Evaluation of Induction Heating Effects on Asphalt Concretes Containing Waste Steel Shavings and Iron-based Particles

Qi Pang1*, Jiangbo Zhang1, Lei Gao1, Bo Sun1, Shenglei Yao1
1China Changjiang Construction Investment. Corp. Ltd, Chengdu, 610000, P.R. China
*Corresponding author’s e-mail: 1163637410@qq.com

Abstract. The self-healing ability of asphalt has great benefits for the service of asphalt pavement, while this ability is not significant at room temperature. This paper utilized waste steel shavings (WSS) and iron-based particles (IBP) as conductor materials, and induction heating technology to heat asphalt concretes. High temperature rutting test, low temperature cracking test and freeze-thaw splitting test were carried out to evaluate the effect of WSS and IBP on the pavement performance of asphalt concretes, and induction heating test was conducted to analyse the heating efficiency. Results shows that both WSS and IBP are beneficial to high temperature performance of asphalt concrete, but not good for low temperature performance. Besides, WSS and IBP has no significant impact on the water stability. Considering the pavement performance and induction heating efficiency, 6%-8% WSS with 2% IBP is recommended.

1. Introduction
As a kind of viscoelastic material, asphalt has the ability of self-healing after being damaged, which has been widely recognized by researchers [1]. Researchers are also trying to make use of this characteristic of asphalt to realize self-healing of the asphalt pavement. The representative technologies include microcapsules [2], electromagnetic induction heating [3-5], microwave heating [6] and so on. Compared with the other methods, induction heating has the advantages of simple process, multiple repairs and uniform heating [7].

The induction heating technology is to add some conductor materials to the asphalt mixture and heat the mixture by the alternating magnetic field (AMF) [3]. Commonly used conductor materials are waste steel shavings (WSS) [3], steel wool fibres [8], iron-based particles (IBP) [5] and iron power [9].

Liu et al. studied the heating performance of asphalt mixture with different WSS content, heating power and frequency, and found that the induction heating uniformity (IHU) was affected by these three factors and the heating effect was obvious [3]. Jeoffroy et al. utilized iron-based particles as the conductor material and investigated the effect of sizes and chemical compositions of iron-based particles to heal the crack. The results showed that the particle size under 1 mm had uniform heating effect and the crack healed with 80% performance recovery by heating the asphalt sample to 104°C [5]. Apostolidis et al. studied asphalt mastic and mortar containing steel fibers and iron power. He reported that the electrical conductivity of asphalt material was improved by steel fibers and iron power, but the effect of steel fibers is better [9].

Considering the high induction heating efficiency of WSS and good heating uniformity of IBP, this paper utilized WSS and IBP as the asphalt induction heating materials and explored both heating effect and pavement performance of asphalt concretes with conductive additives. The addition of IBP
is expected to enhance the induction heating uniformity and efficiency of asphalt concrete containing WSS. This paper aims to provide an optimum content of the conductive additives.

2. Materials and methods

2.1. Materials

An SBS modified asphalt supplied by Sinopec Group was used. The aggregates were limestone gravel and the mineral powder was made of high quality limestone. The WSS and IBP were purchased from Guangzhou West tier Industrial Products Co., Ltd. The basic technical indexes of all the materials were listed in Table 1 and Table 2.

Table 1. Basic technical indexes of materials

| Materials | Properties | Test result | Specifications |
|-----------|------------|-------------|----------------|
| SBS modified Asphalt | Penetration (25°C) / 0.1 mm | 57.7 | 40-60 |
| | Softening point / °C | 66.9 | ≥60 |
| | Ductility (5°C) / cm | 25.3 | ≥20 |
| | Viscosity (135°C) / (Pa·s) | 2.19 | ≤3 |
| Waste steel shaving | Length / mm | 3-6 | - |
| | Density / (g·cm³) | 7.7 | - |
| Iron-based particle | Diameter / mm | 1.0 | - |
| | Density / (g·cm³) | 7.4 | - |

Table 2. Basic properties of aggregates and mineral powder

| Specification | 15–25 mm | 5–15 mm | 3–5 mm | 0–3 mm | Mineral powder |
|---------------|----------|---------|--------|--------|----------------|
| Bulk density  | 2.721    | 2.729   | 2.720  | 2.733  | 2.714          |
| Water absorption / % | 0.69    | 0.71    | 0.55   | -      | -              |

2.2. Specimen preparation

AC-13 is selected as the gradation of SBS modified asphalt mixture in this paper, and the mix proportion is designed according to the specification requirements. See Figure 1 for the gradation curve. The asphalt content is 4.6% by mass. WSS and IBP were mixed with aggregates for 90 s before adding the asphalt and mineral powder. The WSS contents (by mass) were 0%, 4%, 6%, 8% and 10%, and each content had two specimens (with and without 2% IBP for comparison).

![Figure 1. Gradation curve of AC-13 SBS modified asphalt mixture](image-url)
2.3. Pavement performance test
High temperature rutting test, low temperature cracking test and freeze-thaw splitting test were employed to evaluate the high temperature performance, low temperature performance and water stability of asphalt concretes containing conductor materials. Dynamic stability, flexural failure strain and TSR of asphalt concretes with different content of WSS and IBP were measured and calculated.

2.4. Induction heating test
As shown in Figure 2, the induction heating tests were carried out with electromagnetic induction coils, a high frequency AC power supply and a cooling device. The power and frequency were set to 8 kW and 120 kHz, respectively. Marshall samples with different content of WSS and IBP were prepared based on the mix proportion. The gap between top of Marshall samples and induction coils was 1 cm. The temperatures of asphalt concretes were measured by an infrared imager (FLIR E6-XT). All the samples were placed below the middle of the electromagnetic induction coils to ensure the same alternating magnetic field.

3. Results and discussion

3.1. High temperature rutting test
Rutting tests were conducted at 60°C under 0.7 MPa of the wheel pressure, and dynamic stability (DS) was gathered to investigate the effect of WSS and IBP on high temperature rutting resistance of asphalt concretes. From Figure 3, it is obvious that the addition of WSS and IBP increases the DS of asphalt concretes, indicating that the effect is positive and high temperature rutting resistance is improved. When WSS content raised up to 10%, DS of asphalt concretes increased 33% and 40%, respectively. Besides, the effect of the same quality of WSS and IBP on the increase of DS is not significant, which means the improvement of high temperature rutting resistance caused by WSS and IBP is almost the same. And the high temperature stability of all the asphalt concretes satisfied the specification.
3.2. Low temperature cracking test
Cracking tests were carried out at -10°C and flexural failure strain was measured to evaluate low temperature cracking resistance of asphalt concrete containing WSS and IBP. As shown in Figure 4, flexural failure strain decreased with the increasing WSS content and the addition of IBP. The variation trend is obvious and basically linear. This result proves that the addition of WSS and IBP is negative to low temperature performance of asphalt concretes. Moreover, when the WSS content raised up to 8%, flexural failure strain of the asphalt concrete with 2% IBP was very close to the specified minimum value of 3000 με. While when the WSS content was 10%, both samples with and without IBP cannot satisfy the specification. This result proves that when the WSS content is increased to more than 8%, the deformation ability of asphalt concrete is too weak to resist low temperature cracking. Thus, considering the cracking resistance of asphalt concrete at low temperatures, it is suggested that the content of WSS should not exceed 8%.

3.3. Freeze-thaw splitting test
Freeze-thaw splitting tests were employed to evaluate the water stability of asphalt concretes. After Marshall samples totally absorbed water in vacuum, they were placed in a refrigerator at -18°C for 16 h. Then these samples were put into constant temperature water tank of 60°C for 24 h. The ratios of Marshall stability of the samples after and before freeze-thaw process were calculated, which is TSR. From Figure 5, it can be seen that the variation of TSR shows low significant correlation with WSS and IBP. It is hard to say the effect of WSS and IBP on water stability of asphalt concretes. Besides, the fluctuation range of TSR is relatively small. In addition, TSRs of all the specimens were higher than 90%, which indicated good water stability.
3.4. **Induction heating test**

Heating efficiency was measured by induction heating test. According to the previous literature [1], asphalt mixture has strong self-healing ability above 100°C. While the temperature should not be too high to prevent the mixture from loosening. In this test, the upper temperature limit was set to 160°C to get the heating trend. But when choosing the best content of WSS, the temperature is still 100°C. As shown in Figure 6, the temperatures of asphalt concretes increased with the addition of WSS and IBP. Induction heating efficiency significantly increased with the increasing WSS content. Even the induction heating effect of 2% IBP is significant, and the temperature of asphalt concrete can reach 70°C. Besides, when WSS content was higher than 6%, the asphalt concretes can be heated up to over 100°C in 60 s with the help of IBP. When WSS content is increased to 10%, the temperature can even reach 100°C in 30 s, which shows very high induction heating efficiency. Thus, it is suggested that WSS content is not less than 6% with the addition of IBP, according to the test results.

![Figure 5. Freeze-thaw splitting test results](image)

![Figure 6. Induction heating test results](image)

4. **Conclusions**

In this paper, SBS modified asphalt concretes containing different contents of WSS and IBP were prepared and tested. The pavement performance and induction heating efficiency were measured and evaluated. The main conclusions are shown as follows:

1. WSS and IBP have positive effect on the high temperature performance of asphalt concretes, but not good for low temperature performance. Besides, the water stability of asphalt concretes shows low significant correlation with WSS and IBP.
(2) According to induction heating test results, the heating efficiency is positively correlated with the content of WSS and IBP. Asphalt concrete can be heated up to over 100°C in 60 s with WSS content of 6% and IBP content of 2%.

(3) Considering both low temperature performance and heating efficiency, 6%-8% WSS and 2% IBP are recommended.

Acknowledgments
Thanks for the assistance and support from China Changjiang Construction Investment. Corp. Ltd.

References
[1] Sun, D., Sun, G., Zhu, X., Guarin, A., Li, B., Dai, Z., & Ling, J. (2018). A comprehensive review on self-healing of asphalt materials: Mechanism, model, characterization and enhancement. Advances in colloid and interface science, 256: 65-93.
[2] Sun, D., Lu, T., Zhu, X., Li, B., & Tian, Y. (2018). Optimization of synthesis technology to improve the design of asphalt self-healing microcapsules. Construction and Building Materials, 175: 88-103.
[3] Liu, K., Dai, D., Fu, C., Li, W., & Li, S. (2020). Induction heating of asphalt mixtures with waste steel shavings. Construction and Building Materials, 234, 117368.
[4] Dinh, B. H., Park, D. W., & Le, T. H. M. (2018). Effect of rejuvenators on the crack healing performance of recycled asphalt pavement by induction heating. Construction and Building Materials, 164: 246-254.
[5] Jeoffroy, E., Bouville, F., Bueno, M., Studart, A. R., & Partl, M. N. (2018). Iron-based particles for the magnetically-triggered crack healing of bituminous materials. Construction and Building Materials, 164: 775-782.
[6] Norambuena-Contreras, J., & Garcia, A. (2016). Self-healing of asphalt mixture by microwave and induction heating. Materials & Design, 106: 404-414.
[7] Garcia, A., Norambuena-Contreras, J., & Partl, M. N. (2013). Experimental evaluation of dense asphalt concrete properties for induction heating purposes. Construction and Building Materials, 46: 48-54.
[8] García, A., Norambuena-Contreras, J., Bueno, M., & Partl, M. N. (2014). Influence of steel wool fibers on the mechanical, thermal, and healing properties of dense asphalt concrete. Journal of Testing and Evaluation, 42(5): 1107-1118.
[9] Apostolidis, P., Liu, X., Scarpas, A., Kasbergen, C., & van de Ven, M. F. C. (2016). Advanced evaluation of asphalt mortar for induction healing purposes. Construction and Building Materials, 126: 9-25.