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Research on gradient characteristics and its prediction method of induction heating asphalt concrete

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ABSTRACT

In this paper, a method to predict the healing effect of induction heating asphalt concrete at vertical depths was proposed and verified. At first, AH-70 asphalt concrete and SBS modified asphalt concrete of AC-13 gradation were designed and prepared. R-DT (Relationship of Depth and Temperature) was quantified through induction heating test. R-HT (Relationship of Healing rate and Temperature) was quantified through fracture-healing–-fracture test and X-ray micro computed tomography test with oven heating. Then, linear regression was used to verify the rationality of R-HT compared with the pre-relationship in previous studies. Finally, R-DH (Relationship of Depth and Healing rate) was predicted by fitting approach. It was found that R-DT and R-HT presented significant linearity, the existence of which was independent from the type of asphalt materials. While, more sensitive of SBS modified asphalt concrete showed that the response to gradient characteristics of R-DT was related to the higher overall temperature. Additionally, R Square-values = 0.963 of linear regression proved the oven heating method was suitable for the quantification and prediction of gradient characteristics. Furthermore, the prediction of R-DH was obtained successfully, which established the continuous distribution of the healing effect at vertical depths and revealed the linear relationship of the continuous distribution.

1. Introduction

Asphalt materials have been widely applied in pavement engineering, especially in highway construction. In China, asphalt pavement accounts for over 90% of expressway with the total mileage of 149,600 km [1]. However, under the negative impact of heavy sunshine, moist weather and continuous loading, various damages would be generated in the pavement, such as raveling, fatigue and thermal cracking [2–4]. These damages deteriorate the service performance of asphalt pavement and affect the driving safety negatively, which increases the maintenance demand of asphalt pavement. Urgently, the highway maintenance mileage accounts for more than 98% of the total mileage in China, thus the heavy maintenance tasks are in desperate need of effective rehabilitation methods [5]. Fortunately, asphalt materials can heal the micro-cracks spontaneously at ordinary temperatures though the healing process is tardy [6,7]. Based on this phenomenon, researchers focused on methods to trigger and accelerate the healing process, among which induced healing technology has been approved widely to achieve the effective healing [8,9]. This technology is mainly divided into two categories: induction heating and microwave heating, the main difference between which are the way heat to recover the cracks is generated [10].

At present, induction heating is promising to become a mainstream method of the induced healing technology [11]. The healing mechanism of induction heating method is that enough heat generated by heating unites can promote the capillary flow of asphalt materials to heal micro-cracks. The heat relies on eddy current generated through the cutting of alternating magnetic field lines in alternating electromagnetic field. As early as 2008, Garcia et al. firstly proposed the induction heating method to close cracks on asphalt concrete [12]. Then, the induction heating technology for asphalt materials and pavements has been studied by several research groups, such as TU Delft [13], EMPA [14,15], and others [16]. Meanwhile, researches concerned about characteristics of conductive and magnetically susceptible additives,

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Table 1
The basic properties of AH-70 asphalt, SBS modified asphalt and steel wool fibers.

Materials	Properties	Values	Requirements in China
AH-70 asphalt	Penetration (25 °C, 0.1 mm)	62.4	60 ~ 80
	Ductility (15 °C, cm)	> 100	≥40
	Softening point (°C)	46.8	≥43
	Density (g/cm^3)	1.018	–
SBS modified asphalt	Penetration (25 °C, 0.1 mm)	68.7	60 ~ 80
	Ductility (5 °C, cm)	43.3	≥30
	Softening point (°C)	74.1	≥55
	Density (g/cm^3)	1.043	–
Steel wool fibers	Average length (mm)	4.2	–
	Diameter range (μm)	70–130	–
	Density (g/cm^3)	7.85	–

impacts of induction heating on asphalt binder and asphalt concrete, factors of healing effect and additional functions of induction heating methods were studied successively [17–20]. Objectively, the above research results can support the idea that the induction heating method is positive to damages healing and life extension of asphalt pavement.

Nevertheless, the phenomenon of nonuniform temperature field distribution with the pavement thickness limits the application of induction heating method significantly [21,22]. This phenomenon dates from the characteristics of electromagnetic field: according to Faraday's law of electromagnetic induction, the magnetic induction intensity will decay rapidly with the increment of distance to the coil [23,24]. Based on the characteristics, electromotive forces across conductive and magnetically susceptible additives depend on the position where the additions are located in the field. Therefore, the heat generated by the conductive and magnetically susceptible additives at different vertical depths are gradient, which results in nonuniform temperature field distribution. Previous studied mainly concentrated on the characteristics of temperature field distribution, the gradient healing characteristics of asphalt concrete and so on. Garcia et al. described the nonuniform temperature field distribution as a relatively large temperature gradient between the upper and lower layers in asphalt concrete created by induction heating [25]. During induction heating process, Liu et al. proved the temperature gradient between the surface and bottom of the asphalt concrete increased in the increment of heating time [26]. On the contrary, during the cooling process, Liu et al. found that the temperature gradient gradually decreased with the cooling time accumulated, except that the temperature rose at the middle and bottom of the samples slightly [27]. Jeoffroy et al. found that inhomogeneous heating phenomenon also existed in asphalt concrete containing iron-based particle during the exposure to an alternating magnetic field [28]. Moreover, Li et al. quantified the induction heating temperature field related to heating distance and time, then revealed the contradiction between depth and healing effect [29,30]. To recap, the gradient characteristics in asphalt concrete are derived from the temperature field which are related to depth and healing rates. However, the researches above indicated that the quantification of the gradient characteristics in asphalt concrete wasn't investigated clearly, especially the relationship

Table 2
The basic properties of aggregates and fillers.

Parameter measured		Coarse aggregate			Fine aggregate	Fillers	Requirements in China
		16–9.5	9.5–4.75	4.75–2.36	2.36–0	0.075–0	
Apparent specific gravity		2.916	2.924	2.921	2.763	NA	≥2.6
Flakiness and elongation (%)		9.8	11.2	NA	NA	NA	≤18.0
Los Angeles abrasion (%)		22.7	22.7	20.7	NA	NA	≤28.0
Crush value (%)		17.8	NA	NA	NA	NA	≤26.0
Fine aggregate angularity (%)		NA	NA	NA	39.2	NA	≥30
Sand equivalent (%)		NA	NA	NA	64.1	NA	≥60
Specific gravity (g/cm^3)		NA	NA	NA	NA	2.737	≥2.5
Percent passing (%)	0.6 mm	NA	NA	NA	NA	100	100
	0.15 mm	NA	NA	NA	NA	96.2	90–100
	0.075 mm	NA	NA	NA	NA	85.7	75–100

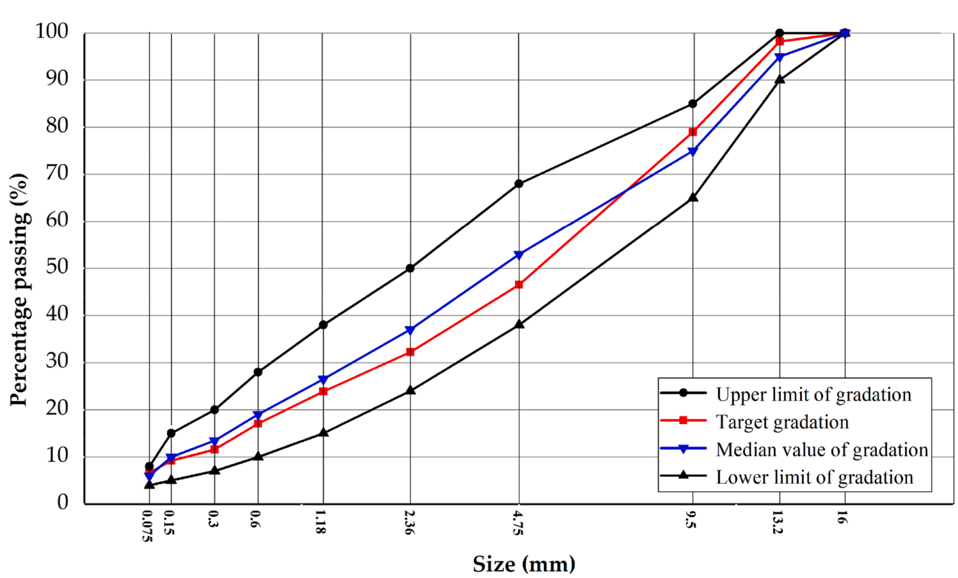


Fig. 1. Gradations used in this research.

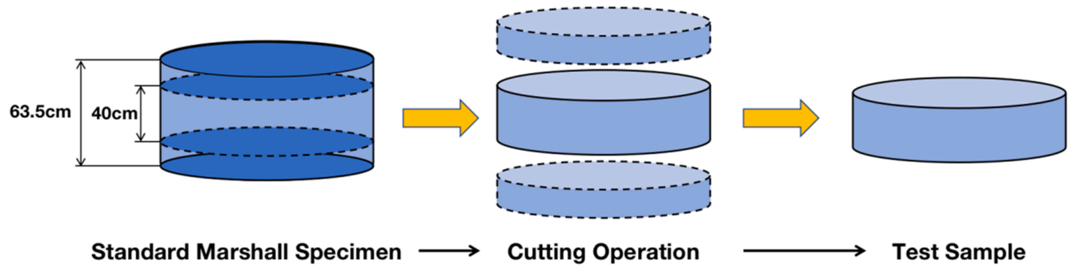


Fig. 2. Preparation of the samples in Induction heating test.

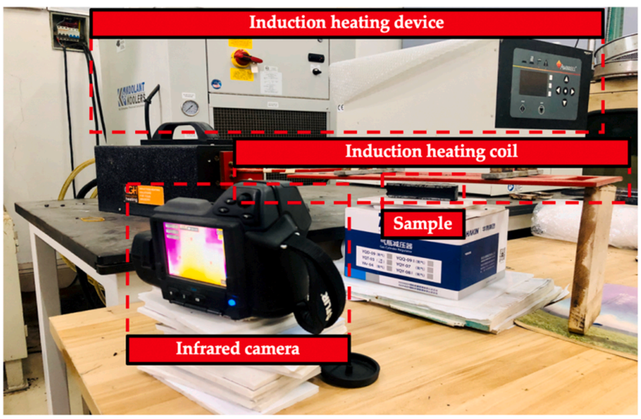


Fig. 3. System of induction heating test.

between depth and healing rate. The healing effect of induction heating asphalt concrete at different depths is undefined, so it is necessary to quantify the relationships among temperature, depth and healing rates.

In this research, a method to predict the healing effect of asphalt concrete at vertical depths after induction heating was proposed. Two kinds of induction heating asphalt concretes were prepared with steel wool fibers used as induction heating units in asphalt materials when exposed to alternating electromagnetic fields generated by an external induction unit. Induction heating test was applied to quantify the relationship between temperature and depth in asphalt concrete. Fracture-healing-fracture test and CT test were conducted to quantify the gradient relationship between healing rates and temperature in asphalt concrete. Then, the rationality of the method was analyzed by linear regression. According to the relationships obtained, the relationship between healing rates and depth was predicted by fitting approach. Finally, the continuous distribution of healing effect at vertical depth of asphalt concrete was established.

2. Materials and preparation of samples

2.1. Materials

In this research, AH-70 asphalt and SBS modified asphalt are selected as the binder. Steel wool fibers are used as the induction heating units. The used coarse and fine aggregates are determined as basalts. Limestone powders was functioned as fillers in the asphalt concrete. Basic characteristics of raw materials were measured according to ASTM standards [31–37]. The basic properties of bitumen and steel wool fibers are listed in Table 1 and the basic properties of aggregates and fillers are listed in Table 2

2.2. Preparation of samples

In this study, AH-70 asphalt concrete and SBS modified asphalt concrete with nominal maximum size of 16 mm are designed by Standard Marshall Method. The hybrid gradation is shown in Fig. 1 and the optimum asphalt content (OAC) is determined to be 4.9%. With the addition of steel wool fibers accounting for 6% of bitumen volume, the asphalt concretes are prepared. The dosage of steel wool fibers is considered to grant asphalt concrete best mechanical properties and most suitable induction heating efficiency [38]. Meanwhile, OAC increased to 5.1% due to the fact that steel wool fibers tend to seize more bitumen.

3. Research methods

3.1. Induction heating test

As shown in Fig. 2, the samples in this test were obtained from the standard Marshall specimens. The induction heating test was performed by applying the induction machine with a power output of 7.8 kW, a frequency of 123 kHz and a voltage of 600 V. During the test, the samples were fixed under the coil of induction machine, and the distance between the coil and the top surface of the sample was determined as 10 mm. The temperature changings were detected with a full color infrared camera of 320dpi*240dpi during induction heating process. To get a better recognition of the induction heating system, Fig. 3 presents the

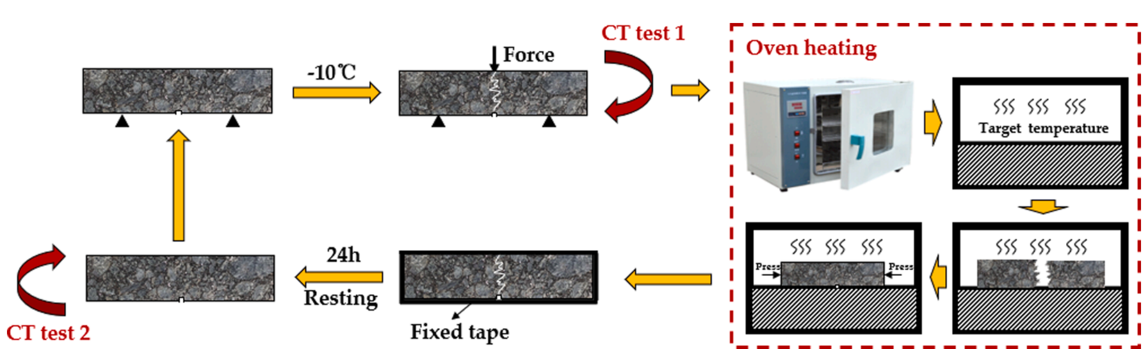
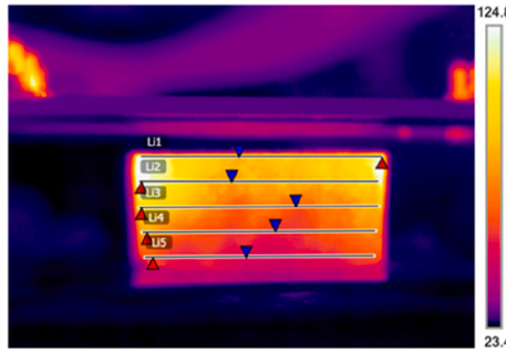
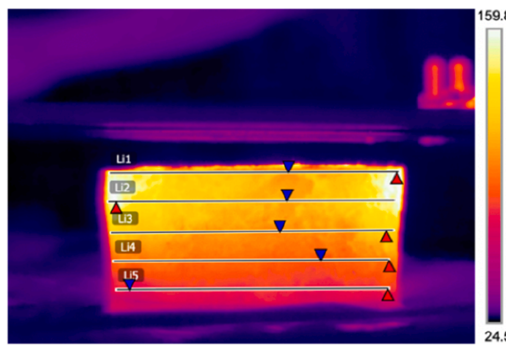


Fig. 4. Procedure of fracture-healing-fracture test.

Table 3
The temperature of asphalt concrete at the chosen depths.

Asphalt concrete	Depths	Infrared image	Temperature
AC-70	0 mm 10 mm 20 mm 30 mm 40 mm		100.6 °C 96.8 °C 82.5 °C 70.4 °C 59.6 °C
AC-SBS	0 mm 10 mm 20 mm 30 mm 40 mm		131.3 °C 124.6 °C 118.8 °C 103.3 °C 88.1 °C

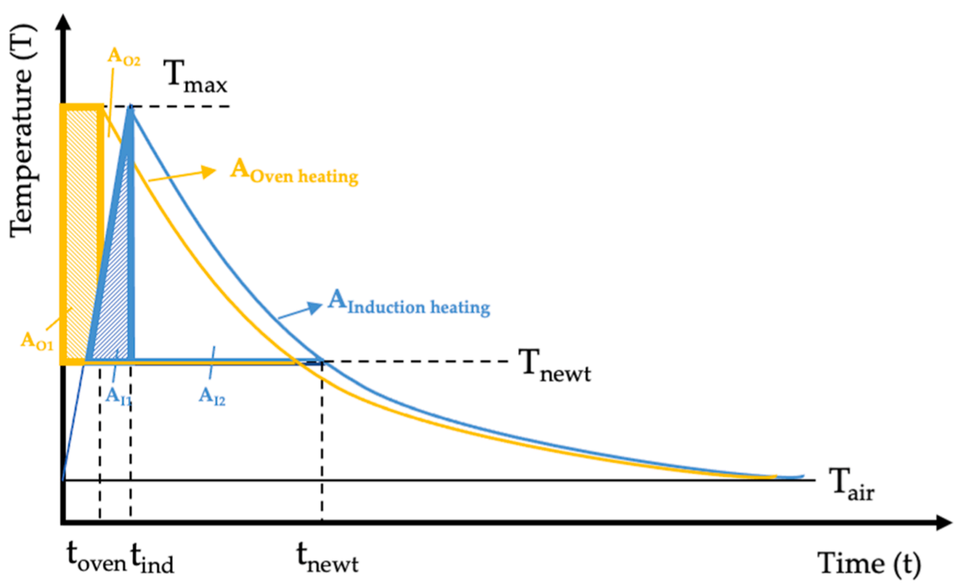


Fig. 5. Temperature changes in asphalt concrete by induction heating and oven heating.

system by the method of schematic form.

3.2. *Fracture-healing-fracture test*

3.2.1. Steps of the test. The samples in this test are the beams with a size of 15 mm × 15 mm × 70 mm, cut from the standard Marshall specimens. A notch with depth of 2 mm and thickness of 1 mm are conducted at the bottom of the samples along thickness direction. Oven heating are selected as healing methods for broken samples. The schematic form of Fracture-Healing-Fracture test is shown in Fig. 4.

Steps and instrumental parameters are as follows: (1) First, the sample is kept in −10 °C for 4 h; (2) A three-points bending test is performed: UTM-25 is used to break the sample, parameters of which are as followed: the distance of supporting points is 50 mm, and the loading speed is 0.5 mm/min. Moreover, the initial breaking strength F_1 is obtained; (3) The sample is placed flatly until its temperature approaching the ordinary. Thereafter, CT test 1 is performed on the sample meanwhile the breaking characteristics of cracks are obtained; (4) The sample is healed by oven heating method, procedures of which are explained in 3.3.2; (5) The sample is placed flatly until cooling down to ordinary and tied by insulating tape for 24 h, then the sample is conducted CT teat 2. The healing characteristics of crack are obtained; (6) Finally, the three-

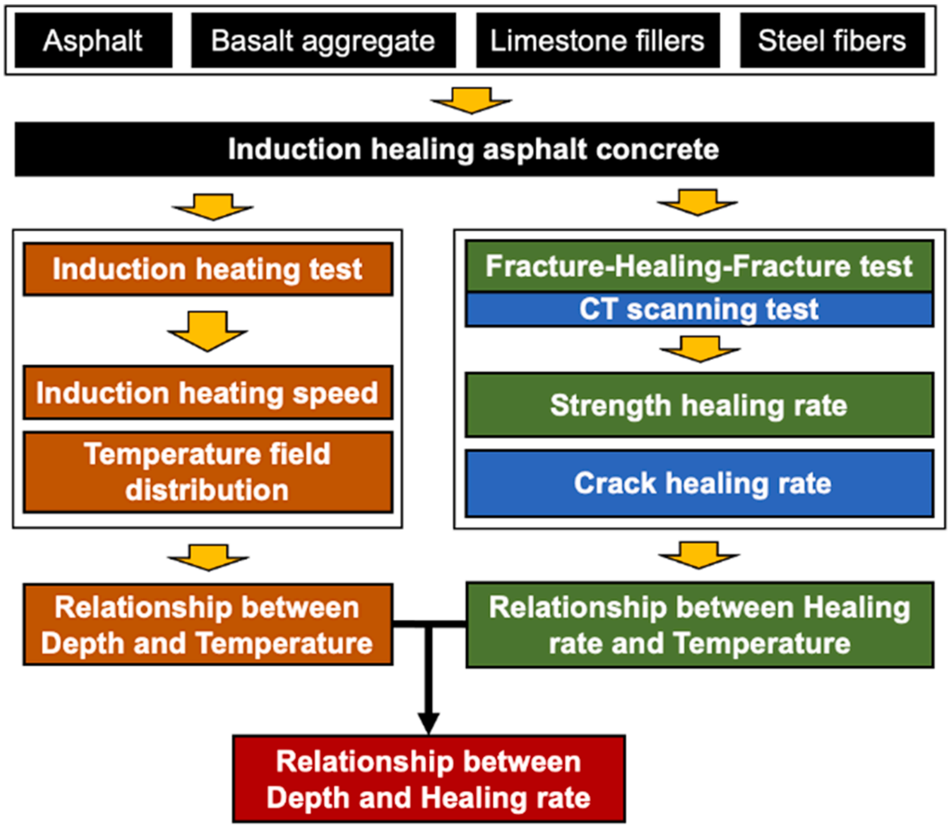


Fig. 6. Experimental plan of this research.

points bending test is performed again to obtain the breaking strength F_2.

3.2.2. Oven heating healing method. Steps are as follows: (1) Target temperature determined in Table 3 is set up in the oven; (2) Then, the fractured sample is kept in the oven until the temperature of the sample is detected to have reached the target temperature by the infrared camera; (3) Presses are imposed on the sides of the sample for 70 s (AH-70 asphalt concrete)/102 s (SBS modified asphalt concrete) to recover an entirety, then the samples are taken out to the environment.

The heating time is determined as per the previous research and the area below the cooling curve (shown in Fig. 5), between t = 0 and t = t_{newt}, can be calculated [25]:

$$\tau = \frac{T_{air}\xi A t_{newt} - (T_{max} - T_{air})(e^{(-\xi A t_{newt})})}{\xi A} - T_{newt}t_{newt} \quad (1)$$

where T is the temperature of the asphalt concrete surface, T_{air} is the temperature of the environment, A is the surface area across which the heat is being transferred and T_{max} is the maximum temperature of asphalt concrete. And an appropriate healing level is reached when bitumen is heated for a sufficient time above the temperature at which it behaves as a Newtonian fluid (T_{newt}).ξ is referred as a simplification that values the quotient of heat transfer coefficient and the product of mass of asphalt concrete and its specific heat.

This parameter will be called tau (s) from now, its units are K s and gives an impression of the total amount of heat in asphalt concrete during the healing process. To unify the healing effect of induction heating and oven heating, the value of t_{Oven} is required to ensure $A_{Ovenheating} = A_{Inductionheating}$.

The following equations demonstrate the composition of $A_{Ovenheating}$ and $A_{Inductionheating}$:

$$A_{Ovenheating} = A_{O1} + A_{O2} \quad (2)$$

$$A_{Inductionheating} = A_{I1} + A_{I2} \quad (3)$$

Due to the fact that the T_{max} of the two heating methods is identical, it can be inferred that $A_{I2} = A_{O2}$. Therefore, it can be also inferred that $A_{I1} = A_{O1}$. The following equations demonstrate the value of A_{I2} and A_{O2}.

$$A_{I1} = t_{ind}\frac{T_{max} - T_{newt}}{T_{max} - T_{air}}(T_{max} - T_{newt}) \times 0.5 \quad (4)$$

$$A_{O1} = t_{Oven}(T_{max} - T_{newt}) \quad (5)$$

Eventually, the value of t_{Oven}can be obtained after some simplification and elimination shown as followed:

$$t_{Oven} = \frac{t_{ind}}{2} \quad (6)$$

Therefore 70 s (AH-70 asphalt concrete)/102 s (SBS modified asphalt concrete) to recover an entirety are determined with t_{ind} obtained from Fig. 7.

3.2.3. CT scanning test. This test aims to evaluate the healing property of asphalt concrete by crash healing rate. A high-resolution 3D X-ray microscope computed tomography (CT) is determined to obtain the 3D imaging of the samples, which was widely used in earlier studies [39]. The working principle of the CT instrument is that X-ray would penetrate through the sample and the sample would be magnified into two-dimensional images. With the two-dimensional images at different angles superposed, the sample is reconstructed into three-dimensional images by mathematical operation, which truly reveals the three-dimensional microstructure inside the material.

3.2.4. Healing rates. Healing rate of strength is defined by Eq. (7).

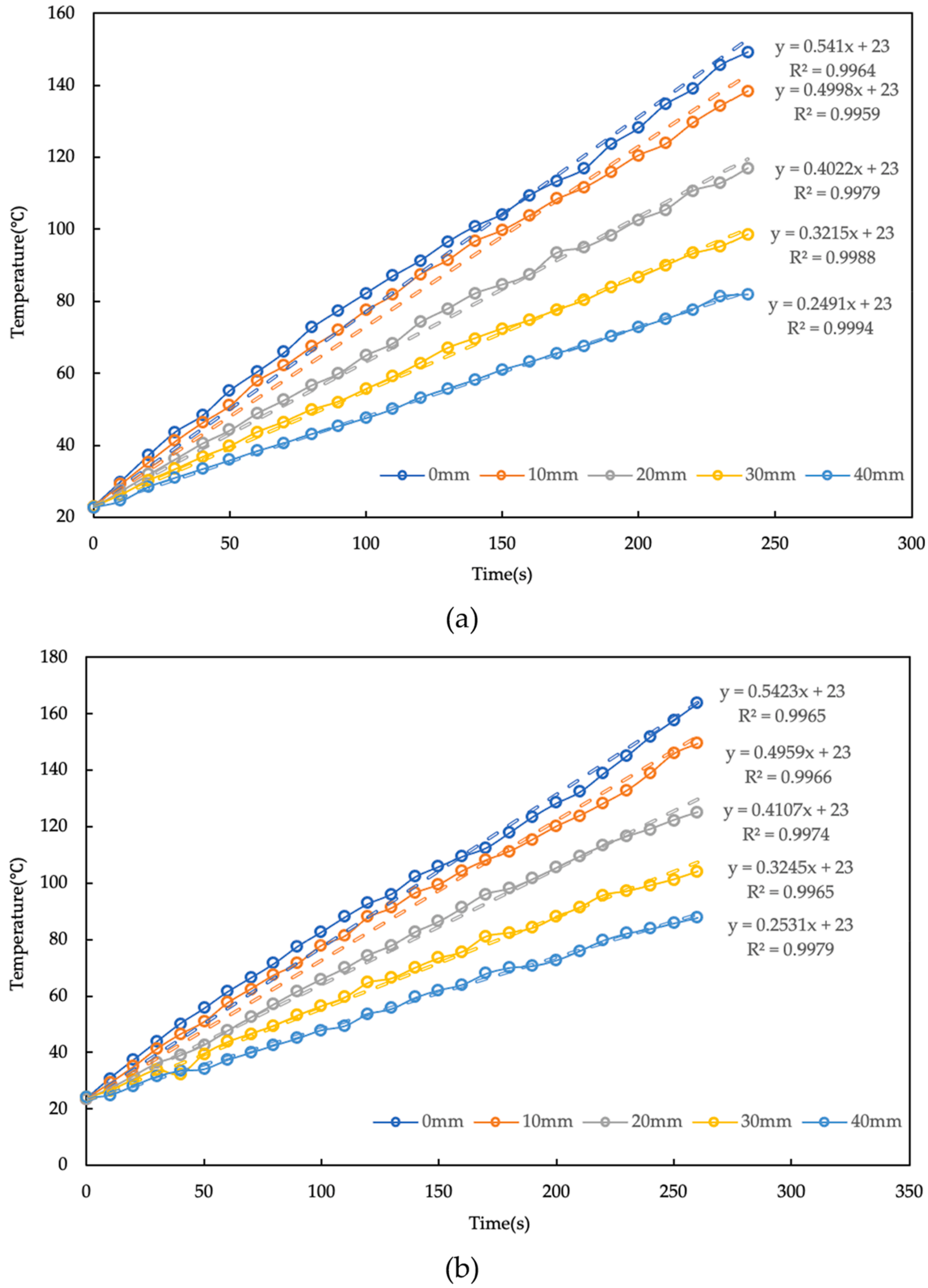


Fig. 7. Induction heating curve of (a) AC-70, (b) AC-SBS.

$$HI_S = \frac{F_2}{F_1} \times 100\% \quad (7)$$

HI_S is healing rate of strength. F_1 is the breaking strength before healing and F_2 is the breaking strength after healing.

The healing rate of crack is defined by Eq. (8).

$$HI_C = (1 - \frac{C_2}{C_1}) \times 100\% \quad (8)$$

HI_C is healing index of crack. C_1 is the crack volume before healing and C_2 is the crack volume after healing.

3.3. Experimental plan

Experimental plan of this research is shown in Fig. 6.

4. Results and discussions

4.1. Relationship between depth and temperature (R-DT)

4.1.1. Induction heating speed

The induction heating curve of AC-70 and AC-SBS are shown in Fig. 7, displaying the dissimilarity of temperature and heating rates of asphalt concrete at different depths during induction heating. The temperature gaps between any two depths climb gradually and reach the highest level before the heating stopped. With an increment from 0 mm to 40 mm of depth, the average temperatures of AC-70 and AC-SBS describe a general and consistent downward trend. Moreover, the gradient phenomenon is more obvious with increasing of time. A sharp temperature gap of nearly 50 °C is presented between the depth of 0 mm and 40 mm, which demonstrates gradient characteristics of temperature

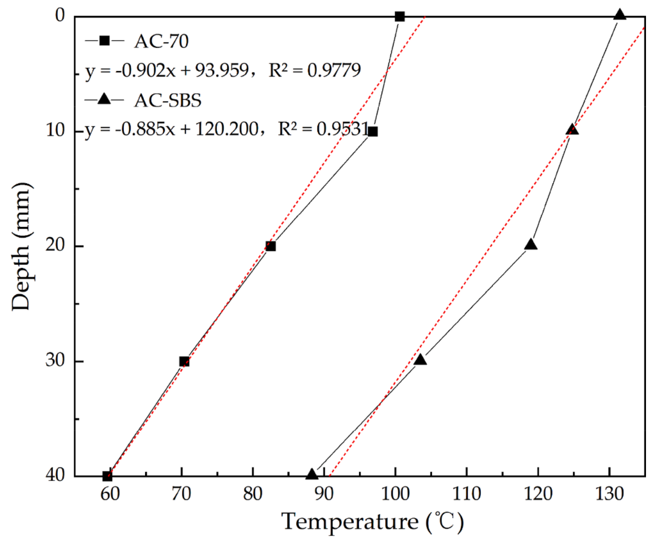


Fig. 8. Depth-temperature curve of asphalt concrete after induction heating.

of asphalt concrete. The heating rates of asphalt concrete at the depth of 0 mm (surface), 10 mm, 20 mm, 30 mm and 40 mm are 0.541 °C/s, 0.500 °C/s, 0.402 °C/s, 0.322 °C/s and 0.249 °C/s (AC-70), and 0.542 °C/s, 0.500 °C/s, 0.408 °C/s, 0.322 °C/s and 0.250 °C/s (AC-SBS). The similar values of temperature and heating rates are found between AC-70 and AC-SBS, which indicates the values are of little correlation with the type of asphalt.

4.1.2. Temperature field distribution

In this section, the temperature field distribution under the optimal healing temperature is necessary to be quantified. 100 °C of AC-70 and 130 °C of AC-SBS are determined as the optimal healing temperature. The temperature of asphalt concrete at the chosen depths and infrared photographs are listed in Table 3. In the infrared photographs, Li1, Li2, Li3, Li4, Li5 are corresponding the depth of 0 mm, 10 mm, 20 mm, 30 mm and 40 mm of asphalt concrete.

Based on the temperature of asphalt concrete at the chosen depths, the depth-temperature curves of AC-70 and AC-SBS are shown in Fig. 8. Relationship between depth and temperature (R-DT) of AC-70 is satisfied with the linear relationship of $y = -0.902x + 93.959$. The temperature is decreasing continuously with the increasing of depths; the temperature of AC-70 reaches the maximum at the surface while the minimum at the depth of 40 mm, and the temperature gap has been more than 40 °C. A similar trend of R-DT is found in AC-SBS; the temperature of AC-SBS at the surface is 131.3 °C but the temperature at the depth of 40 mm is 88.1 °C, and there is an increase over 40 °C in the vertical of asphalt concrete. As for AC-SBS, its R-DT is satisfied with the linear relationship which is $y = -0.885x + 120.200$. The slope of R-DT represents the corresponding of temperature to depth of the asphalt concrete, while the slopes of AC-70 and AC-SBS reveal the significant difference. A higher sensitivity to depths of AC-SBS might be caused by the higher overall temperature in comparison with AC-70.

4.2. Relationship between temperature and healing rate (R-TH)

4.2.1. Healing rate of strength

Fig. 9 presented the HI_S of the asphalt concretes. At the temperature of 59.6 °C, 70.4 °C, 82.5 °C, 96.8 °C and 100.6 °C, the HI_S of AH-70 asphalt concrete were 35.4%, 46.9%, 54.5%, 61.7% and 71.3%. At the temperature of 88.1 °C, 103.3 °C, 118.8 °C, 124.6 °C and 131.3 °C, the HI_S of SBS modified asphalt concrete were 26.4%, 31.1%, 39.8%, 45.6% and 50.3%. With an increase of heating temperature, the HI_S of AH-70 asphalt concrete is increasing gradually from 35.4% at 59.6 °C to 71.3% at 100.6 °C. Similar trend is shown in the HI_S of SBS modified asphalt concrete which increase from 26.4% at 88.1 °C to 50.3% at 131.3 °C. In comparison, the HI_S of AH-70 asphalt concrete are larger

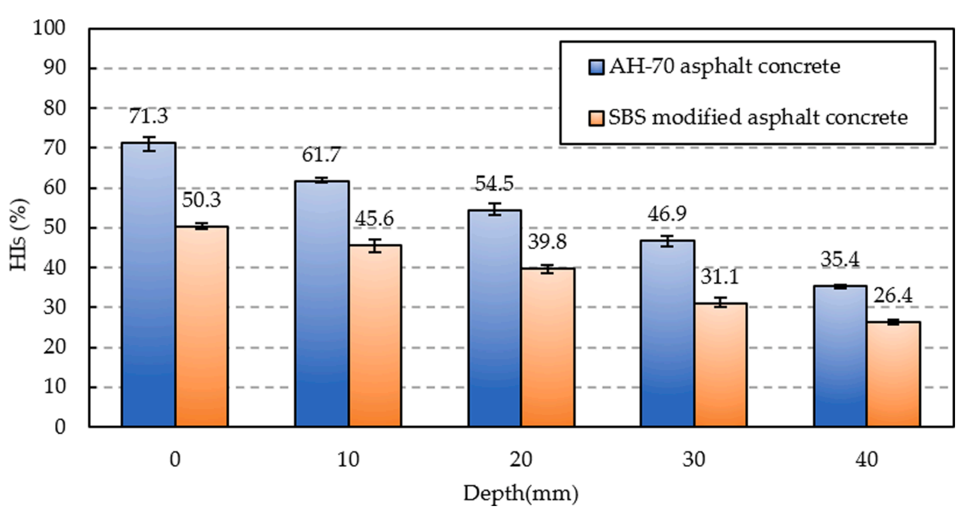


Fig. 9. HI_S of AH-70 asphalt concrete and SBS modified asphalt concrete after oven heating.

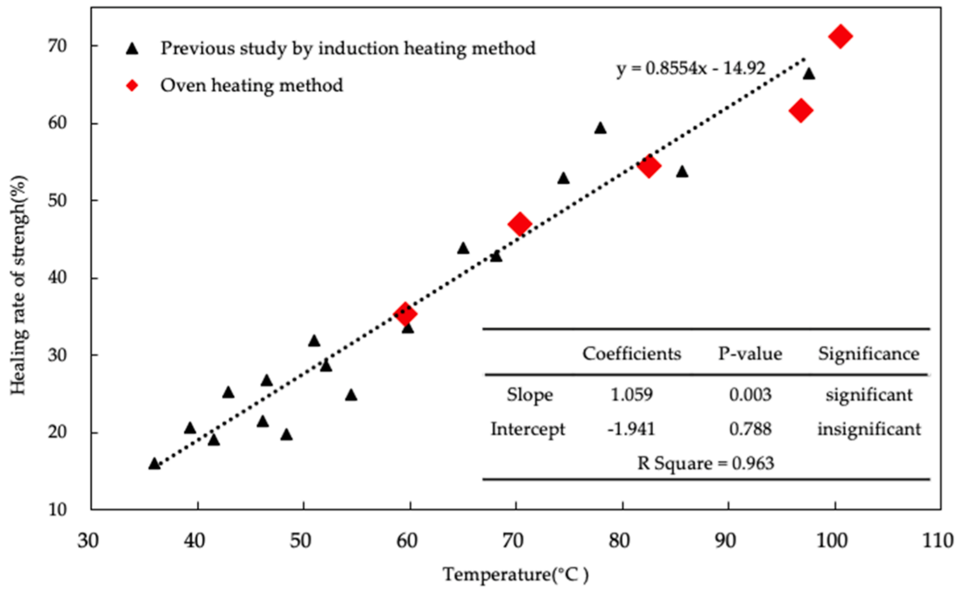


Fig. 10. Linear regression between oven heating method and previous study by induction heating method.

than that of SBS modified asphalt concrete in the respective temperature range. However, SBS modified asphalt concrete supplied better mechanical property due to the fact that the splitting strength of SBS modified asphalt concrete are 5.621kN, nearly 1.53 times as opposed to 3.667kN of AH-70 asphalt concrete. It implied that worse healing property caused by SBS modifier and excellent mechanical property should be given attention in practical engineering of SBS modified asphalt concrete.

Then linear regression is used to verify the reliability of the simulation process with oven heating method compared to the previous research with induction heating method, the results of which is shown in Fig. 10. P-value of the slope and intercept indicates that the statistics by oven heating method are highly linearly correlated with previous studies by induction heating method. R Square of 0.963 also supports the linearly correlation. It demonstrates that the oven heating method in this research can simulate the healing process of induction heating.

4.2.2. Healing rate of crack

At present, the researches tended to evaluate the self-healing performance of asphalt concrete through the mechanical test, but seldom through characteristics of crack in asphalt concrete. However, it is necessary to evaluate the effect of crack healing on the macroscopic performance of asphalt concrete from a microscopic point of view. In this section, relationship between temperature and healing rate of crack is necessary to determine.

Fig. 11 presents crack trend of asphalt concrete before and after oven heating respectively at chosen temperature. Before the oven heating of 59.6 °C, the crack in the AH-70 asphalt concrete is created at the weak conjunction between aggregate and asphalt mortar meanwhile the crack also crosses the aggregate. During oven heating, it can be found that the cracks are closing and the overall structure of sample remains the initial status. Before the oven heating of 70.4 °C and 82.5 °C, the crack in the AH-70 asphalt concrete is also created at the conjunction between coarse aggregate and asphalt mortar, however, the crack steers clear of the aggregate. During oven heating, it can be found that the crack is almost disappeared due to the fact that the aggregate is not broken and the heating temperature is higher. Before the oven heating of 96.8 °C, crack penetrate more through the aggregate and walk along the weak point where asphalt mortar and aggregate are connected. During oven heating, the crack is still observed easily due to the fact that crack cross the aggregate although the heating temperature is higher. Before the oven heating of 100.6 °C, the crack walks along with the conjunction between coarse aggregate and asphalt mortar meanwhile the crack cross the aggregate without contact. Moreover, the crack was difficult to detect after oven heating. As for SBS modified asphalt concrete, the cracking trend shows similar characteristics which can be presented in Fig. 11.

Some unified characteristics are shown as followed: Firstly, crack cross the joint where asphalt binder connect with coarse aggregate. The coarse aggregate mainly plays the role of skeleton support in asphalt concrete without providing cohesive force, which is considered as weak point when asphalt concrete subjected to tensile stress, therefore the cracks easily create along with coarse aggregate. Secondly, the cracks also pass through the internal voids, which mainly plays the role of buffer zone when the asphalt concrete is subjected to temperature stress and avoids various mechanical and structural problems caused by temperature expansion and contraction of asphalt concrete, however asphalt concrete is in contraction state at low temperature, which leads to the increment of overall voids. So the voids also belong to weak point and the crack can easily cross the void. Furthermore, aggregate is more rigid compared to asphalt binder. Cracks are easier to pass through aggregate however the heating healing is aimed at asphalt binder rather than aggregate, which is also the reason why healing rate of strength and crack are hard to improve.

The crack volume change of AH-70 asphalt concrete and SBS modified asphalt concrete are shown in Fig. 12 respectively. With the increment of temperature, the healing rate of crack gradually increases and the area of crack in certain place is disappearing more and more. The results proved that the healing rate of crack of AH-70 asphalt concrete is higher than that of SBS modified asphalt concrete, which is similar to the trend of healing rate of strength. AH-70 asphalt is more sensitive to temperature and can heal the asphalt concrete at high temperature. The temperature enables asphalt to flow smoothly and sufficient thermal stress help the fusion of asphalt beside the crack.

4.3. Relationship between depth and healing rate (R-DH)

This section aims to investigate the relationship between depth and healing rate. Based on the relationship between temperature and depth and the relationship between temperature and healing rate, the relationship between depth and healing rate is as shown in Fig. 13, which demonstrated that the healing effect is decreasing with the increment of depth after induction heating. From the top to 40 mm depth of asphalt concrete, the relationship between healing rate of strength and depth of asphalt concrete prepared by AH-70 asphalt and SBS modified asphalt

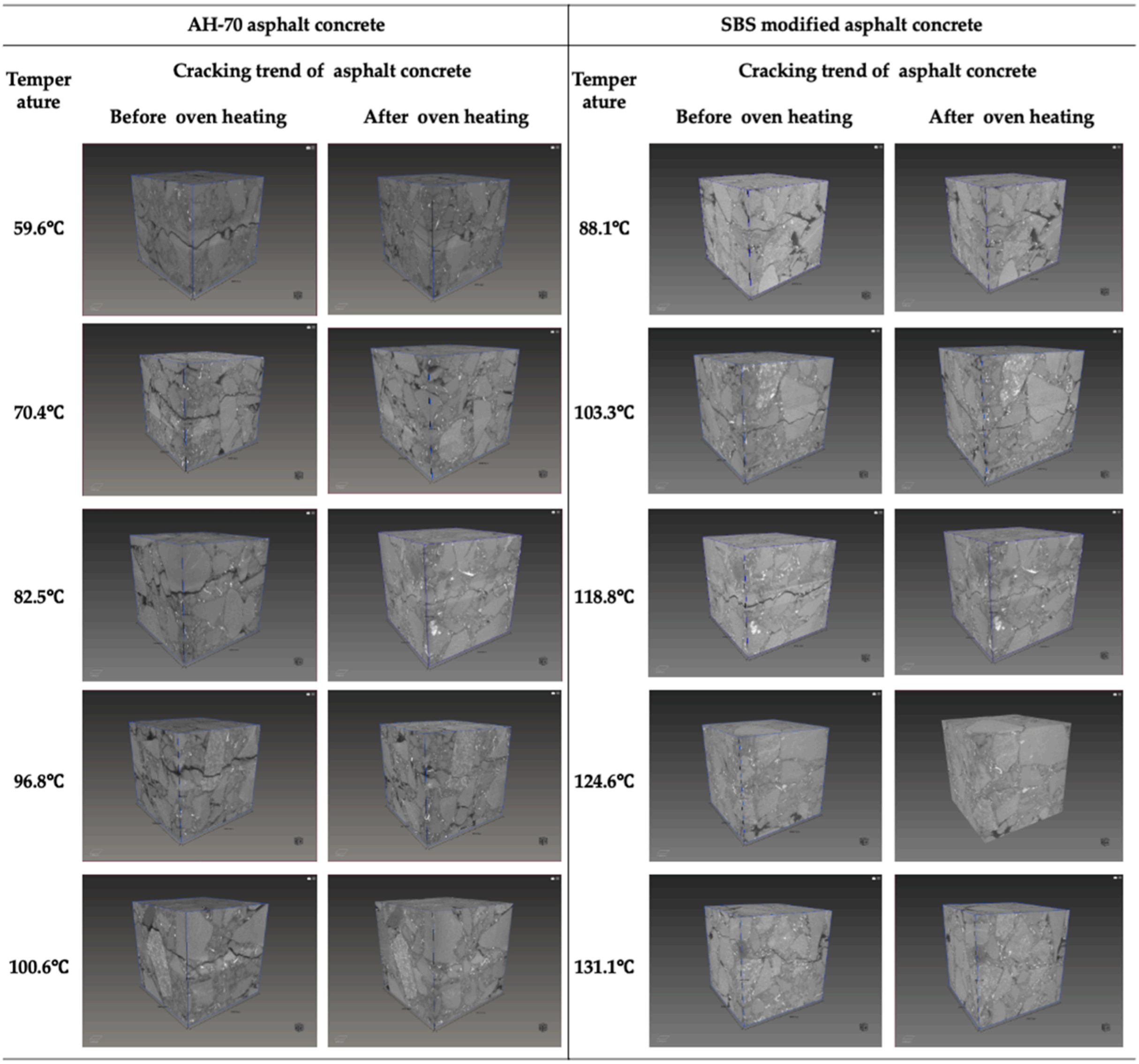


Fig. 11. Comparison of cracks before and after oven heating of AH-70 asphalt concrete and SBS modified asphalt concrete.

were satisfied with the liner relationship respectively as followed: $y = -1.1467x + 81.877$ and $y = -1.5876x + 81.346$. The relationship between healing rate of crack and depth of asphalt concrete prepared by AH-70 asphalt and SBS modified asphalt are satisfied with the liner relationship respectively as followed: $y = -1.0809x + 90.409$ and $y = -1.4568x + 106.070$. Moreover, there is good positive correlation between depth and healing rate by liner analysis.

4.4. *Prediction method of gradient healing effect of asphalt concrete via induction heating*

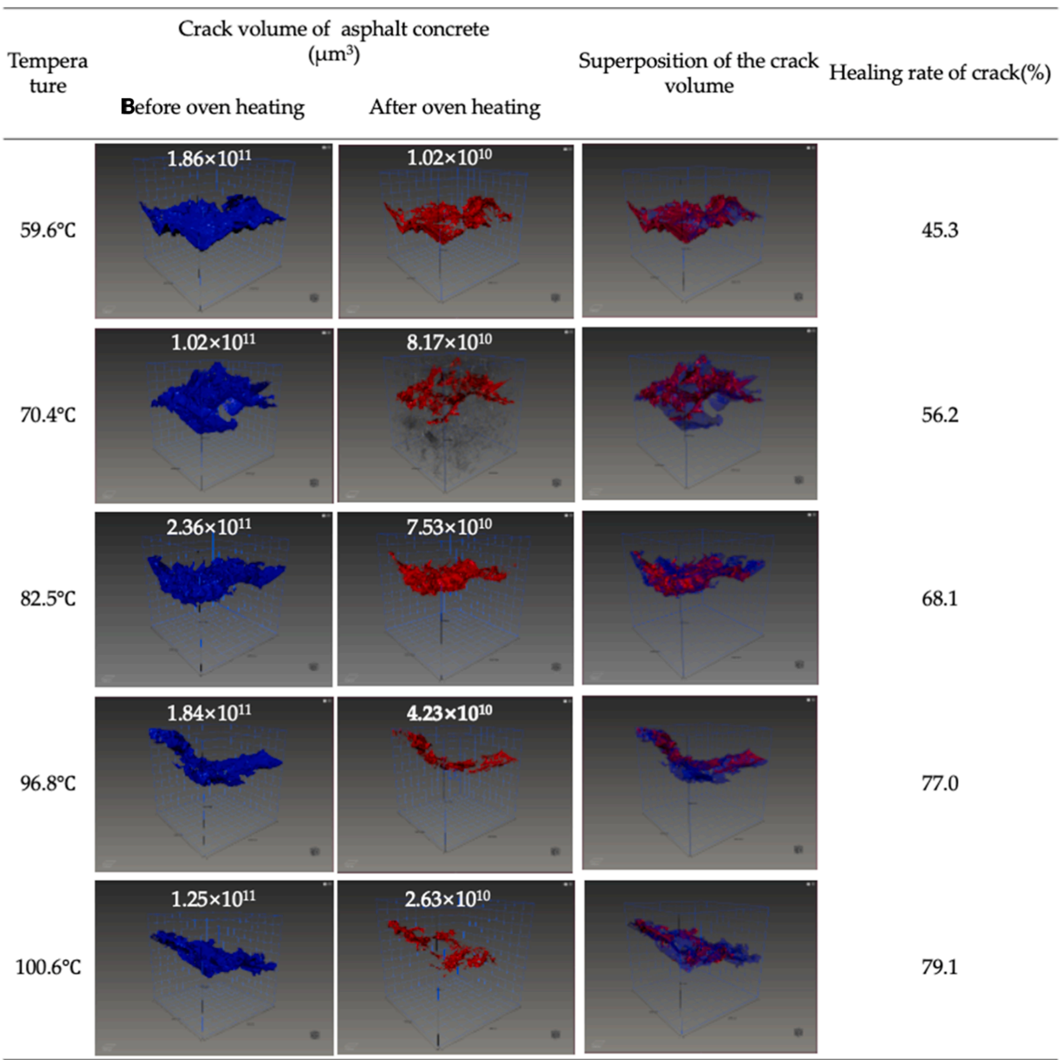
The prediction method of gradient healing effect of asphalt concrete after induction heating is shown in Fig. 14. R-DT (Relationship of Depth and Temperature) is quantified through induction heating test. R-HT (Relationship of Healing rate and Temperature) is quantified through fracture-healing–fracture test and X-ray micro computed tomography test with oven heating. Finally, R-DH (Relationship of Depth and Healing rate) is predicted by fitting approach. Furthermore, the continuous distribution of the healing effect at vertical depths is established.

The other four depths points (5 mm, 15 mm, 25 mm and 35 mm) are chosen to evaluate the practicability of the prediction method. The infrared photograph of the asphalt concrete are shown in Table 4, which demonstrated that the temperature of AH-70 asphalt concrete are 98.7℃, 92.1℃, 78.2℃, 65.9℃ at the depth of 5 mm, 15 mm, 25 mm, 35 mm and the temperature of SBS modified asphalt concrete are 128.7℃, 121.7℃, 113.7℃, 98.6℃ at the depth of 5 mm, 15 mm, 25 mm, 35 mm. Then the fracture-healing-fracture test is applied. Table 5 shows the comparison of measured value and forecast value and the results show that the difference between them was less 5% which demonstrated the relationship above can provide a basis for predicting the healing rate of asphalt concrete at different depths.

5. Conclusions

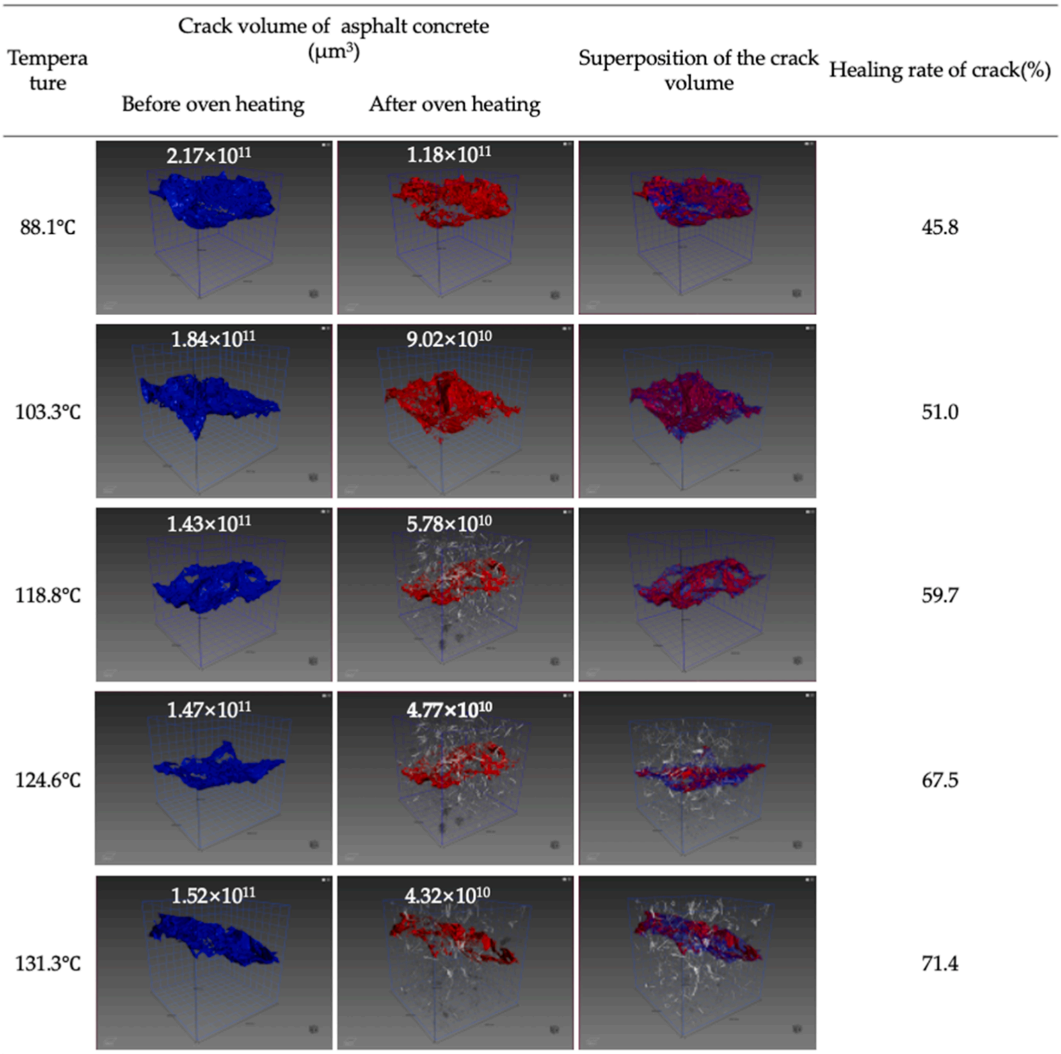
In this research, gradient healing characteristics of asphalt concrete under determining temperature gradient via induction heating was investigated. Based on the results discussed above, the following items can be concluded:

(1) The temperature field exists in asphalt concrete via induction heating and with the increment of depth, the temperature is decreasing. The temperature gap is nearly 50℃ between the depth of 0 mm and 40 mm. The relationship between temperature and depth is accorded with linear relationship strongly.



(a)

Fig. 12. Change of crack volume and Superposition of crack of asphalt concrete before and after oven heating: (a) AH-70, (b) SBS modified asphalt.



(b)

Fig. 12. (*continued*).

(2) AH-70 induction heating asphalt concrete is excellent in self-healing property but poor in mechanical property compared to SBS modified one. The healing rates of strength and crack are decreasing with decrement of the chosen temperature. The regression R Square-values = 0.963 indicates that the oven heating method is suitable for quantifying and predicting gradient characteristics.
(3) Based on the relationships obtained above, the relationship between depth and healing rate is determined, which establishes the continuous distribution of the healing effect at vertical depths and revealed the linear relationship of the continuous distribution.
(4) Prediction method of gradient healing effect of asphalt concrete via induction heating is proposed. The measured healing rate at different depth are accorded with predictive value of the model, which proved the availability of the prediction model. It is suggested that this model should to be tested in engineering practice in the future research.

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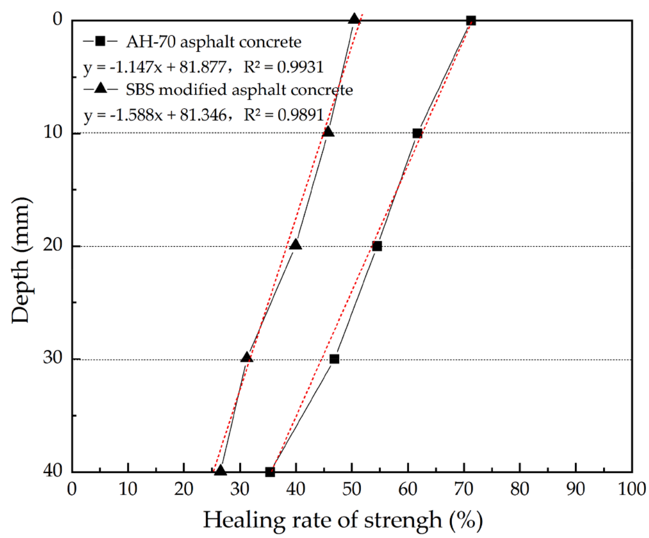
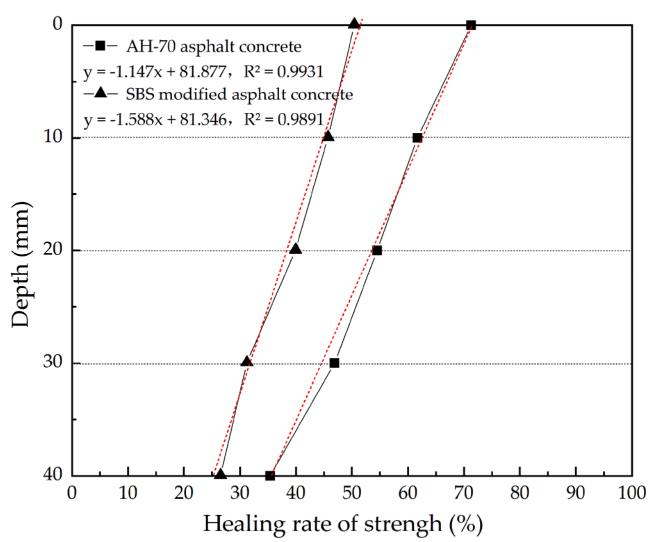
CRediT authorship contribution statement

Haiqin Xu: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Yingxue Zou:** Methodology, Writing - review & editing. **Shaopeng Wu:** Conceptualization, Methodology, Project administration, Funding acquisition, Supervision. **Hechuan Li:** Conceptualization, Methodology, Investigation, Data curation, Software, Validation, Writing - review & editing. **Shi Xu:**



(a)



(b)

Fig. 13. Gradient change of healing rate of asphalt concrete after induction heating: (a) Healing rate of strength, (b) Healing rate of crack.

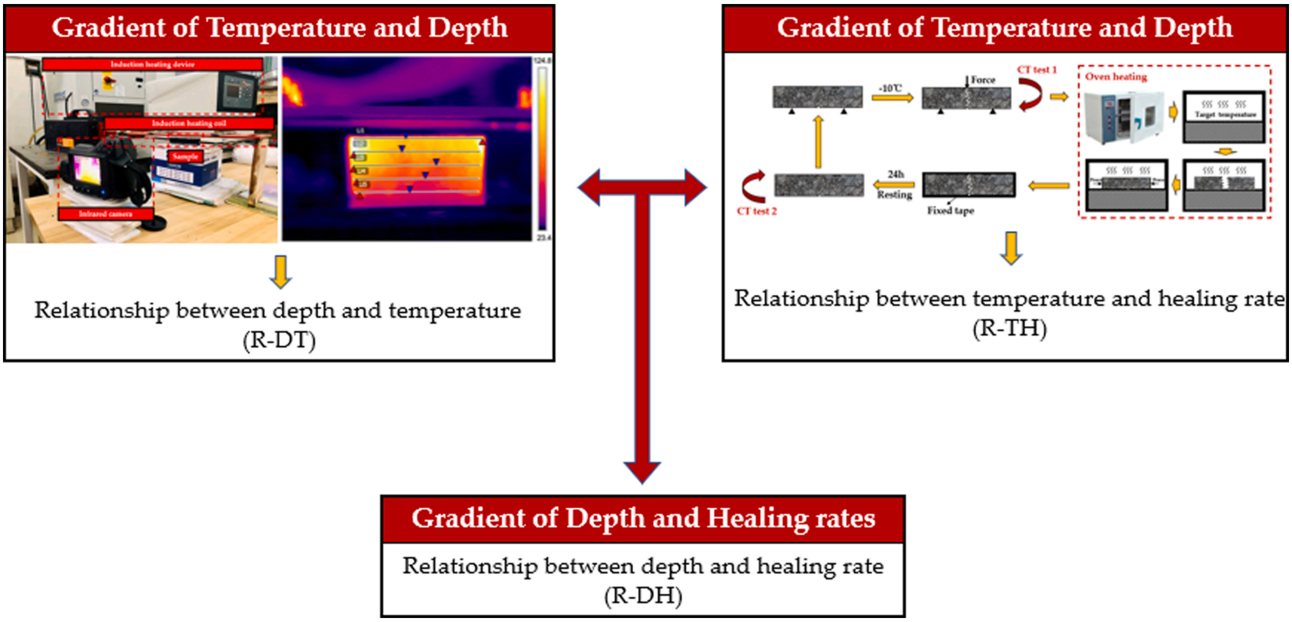


Fig. 14. Prediction method of gradient healing effect of asphalt concrete after induction heating.

Table 4
The temperature of asphalt concrete at other chosen depths.

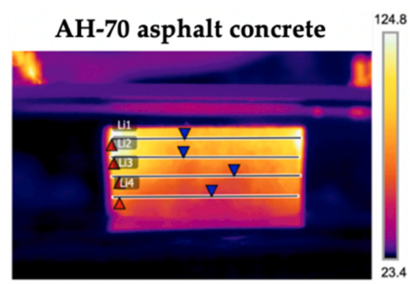
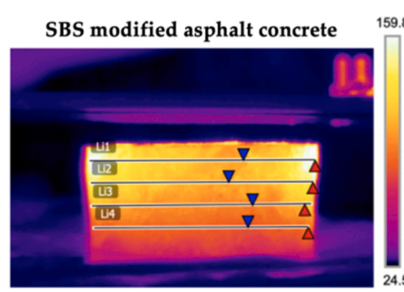
Asphalt concrete	Depths	Infrared image	Temperature
AC-70	5 mm 15 mm 25 mm 35 mm		98.7 °C 92.1 °C 78.2 °C 65.9 °C
AC-SBS	5 mm 15 mm 25 mm 35 mm		128.7 °C 121.7 °C 113.7 °C 98.6 °C

Table 5
Comparison between the predicted value and the measured value of the healing rate of the asphalt concrete after induction heating.

		Healing rate of strength				Healing rate of crack			
AH-70 asphalt concrete	Depth (mm)	5	15	25	35	5	15	25	35
	Temperature (°C)	98.7	92.1	78.2	65.9	98.7	92.1	78.2	65.9
	Predictive value (%)	67.0	58.3	49.6	40.9	79.0	73.5	60.5	51.3
	Measured value (%)	69.8	56.6	53.9	37.2	81.1	70.2	65.3	55.0
	Error (%)	+2.8	−1.7	+4.3	−3.7	+2.1	−3.3	+4.8	+4.7
SBS modified asphalt concrete	Depth (mm)	5	15	25	35	5	15	25	35
	Temperature (°C)	128.7	121.7	113.7	98.6	128.7	121.7	113.7	98.6
	Predictive value (%)	48.1	41.8	35.5	29.0	69.4	62.5	55.6	48.4
	Measured value (%)	44.5	45.1	37.6	24.0	67.5	67.1	58.7	46.5
	Error (%)	−3.6	+3.3	+2.1	−5.0	−1.9	+4.6	+3.1	−1.9

Methodology, Data Curation, Writing - Reviewing and Editing. **Yuechao Zhao:** Resources, Data curation, Software, Validation. **Yang Lv:** Resources, Data curation, Software, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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