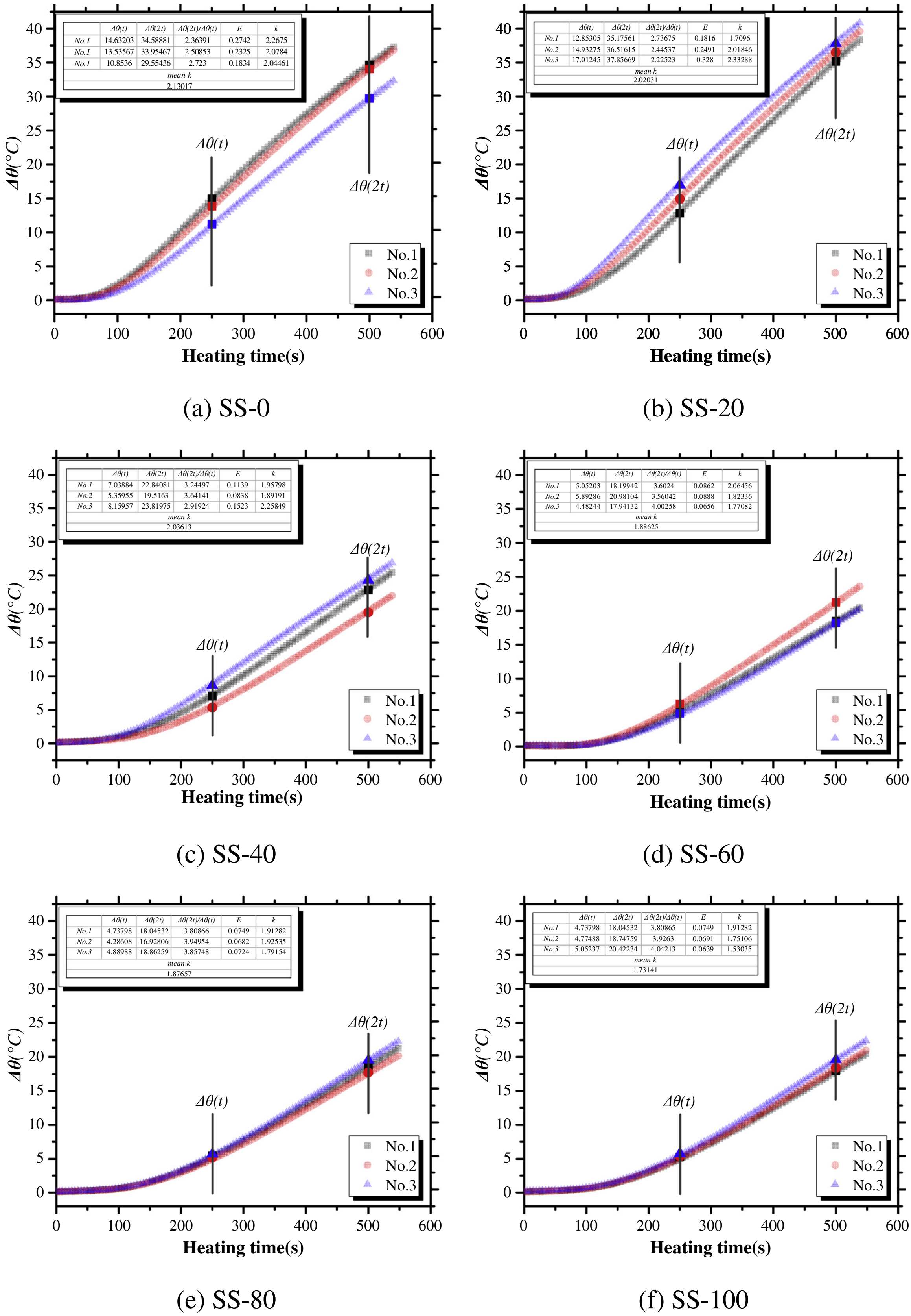
3. Results and discussion

3.1. Microwave heating capacity of steel slags

In order to determine whether the different sizes of steel slag have similarly MH performance, the steel slags with 10 different particle sizes (filler-13.2 mm) were placed into microwave oven together and the infrared image was captured after 15 s radiation, the infrared image of their surface temperatures are shown in Fig. 7.

In Fig. 7, the surface temperature difference between steel slags with different particle sizes can be clearly observed. It is known that steel slag is a bitumen-consumption aggregate for asphalt concrete due to its porosity, which certainly has significantly increased manufacturing cost. Therefore, particle size selection of steel slags is critical to enable the asphalt concrete with MH deicing function by using its minimum content. With the purpose to distinguish the MH performance of each particle size of steel slag more comprehensively and specifically, its surface temperature through different duration of radiation is shown in Fig. 8.

The results in Fig. 8 support that the MH capacity of slags is highly related to its particle size. Evidently, the surface temperature of steel slags increases with the increase of its particle sizes. To be specific, the surface temperature of steel slag is maintaining in a correspondingly high level when the particle size is larger than 0.6 mm. On the other hand, the surface temperature of steel slags with smaller particle sizes is still much higher than that of



(a) SS-0

(b) SS-20

(c) SS-40

(d) SS-60

(e) SS-80

(f) SS-100

Fig. 12. Details of k calculation and temperature-time curve.

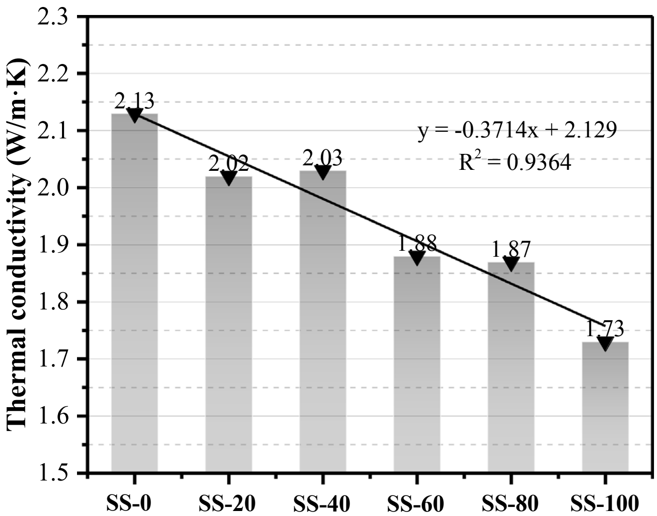


Fig. 13. The results of thermal conductivity.

limestone, though a significant decline in temperature is emerged in contrast to that of larger particle sizes of steel slags. Therefore, the particle sizes with the highest temperature at different duration are considered as the most effectively. In this case, particle sizes of 9.5 mm (20 s), 2.36 mm (40 s, 60 s) and 0.6 mm (80 s) are selected to conduct replacement together.

Previous studies (Xia and Pickles, 1997; Tinga, 1988; Wong, 1975) have a clearly conclusion on the microwave heating behavior of common mineral, as presented in Fig. 9. These results were classified based on the heating rate into hyperactive (Fe_3O_4), active (Fe_2O_3 and FeS), difficult-to-heat (MaO and Al_2O_3) and inactive (SiO_2 and CaO). It demonstrated that microwave energy could be more effectual into heat energy if minerals or inorganic compounds contain higher iron content.

As is known, the main chemical compositions of steel slag are black calcium silicate phase ($3CaO \cdot MgO \cdot 2SiO_2$, $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot 2SiO_2$, $CaO \cdot SiO_2$), gray calcium-iron phase ($CaO \cdot Fe_2O_3$) and white iron-magnesium phase (Fe_2O_3, MgO) (Kryvinska et al., 2005). To determine the existent form of iron in steel slag, the EMPA was carried out to investigate the elements distribution on the surface of steel slag. As shown in Fig. 10 and Table 3, the main component of steel slag is gray calcium-iron phase with inadequate iron content (2.05%–4.33%). The white iron-magnesium phase possesses the highest iron content (43.60%–83.54%); while the black calcium silicate phase merely possesses 1.25%–4.21%. Thus, the most active ingredient for microwave heating existing in steel slag is the white iron-magnesium phase.

In addition, the main mineral components difference between steel slag and limestone can be clearly observed by the results shown in Fig. 11. Limestone basically contains only one mineral, calcite. On the other hand, the steel slag contains multiple minerals, especially the existence of magnetite, which is considered as hyperactive for microwave heating. In summary, the microwave heating capacity between steel slag and limestone can eventually explained by their mineral components difference.

3.2. Thermal conductivity of asphalt mixtures

Fig. 12 presented the details of temperature-time (T-T) curves recorded by TS. As shown in Fig. 12, the relationship between time and temperature is not linear resulting from the unstable current in the beginning of the measurement; and then the temperature is nearly linear with the time when the heat is transfer to the position of the sensors. This remarkable phenomenon can be observed in all time-temperature (T-T) curves. Theoretically, the slope of T-T curve essentially reflects the heating rate of material. Therefore, the slopes of three curves in the same specimen are basically consistent despite the temperature data recorded by three sensors are slightly different, indicating that the thermal conductivity can be precisely determined by using parallel hot-wire method.

In reference to the data provided by Fig. 12, the thermal conductivity (k) of Marshall specimens with different content of steel slag can be calculated, which is illustrated in Fig. 13. The k value of SS-20 and SS-40 is quite close and they decrease 5.16% and 4.22% in comparison with SS-0, respectively. In addition, the k value is evidently declined at SS-60 and SS-80; and their k values are decreased by 11.73% and 12.20% compared with SS-0, respectively. More importantly, the k value of SS-100 is decrease 18.78% in contrast to that of SS-0. Obviously, the results in Fig. 13 indicate that the k value is significantly reduced with the increase of steel slag content. The above phenomena resulting from that the steel slag is a typical porous material and it possesses higher void fraction than limestone. Because the k value of solid components in the steel slag is significantly higher than that of the air, the material with higher void fraction most likely possesses lower k value. Accordingly, the void fraction is higher when more steel slags are used in asphalt mixtures.

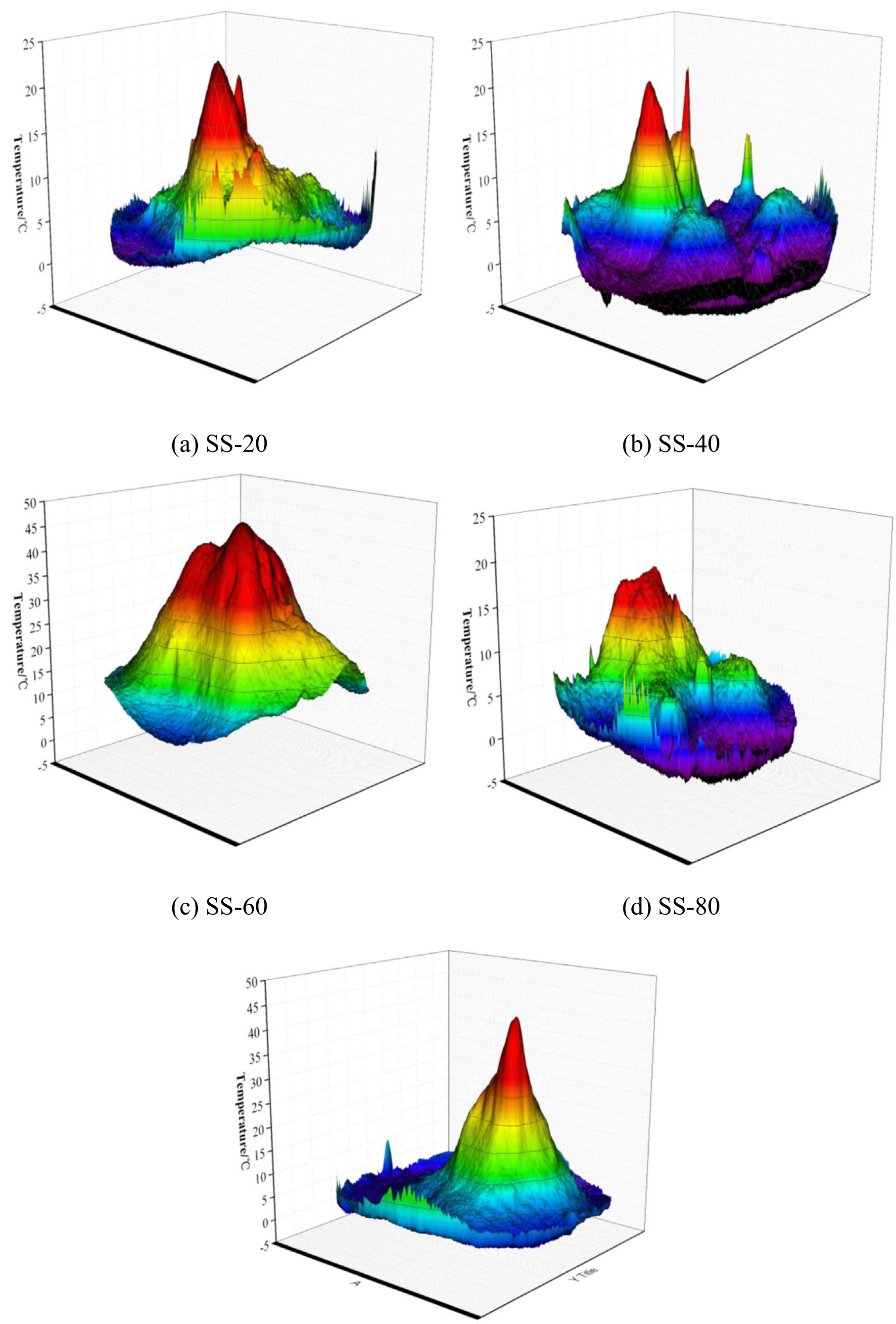
3.3. Microwave heating uniformity

Microwave heating uniformity is another key concern when the MH technology is introduced into the application phase. Technically speaking, the ice layer upon MH pavement will be incompletely removed if the surface of MH pavement possesses too much difference in heating ability. Fig. 14 shows the difference of surface temperature distribution with different steel slag content under 20 s microwave radiation. One or several temperature peaks can be observed in each image, suggesting that the surface temperature distribution is not uniformity as expected.

In order to quantitatively determine the level of steel slag content that can enable the asphalt mixture to have a desirable microwave heating uniformity, the standard deviations of surface temperature at R_0 (20 s for common cold and 60 s for extremely cold) are calculated, as shown in Fig. 15.

In Fig. 15, the standard deviations of surface temperature increase with the increase of the steel slag content. The specimen of SS-0 has optimum MH uniformity because it has the same aggregate composition with limestone. On the other hand, with the increase of steel slag content, the internal temperature distribution of asphalt mixture becomes more unevenly because of the huge difference of MH capacity between steel slag and limestone. Under the microwave radiation, the steel slags are firstly heated; the heat is transferred to the limestone aggregate via the asphalt mortar filled between limestone aggregate and steel slag; then the temperature of limestone aggregate begins to increase. As the heat continues to accumulate, the temperature difference between steel slag and limestone is shrinking until the whole specimen possesses a stable temperature. However, the heat transfer process needs an adequate time and this hysteresis of heat transfer eventually results in the non uniformity of MH pavement. It can be assumed that the MH uniformity can be improved if the asphalt mixtures fully consist of steel slag. However, the heating uniformities of asphalt mixtures are in an acceptable range except SS-80 and SS-100.

As limited by the accuracy internal temperature measurement, the internal heating uniformity of specimen was not conducted. However, the internal temperature can be considered as uniform by giving an appropriate reasoning after make two boundary



(a) SS-20 (b) SS-40

(c) SS-60 (d) SS-80

(e) SS-100

Fig. 14. 3D image of surface temperature.

conditions, which are: a) all steel slag particles are evenly distributed in the mixture and b) the pavement surface is irradiated by incident electromagnetic wave uniformly. This two boundary conditions are not difficult to be achieved through the necessary process. Therefore, the temperature uniformity of any pavement cross section is similar to that of the pavement surface despite the internal temperature and the surface temperature may vary.

3.4. Microwave heating surface temperature

Whether the MH deicing pavement can eventually access to the practical stage depends largely on the fact that whether it has sufficient operating efficiency, which means that its surface temperature should be increased to at least 0 °C with the shortest radiation time as possible. Therefore, the shortest radiation time is highly necessary instead of extremely high surface temperature. Two indicators are designed correspondingly, which are the moment to reach 0 °C for the first time (R_0) and MH thawing time needed. And also, atmospheric temperature that MH pavement working cannot be ignored, thus 2 initial temperatures are set as the common cold (−5 °C) and extreme cold (−20 °C). The results of MH surface temperature are shown in Fig. 16.

In Fig. 16, the none irradiation specimen was placed at room temperature with 180 s, the surface temperature of the specimen is

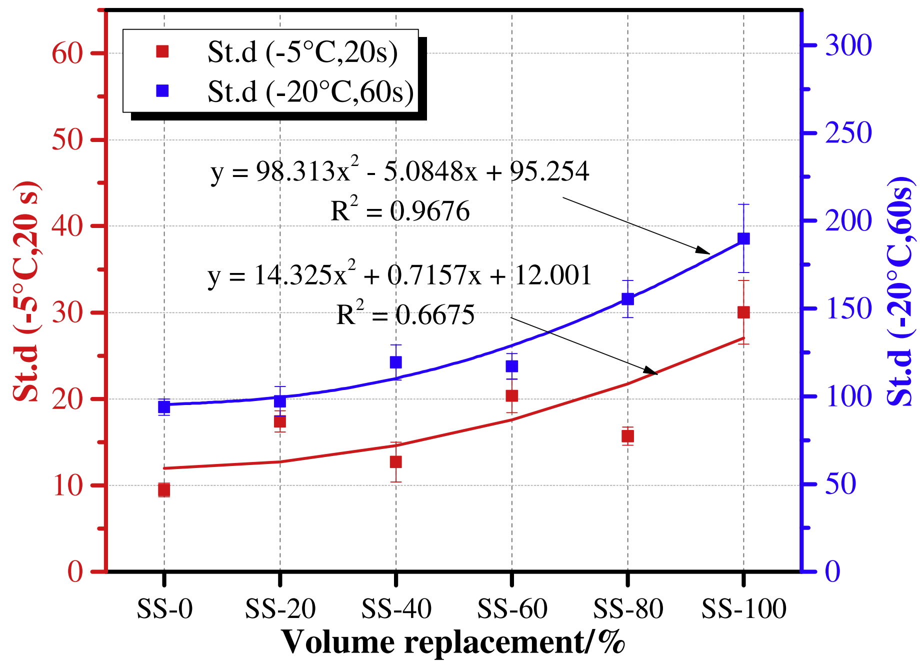


Fig. 15. Standard deviations of surface temperature.

increased approximately 3 °C, indicating that despite this test is carried out in room temperature instead of environmental chamber, but no significant error of results is caused. In general, the surface temperature basically increases with the increase of the steel slag content. It is noteworthy that the surface temperature of SS-100 is not as high as expected and the difference between SS-100 and SS-80 is more indistinctive than that of others. It may result in the lower k value, making the SS-100 possess lower efficiency to conduct heat produced by its own. In Fig. 16(a), when initial temperature condition was −5 °C, the R_0 is 20 s except for SS-0 and SS-20, indicating that both of them present insufficient MH efficiency. In Fig. 16(b), when the initial temperature condition was −20 °C, the surface temperature of all specimens exceeded 0 °C at the 60 s, namely R_0 is 60 s in this case. The results shown in Fig. 16 suggest that the initial atmospheric temperature directly affect the MH efficiency, indicating the lower initial atmospheric temperature leading to the lower R_0 after the same radiation time. And also, after addition of steel slag, the ice layer upon the pavement can be easily removed by deicing vehicle in 20 s and 60 s under common cold and extremely cold condition, respectively. Additionally, a series of laboratory deicing experiments were conducted to verify the authenticity of the above conclusions and the results are shown in Fig. 17.

Due to the limitation of test conditions, the MH thawing test for make exfoliation of ice layer carried out in this research is fully dependent on the gravity of the ice layer instead of any external force. As seen in Fig. 17, the universal rule is that the MH thawing time is reduced dramatically with the addition of steel slag. To be specific, when the initial temperature condition is −5 °C, the MH thawing time can be reduced to 57.5%–67.3% in comparison with SS-0; namely MH efficiency increases about 2.3–3.1 times. Similarly, when the initial temperature condition is −20 °C, the MH efficiency is increased about 2.1–2.6 times. It should be noticed that there is barely significant correlation between steel slag content and thawing times. We speculate that it was caused by the difference in the specimen' surface texture or the limitations of used test method for thawing time test because the absence of the external force application device. Obviously, the deicing efficiency of MH pavement is not highly sensitive to the steel slag content without the help of using external force. However, the practicability of steel slag as microwave-absorbing aggregate for asphalt pavement microwave deicing has been confirmed.

In addition, at the initial temperature conditions of −5 °C and −20 °C, the MH thawing time of the specimens is 35s - 50s, which is longer than its R_0. It indicates that the external force, e.g. deicing vehicle for removing ice layer, is extremely essential. Therefore, another hypothesis confirmed here is that if the ice layer is removed only by continuous heating instead of using external forces, the ice layer can be constantly melted into water as shown in Fig. 18 and can be certainly re-freezing under severe cold environment.

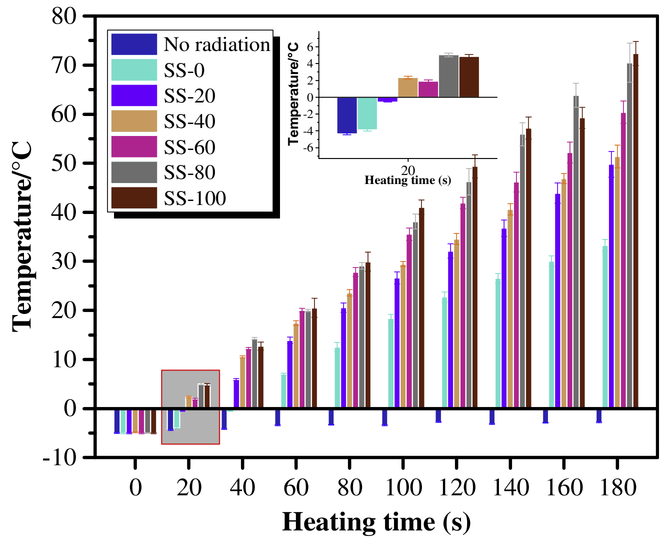
As shown in Fig. 19, based on the discussion on the performances of (a) the moment to reach 0 °C, (b) thermal conductivity, (c) temperature uniformity and (d) thawing time, the recommended steel slag volume contents are 40 vol% and 60 vol% limestone aggregate with 0.6 mm, 2.36 mm and 9.5 mm particle sizes.

3.5. Comprehensive feasibility analysis

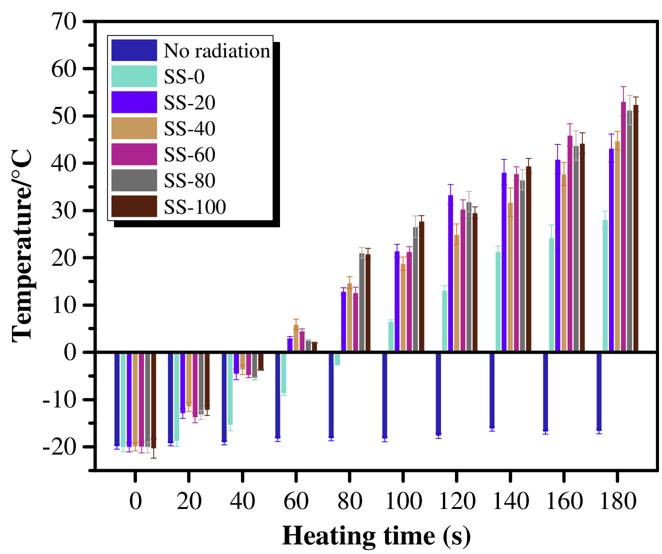
The current greatest challenges for MH pavement are the insufficient development of microwave absorbing materials, higher construction cost but lower efficiency of deicing. Therefore, the exploration of the microwave absorbing materials with performance of the desirable MH ability, low cost and easy access has a decisive impact on the development of the MH pavement. Obviously, after the feasibility of the steel slag as the asphalt pavement microwave heating material has been proved, its practicability should be analyzed to verify that it is suitable for MH pavement.

3.5.1. Sources of steel slag

According to the characteristics of highway construction, the supply of raw materials especially mass freight supply, such as aggregate, sand and gravel, should depend on local resources to reduce its construction cost. To the MH pavement, the used



(a) under common cold condition (-5 °C)



(b) under extremely cold condition (-20 °C)

Fig. 16. Surface temperature of Marshall samples after microwave heating.

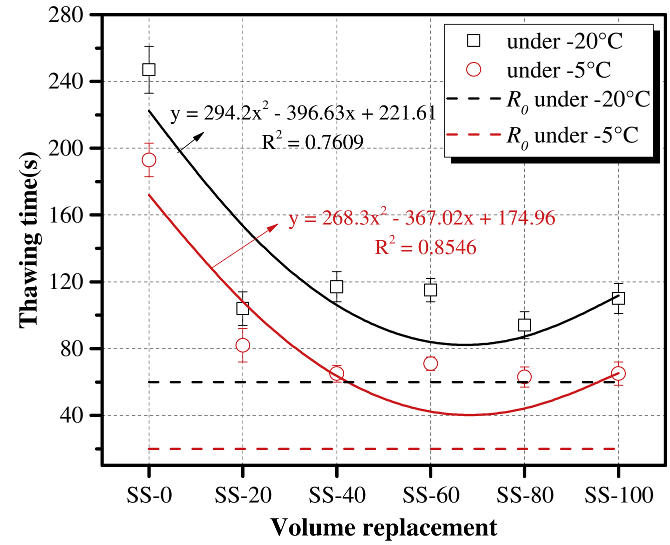


Fig. 17. The results of thawing time.

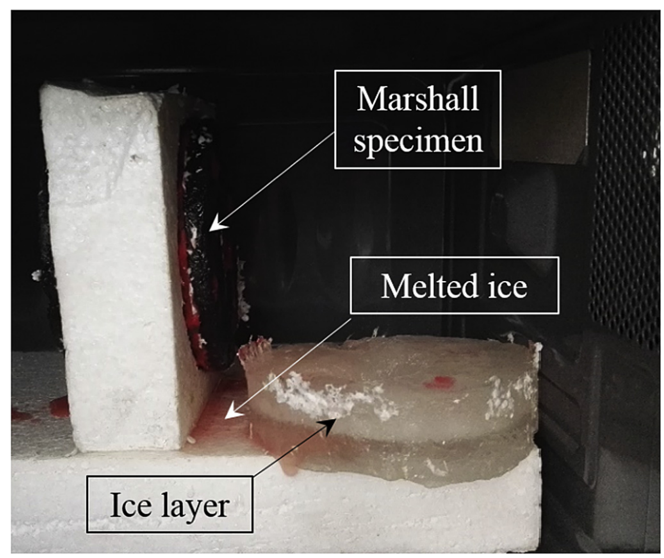


Fig. 18. Ice melting into water under microwave radiation.

microwave absorbing material should have a stable, extensive and easy available sources, which make the construction of the MH pavement has a basic feasibility. Fig. 20 shows that the crude steel productions are mainly distributed in North, East and Northeast China where over 77% of the total annual outputs of China's crude steel are produced (CIIN, 2016). Therefore, the steel slag reservation is enormously abundant in these areas. Meanwhile, Fig. 20 also shows that the average temperatures in Winter in the areas of North and Northeast China are −6.7° C and −13.5° C (Zhang et al., 2011; He et al., 2013), respectively, which means that there is enough steel slag for MH pavement in the cold regions (Northeast and North China). Therefore, the utilization of steel slag as aggregate for MH pavement has a great feasibility resulting from the intense demand for pavement deicing in cold regions and the wide distribution of steel slag.

3.5.2. Ecological hazardous assessment

Steel slag is a kind of industrial waste containing trace heavy metal ions (eg. Pb, Hg, Cd, Cr, As, Ni, Cu, Mn, Zn et, al). Therefore, when steel slag is used as aggregate for MH pavement, the potentially damage influence of heavy metal ions, which are separated from MH pavement under the rain-wash, on the groundwater, surrounding soil and human health should be thoroughly evaluated.

Oluwasola et al. (2016) made a reliable conclusion which showing that the heavy metal ions of copper, Cu; Chromium, Cr; Lead, Pb; Cadmium, Cd and Nickel, Ni contained in the steel slag can be detected via toxicity characteristic leaching procedure (TCLP). As the main heavy metal ions contained in the steel slag, the leaching amount of lead ion in steel slag exposing in the natural environment is much higher than that of steel slag was wrapped in asphalt concrete. Furthermore, previous studies conducted by Onuaguluchi and Eren (2012), Nikolić, et al. (2016) also indicate that the incorporation of steel slag into asphalt concrete is nontoxic for ecological

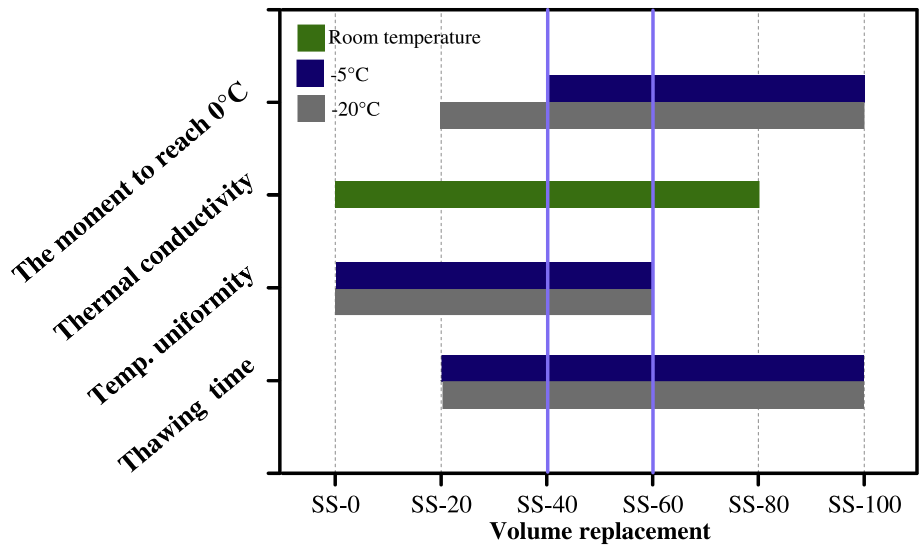


Fig. 19. Comprehensive comparison on performance with different steel slag contents.

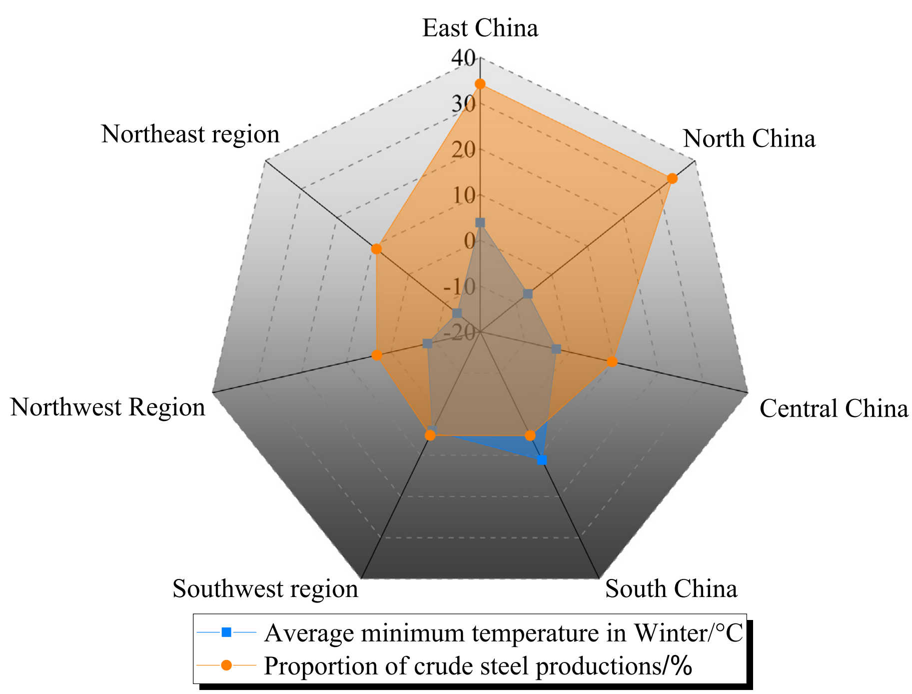


Fig. 20. The proportion of crude steel output in different regions of China and the average temperature of producing areas in Winter.

environment. Therefore, the MH pavement would exert no hazardous effects on the groundwater, surrounding soil and human health instantly or chronically.

3.5.3. Cost performance analysis

Asphalt concrete can possess the microwave heating capacity through the addition of microwave absorbers, such as effective absorption materials (e.g. carbon fiber, carbonyl iron powder or steel fiber) and some composites (e.g. steel slag or magnetite). However, the cost of effective absorbers for MH pavement is enormously high. After the investigation and summary of the research results reported by Wang et al. (2014, 2011), Guo and Sha (2012) and Liu et al. (2010), the raw materials cost increment of asphalt concrete caused by the incorporation of microwave absorbing materials into MH pavement and their heating efficiency were shown in Table 4. Microwave absorbing materials are costly resulting from its highly commercial value and versatile applications. However, preparation for uniform asphalt mixtures with absorbing materials is a challenging work where special equipments and sophisticated techniques are needed due to the highly viscosity of asphalt (such as the mixing process of carbonyl iron powder and asphalt). In spite of this, the microwave heating rate of MH pavement with absorbing material shows no significantly higher than those of steel slag or low-grade magnetite.

Another notable feature is that the cost increment caused by incorporation of steel slag is negative, which indicates that the construction cost of MH pavement can be reduced by the incorporation of steel slag; while the addition of other microwave

Table 4
Properties of MH pavement with different absorbing materials.

Base material	Absorber	Content/%	Initial temp./°C	Heating time/s	Temp. increment/°C	Heating rate °C/s	Cost increment m^3/Yuan (¥)
Asphalt mixture	–	–	−24	342	24	0.07	0
	Low-grade magnetite	100	−10	7	10	1.42	90
		67	−10	10	10	1.00	50
		44	−10	13	10	0.77	33
		38	−10	20	10	0.50	28
	Carbonyl iron powder	0.29	20	60	80	1.33	348
	Steel fiber	4	25	30	9	0.3	15
		8	25	30	28	0.93	30
		1.2	25	30	41	1.36	45
	Steel slag	9	−5	20	19	0.97	−30
		19	−5	20	22	1.11	−63
		28	−5	20	22	1.09	−94
		37	−5	20	25	1.25	−124
		45	−5	20	24	1.24	−151
Micro-surfacing asphalt mixture	Carbon fiber	0.12	−10	150	25	0.17	144
		0.36	−10	120	25	0.21	432
		0.60	−10	200	25	0.12	720

Note: The absorbing materials content is the mass fraction of the composite; The heating test conditions were 100 kW/m^2 power and 2.45 GHz frequency, except for that of steel fiber (70 kHz); The unit price of the absorber is investigated in the Chinese market (March 2016th). This discussion is a qualitative analysis in consideration of the various unit price of materials in different country or market.

absorbing materials can result in the cost increase of the MH pavement in different degrees.

3.5.4. Analysis of potential overheating problems

Asphalt mixture is a kind of temperature sensitive material thereby the substantial change of temperature has a significant effect on the pavement performance. Therefore, the problems that MH pavement may facing is that the temperature of local areas or steel slag particles will exceeding a reasonable range (overheating) thereby causing adverse effects on pavement performance. Obviously, the potential overheating problems should be evaluated.

For local areas overheating, the first condition is that the steel slag particles are highly clustered in the local areas of pavement. Under this condition, if the heating time for the pavement which steel slag evenly distributed area was adopted to heating this local area, then the surface temperature of the area which the steel slag clustered will be certainly overheated. Therefore, the reasonable processes for mixture mixing should be employed to overcome this type of overheated. The second condition is that the error operation. The temperature of pavement could be extremely high if the heating time in the same position lasted too long during the microwave deicing operation. This kind of overheating can be prevented by careful operation.

For steel slag particles overheating, the surface temperature of particles could be very high after microwave irradiation in room temperature. Generally, the bond interface of steel slag and asphalt binder can be melted under this temperature. However, when steel slag was added in asphalt mixture, the heat generated by steel slag will be partly transfer to mixture and ice layer persistently. Since the heat transfer is a dynamic process, the heat generating and heat losing of steel slag particles should be going simultaneously, thereby the actual surface temperature of steel slag particles may not as high as in room temperature.

4. Conclusions

In this work, the feasibility of simultaneously using steel slags aggregate and conventional limestone aggregate in asphalt mixtures for pavement microwave deicing application was evaluated. Based on the results discussed above, the following conclusions can be drawn:

The thick ice layer removal is considered as a technological difficulty resulting from the presence of freezing adhesion action on the interface between ice layer and pavement surface. With the assistance of microwave deicing vehicle, the best opportunity for microwave deicing is when the pavement surface temperature reached 0 °C to remove the freezing adhesive interface while prevent the water melting from ice layer to re-freezing under low-temperature atmosphere.

In contrast to limestone aggregate, steel slag possesses much higher MH capacity resulting from the higher hyperactive (Fe_3O_4) and active (Fe_2O_3 and FeS) content contained in steel slag. The surface temperature of steel slag maintains in a correspondingly high level when the particle size is larger than 0.6 mm, showing that the microwave heating capacity of steel slag varies with its particle sizes. The most effective particle sizes are selected as 9.5 mm (20 s), 2.36 mm (40 s, 60 s) and 0.6 mm (80 s).

The parallel hot-wire method is suitable for determine the asphalt mixture thermal conductivity (k) conveniently and precisely. The thermal conductivity of asphalt mixtures significantly decreases with the increase of steel slag content due to the porous characteristics of steel slag, the k value of SS-20, SS-40, SS-60, SS-80 and SS-100 are decreases 5.16%, 4.22%, 11.73%, 12.20% and 18.78% compared with SS-0, respectively.

Microwave heating uniformity plays important role to deicing efficiency of MH pavement. The standard deviations of surface temperature increases with the increase of the steel slag content, and the heating uniformities of asphalt mixtures are in an acceptable range except for SS-80 and SS-100.

The microwave thawing efficiency is directly affected by its initial atmospheric temperature. The R_0 for common cold and extremely cold condition are 20 s and 60 s, respectively. After the addition of steel slag, the MH thawing efficiency of specimens is increased about 2.3–3.1 times and 2.1–2.6 times in contrast to the SS-0 under common cold and extremely cold condition, respectively.

Finally, the steel slag as aggregate for asphalt pavement microwave deicing has the advantages of wide sources, eco-friendly and lower construction cost in comparison with other microwave absorbers such as carbon fiber, carbonyl iron powder, low-grade magnetite and steel fiber. The utilization of steel slag for MH pavement is a novel application for recycling steel slags, which can alleviate the supply shortage of natural raw materials and improve the safety of road traffic in winter.

5. Further study

This study has made a preliminary study of utilization of steel slag as aggregate in asphalt mixtures for microwave deicing to exploring its feasibility. The obtained conclusions are desirable, but there are several concerns should be further studied. Although we have discussed the potential overheating problem that MH pavement may facing, but there are insufficient experimental data to support our point view on this matter, thereby the long-term performance of MH pavement, for instance, the aggregate-asphalt bonding and asphalt aging, should be further investigated to prevent its performance degradation.

Acknowledgements

This work was jointly supported by the National and Local Joint Engineering Materials Laboratory of Traffic Engineering and Civil Engineering, Chongqing Jiaotong University (No. LHSYS-2016-002), the Fundamental Research Funds for the Central Universities (No. 310831153504 and 310831163113), and National Science and technology support program in 12th Five-Year (2014BAG05B04). Additionally, the writers also express their thanks to Dr. Liqun Hu, Dr. Wei Jiang, Dr. Liang Zhou of Chang'an University for their valuable assistance. Finally, the authors are grateful to Miss Ruiqing Liu of New Oriental School for English revision.

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