Thermal Exchange and Skid Resistance of Chip Seal with Various Aggregate Types and Morphologies

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Abstract: Steel slag, the by-product of steeldmaking, is a desirable alternative material for natural aggregate. However, there are few studies applying steel slag in the preventive maintenance of asphalt pavements, especially chip seal. The main objective of this study is to explore the feasibility of applying steel slag in chip seal and the effect of steel slag on the thermal exchange and aggregate retention properties. Furthermore, the surface features, including texture depth and skid resistance, of chip seal were also evaluated. The results show that the thermal exchange performances of chip seal vary with aggregate types. The ranking of the chip seal samples according to the cooling rate places ferrochromium (FER) slag as the fastest and basic oxygen furnace (BOF) slag as the slowest, with the basalt (BS) falling in between. The use of FER slag can make the chip seal resume traffic about ten minutes earlier than original samples. The skid resistance and texture depth of FER slag meet the requirements of the specification, although they are less than those of ordinary aggregates. Moreover, FER slag has a better aggregate retention performance than BOF slag and BS due to its spherical particles and alkaline surface. The application of steel slag in chip seal can recycle industrial waste, reduce the consumption of natural resources and promote economic pavement maintenance technology.

Keywords: chip seal; thermal behavior; aggregate morphology; skid resistance; aggregate loss

1. Introduction

Shortages of natural aggregate resources make the substitution of aggregates an area of interest for sustainable road engineering. Steel slag, the by-product of steeldmaking, is a desirable alternative material. Initially, researchers hoped to reduce steel slag production by improving steeldmaking methods, or adding steel slag to the steeldmaking process again. However, these methods are costly and not effective. Therefore, the research direction of steel slag treatment has turned to how to reuse it in other fields [1–3]. At present, there are some studies on the application of slag in asphalt pavement. Ahmedzade [4] evaluated the impact of steel slag on the properties of asphalt mixture, and it was found that steel slag enhanced the mechanical properties and electrical conductivity of asphalt mixtures. Jiao [5] verified the feasibility of recycling steel slag as an aggregate to improve the thermal conductivity of asphalt mixtures. The results show that slag has a positive effect on thermal conductivity, compared with ordinary asphalt mixtures. Wan [6] reused steel slag to prepare a maintenance layer with the function of snow melting, and it was concluded that the snow melting efficiency of the mixture could be improved by steel slag. Although there are some studies on the application of steel slag in asphalt pavement, there is still a lack of research on the thermal exchange and skid resistance of chip seal with steel slag.
pavements, few studies have used steel slag in the preventive maintenance of asphalt pavements, especially chip seals.

Skid resistance refers to the friction force during tire rotation against the pavement surface. It is a crucial parameter of the surface layer of asphalt pavement for traffic safety. Steel slag has been applied to the surface layer of roads to improve the skid resistance due to its rough texture and abundant angularity. Fwa et al. [7] and Kehagia [8] found that the skid resistance of an asphalt mixture made of slag is superior to ordinary aggregates. Therefore, the skid resistance of chip seal-containing steel slag also needs to be explored.

In addition, bleeding and scabbing (loss of aggregate) are major distresses of chip seals. The main reasons for bleeding are the over-usage of asphalt and hot weather, while scabbing occurs as a result of insufficient bonding between asphalt and aggregate. Several studies have concluded that the surface of steel slag is alkaline, which makes it have a stronger adhesion to acidic asphalt than ordinary aggregates [9–11]. Theoretically, the application of steel slag in chip seal can make the adhesion bond between aggregate and asphalt stronger, reduce the possibility of scabbing, and contribute to obtaining a better chip seal performance.

On the other hand, it takes about 1–2 h for the hot-applied chip seal to resume use in traffic after construction since the asphalt is heated to 150–170 °C. Hot asphalt needs to be cooled to normal temperature before it bears the load of a vehicle. As a low-cost and fast-constructed maintenance layer, the time to resume traffic of chip seal is expected to be further reduced. Generally, steel slag has a more complicated chemical composition than ordinary aggregates [12–14], and its thermal exchange rate could be faster than ordinary aggregates. It is hoped that the thermal exchange process of chip seal will be accelerated by steel slag and that traffic can be opened earlier.

The main objective of this study is to explore the characteristics of steel slag, and the effect of steel slag on the thermal exchange and aggregate retention properties of chip seal. Furthermore, the surface features, including texture depth and skid resistance, of chip seal were also evaluated. Firstly, the element and mineral composition, thermal constant and morphology of ordinary aggregates and industrial by-products were tested. Then, the thermal exchange performance and surface features of chip seal-containing steel were detected by infrared camera and laser scanning, respectively. Additionally, a sweep test was conducted on chip seal samples to evaluate their aggregate retention property. The application of steel slag in chip seal recycles industrial waste, reduces the consumption of natural resources and promotes economic pavement maintenance technology.

2. Materials and Methods

2.1. Materials

Basalt from Hubei province, and two kinds of steel slags, were used to vary the elementary and mineral types of aggregates. Basalt is the preferred natural aggregate in Chinese road construction due to its superior physical performance. Basic oxygen furnace (BOF) slag and ferrochromium (FER) slag were chosen as the industrial by-products supplied from Inner Mongolia and Fujian province, respectively. The basic properties of the aggregates are shown in Table 1.

| Sample ID | BS-1 | BS-2 | BOF-1 | BOF-2 | FER-1 | FER-2 | Method |
|-----------|------|------|-------|-------|-------|-------|--------|
| Specific gravity (g/cm³) | 2.65 | 2.68 | 3.15 | 3.21 | 2.98 | 3.02 | ASTM C127 |
| Sand equivalent (%) | 68 | 66 | 74 | 75 | 79 | 79 | ASTM D419 |
| Water absorption ratio (%) | 0.42 | 0.49 | 1.35 | 1.69 | 1.07 | 1.14 | ASTM C127 |
| Soundness by Na₂SO₄ (%) | 2.96 | 3.02 | 2.34 | 2.25 | 1.86 | 1.97 | ASTM C88 |
| Polished stone value | 48 | 44 | 68 | 62 | 57 | 54 | EN 1097-8 |

BS: basalt, BOF: basic oxygen furnace slag, FER: ferrochromium slag.
The numbers 1 and 2 in the sample ID represent different production batches from the same manufacturer. Therefore, there are in total six kinds of aggregate. Only the aggregates labeled 1 were used for microscopic tests, such as elemental composition, phase analysis and thermal constant, since the chemical compositions of two batches are basically the same. The morphological characteristics, skid resistance and aggregate retention performance were applicable to all aggregates and corresponding seals. All experiments were conducted in quintuplicate and average results were kept. Aggregates with sizes 2.36–4.75 mm were selected in this study according to the literature [15].

One SBS (styrene butadiene styrene)-modified hot asphalt with penetration of 51, a softening point of 74.8 °C and a ductility of 35.0 cm, was used as binder in this study. Chip seal specimens were designed and prepared according to the method of Mcleod [16]. The construction temperatures were 160 °C and 25 °C for asphalt and aggregate, respectively. The aggregate application rates of BS, BOF and FER were 11.6 kg/m², 13.5 kg/m² and 12.7 kg/m², respectively, and those of asphalt were 1.3 kg/m², 1.5 kg/m² and 1.4 kg/m².

2.2. Thermal Conductivity and Chemical Composition of Aggregate

The thermal conductivities of BS-1, BOF-1 and FER-1 were tested via the hot-wire method with a QTM-500 thermal conductivity measuring apparatus (ASTM D 5334). The basic principle of this method is to place an electric resistance wire in the sample to be tested. When it emits heat at a constant power, the temperature of the hot wire and the sample near it will increase with time. The thermal conductivity of the sample can be calculated according to the relationship between temperature and time. The schematic diagram of the measuring circuit is shown in Figure 1a.

For the testing of particle materials, two boxes with internal dimensions of 80 mm × 114 mm × 40 mm were used, as presented in Figure 1b. The box below has a bottom, and the aggregate to be tested was filled into this box until it was flush with the upper edge. Then, the measuring probe was placed on the aggregates. The upper box was the same size as the lower box, but without a bottom. Next, the upper box was put on the lower box and the material to be tested filled the upper box. Finally, the box was covered with a lid.

![Figure 1](image-url)

Figure 1. (a) Schematic diagram of measuring circuit and (b) sample boxes.

An infrared camera was used to detect the change of temperature during the temperature-fall period and the cooling rate can be calculated by infrared images. Firstly, 100 g of aggregate was placed on the aluminum plate with a diameter of 200 mm and a thickness of 5 mm, as shown in Figure 2. Next, aggregates were kept in an oven for four hours at 150 °C. Then, the samples were taken out and pictured during the cooling process at room temperature (25.9 °C). The total shooting time for each sample was 20 min, and the interval between two shootings was 4 min.
where \( R \) was spread on the surface to be tested in a circular shape, confirming the surface voids were filled.

\[ \theta \]

where \( n \) is the total number of edge points,

were prepared on the felt and pictured during cooling process at room temperature (25.9 °C). The total shooting time for each sample was 60 min, and the interval between two shootings was 5 min.

### 2.3. Thermal Exchange of Chip Seal

The thermal exchange performance of chip seal was also supervised by infrared camera after aggregates were spread on the hot asphalt and compacted. Culture dishes were used to control the sizes of the chip seal samples and prevent the uneven spreading of asphalt. Firstly, asphaltic felts serving as substrate were put on the culture dishes with a diameter of 100 mm. Then, chip seal samples were prepared on the felt and pictured during cooling process at room temperature (25.9 °C). The total shooting time for each sample was 60 min, and the interval between two shootings was 5 min.

### 2.4. Aggregate Morphology Features

Aggregates in chip seal directly contact with tires, which makes the morphological characteristics of aggregates quite important for skid performance [17]. An aggregate image measurement system (AIMS) was applied to quantize the shape and angularity of fine aggregates [18–20]. Angularity, with a range of 0–10,000, was calculated by the following equation:

\[
\text{Angularity} = \frac{1}{(n^3 - 1)} \sum_{i=1}^{n-3} |\theta_i - \theta_{i+3}|
\]  

(1)

where \( n \) is the total number of edge points, \( \theta \) is the angle between normal and horizontal, and \( i \) is the \( i \)th point on the edge. Shape is characterized by the Form2D index that is calculated by Equation (2), and the standard circle has the zero value of Form2D.

\[
\text{Form2D} = \sum_{\theta=0}^{360-\Delta \theta} \left| \frac{R_{\theta+\Delta \theta} - R_{\theta}}{R_\theta} \right|
\]  

(2)

where \( R_\theta \) is the radius at angle \( \theta \), and \( \Delta \theta \) is the gradient.

### 2.5. Performance of Chip Seal

#### 2.5.1. Surface Features

A laser texture scanner was used to capture the three-dimensional models of chip seal specimens. Macro and micro surface texture were determined by sand patch test (ASTM E 965) and British pendulum test (ASTM E 303), respectively. The sand patch test is widely used to determine the macro texture of pavement surfaces. This test was implemented as followings: firstly, 25 cm³ sand was spread on the surface to be tested in a circular shape, confirming the surface voids were filled.

![Aggregate sample: (a) BS, (b) basic oxygen furnace (BOF) slag, (c) FER slag.](image-url)
Then, the diameter of the sand circle was measured and the texture depth was calculated by the following equation:

$$\text{MTD} = \frac{4V}{\pi D^2}$$  \hspace{1cm} (3)

where MTD is the mean texture depth, V is the volume of sand, and D is average diameter of sand circle.

The British pendulum test quantizes the energy loss by British pendulum number (BPN) when the rubber slide passes through the sample’s surface. First of all, the British pendulum tester was placed over the surface to be tested. Secondly, the slider was put down until its contact path on the sample’s surface was between 124 and 127 mm. Finally, the slider was released at the initial position and the result was recorded.

2.5.2. Aggregate Retention Performance

The aggregate retention performance was detected by sweep test (ASTM D 7000) [15,21–23]. Chip seal specimens were abraded by a Hobart mixer for 60 s after curing at 25 °C for 4 h. Aggregate loss rate (ALR) was calculated by Equation (4) after the loose aggregate was removed,

$$\text{Aggregate loss rate} = \frac{M_B - M_A}{M_B - M_C}$$  \hspace{1cm} (4)

where $M_B$ and $M_A$ are the mass of chip seal before and after abrasion, respectively, and $M_C$ is the mass of felt and asphalt.

3. Results and Discussion

3.1. Properties of Aggregates

3.1.1. Thermal Behavior

Infrared images of three kinds of aggregates during the cooling process are shown in Figure 3. Each infrared image is composed of a thermal picture and temperature scale. In order to facilitate the comparison of the infrared characteristics of samples during the cooling process, the temperature scales in all infrared images were unified, which were between 20 and 200 °C. It was found that BOF slag has the slowest cooling rate among the three aggregates, since the warm color area of BOF slag is the largest in the infrared image for when the cooling time was identical. This indicates that the thermal exchange performance of BOF slag is the worst among them all. In contrast, FER slag has the smallest warm color area, which manifests the largest thermal conductivity.

![Figure 3. Infrared images of aggregates during cooling process.](image-url)
The average temperature of aggregate in each infrared image was captured by FLIR software. The fitted cooling curves and rates based on the average temperature are presented in Figure 4. They show that the mean cooling rate can be given in the order of BOF, BS and FER, from the lowest to highest, with the values of 4.9 °C/min, 5.6 °C/min and 6.1 °C/min, respectively. The results of the hot-wire method indicate that the thermal conductivities of BOF, BS and FER were 0.84 W/m·K, 1.45 W/m·K and 1.82 W/m·K, respectively, which coincide with the regularity of the cooling rates. Previous studies obtained the similar conclusion that the thermal conductivity of concrete is reduced by incorporating BOF slag [24–26].

![Figure 4. Cooling curves of different aggregate.](image)

### 3.1.2. Chemical and Phase Compositions

The chemical compositions of three kinds of aggregates were tested by X-ray fluorescence and the results are presented in Table 2. It can be found from the table that the main chemical composition of basalt is SiO$_2$, which takes up half of all the components. BOF comprises elements such as SiO$_2$ and CaO, and they constitute more than 70% of the chemical component. Fe$_2$O$_3$ was naturally found in BOF. Furthermore, three main chemical elements were captured in FER. They are SiO$_2$, CaO and Fe$_2$O$_3$.

| Materials | MgO/% | Al$_2$O$_3$/% | SiO$_2$/% | CaO/% | Fe$_2$O$_3$/% | Others/% |
|-----------|-------|---------------|-----------|-------|---------------|----------|
| BS-1      | 7.1   | 15.4          | 50.0      | 8.6   | 14.5          | 4.4      |
| BOF-1     | 5.1   | 1.8           | 25.5      | 47.4  | 13.6          | 6.6      |
| FER-1     | 6.1   | 3.1           | 16.0      | 36.6  | 27.6          | 10.6     |

The phases of two kinds of slag were also determined by XRD, and the results are given in Figure 5. The diffraction pattern of BOF shows that the strongest peak is located on 2θ at 32–33°, which belongs to the calcium silicate mineral. Combined with the XRF results of BOF, it can be inferred that dicalcium silicate (C$_2$S) and tricalcium silicate (C$_3$S) are the main phases of BOF. In addition, there are some iron oxide and RO phases (FeO–MgO–CaO–P$_2$O$_5$ solid solution). In the diffraction pattern of FER, although the type of mineral phase is basically the same as that of BOF, the substance corresponding to the strongest diffraction peak is iron oxide, while C$_3$S and C$_2$S correspond to the second strongest peak. This is consistent with the result of XRF suggesting that iron is one of the main chemical elements in FER, indicating that the main mineral phases of FER are iron oxide, C$_3$S and C$_2$S.
Based on the results of XRD and XRF, the reason for the difference in the thermal conductivity of the aggregates can be analyzed to a certain extent. BOF has the lowest thermal conductivity since the calcium silicate mineral phase is its main component, and the thermal conductivity of calcium silicate is only 0.042–0.055 W/(m·K). The thermal conductivity of FER slag is larger than that of basalt since the iron oxide content of FER is higher, the thermal conductivity of which is about 10 W/(m·K) [27], while albite and diopside, which account for the main components of basalt, have thermal conductivities between 2 and 4 W/(m·K).

3.1.3. Morphology

The angularity and form2D results of three kinds of aggregates are presented in Figure 6. It shows that the angularity and form2D of FER are obviously smaller than those of BS and BOF, which can also be intuitively found from Figure 2. According to the specification of AIMS, the aggregate with angularity less than 2100 is considered rounded, and the aggregate with a form2D less than 6.5 is regarded as circular. The rounded and circular FER slag should be attributed to the various ways of forming aggregates. FER slag was treated by the air-granulated technology. The principle of this method is that when the high-temperature liquid steel slag falls and encounters a high-speed airflow, it is impacted and atomized into small droplets and flies in the air, accompanied by a severe heat exchange process. Then, droplets rapidly solidify into spherical slag. However, BOF and BS are broken by thermal and mechanical stress, respectively, which makes them more abundant in their morphologies than FER. As for BS and BOF, it can be found that the average angularity values of these are basically the same, with the values of 3193 and 3205, while the form2D of BOF is observably larger than that of BS. The possible reason is that the thermal stress generated during the rapid cooling of BOF is stronger than BS’s mechanical stress.
and BS-2 have similar angularities, with the values of 3215 and 3194, respectively. Nevertheless, the difference between the two batches of BOF is 11.7%. The reason is that BOF was broken by thermal stress, resulting in the greater shape-randomness of the different batches of products. Therefore, the morphological characteristics may vary greatly due to the influence of the forming method.

3.2. Properties of Chip Seal

3.2.1. Thermal Exchange of Chip Seal

Infrared images, taken every ten minutes, of the chip seal samples during the cooling process are presented in Figure 7, where the temperature scales also averaged from 20 to 200 °C. The thermal exchange performance began to be supervised by infrared camera after uniformly graded aggregates were spread on the hot asphalt and compacted. At the beginning, the color difference between the cold aggregate and the hot asphalt was extremely significant. As the cooling time increased, the temperature of the aggregate and asphalt tended to be consistent. The chip seal sample made of FER had the fastest cooling rate among the three samples, since its infrared images at 50 and 60 min are basically the same, indicating that the cooling process ended before 50 min, while this phenomenon was not found in the BS and BOF samples.

Figure 7. Infrared images of chip seal samples during cooling process.

Figure 8 presents the cooling curves of different chip seal samples based on the average temperature of the infrared images. It is found that ranking the chip seal samples according to cooling rate places FER slag as the fastest and BOF slag as the slowest, with the BS falling in between. Moreover, the temperature decreased first and then flattened with time, indicating that the cooling rate was getting smaller. The times at which the temperatures of the FER and BS samples stabilized were 45 and 55 min, respectively, as shown in Figure 8, while the time required for the BOF sample was more than 60 min, which indicates that the use of FER can make a chip seal that can resume traffic about ten minutes earlier than the original samples. Xu [25] also found that BOF slag has a negative effect on the cooling of the asphalt mixture, and the cooling rate is 0.97 °C/min, which is similar to the 0.91 °C/min measured in this study. This slight difference in cooling rate is because a part of the steel slag in the chip seal was not covered by asphalt, which has a larger contact area with the air compared to the asphalt mixture.
3.2.2. BPN and Texture Depth

Three-dimensional models and surface features of different chip seal samples are shown in Figures 9 and 10, respectively. It was found that the results of BPN suggest the regularity of angularity, while the results of MTD indicate the laws of form2D. For instance, the BPN and MTD of FER are smaller than those of the BS and BOF, and the average BPNs of the BOF and BS are basically the same, with values of 54.5 and 55.0. The reason is that the macro-texture-determining texture depth mainly depends on the form of aggregate. However, the micro-texture that affects skid resistance performance is mainly influenced by the aggregate angularity.

![Cooling curves of different chip seal samples](image)

**Figure 8.** Cooling curves of different chip seal samples.

![Three-dimensional models](image)

**Figure 9.** Three-dimensional models of chip seal made of basalt (a), BOF slag (b) and FER slag (c).

![Surface features of different chip seal samples](image)

**Figure 10.** Surface features of different chip seal samples: (a) BPN, (b) MTD.

Furthermore, BPN values more than 45 and MTD values more than 0.6 mm are the criteria that are often used to allow traffic after the surface treatment of asphalt pavements. Although the BPN and MTD values of FER are less than those of ordinary aggregates, it can still meet the requirements of the
specification, which is the opposite of the results of Volkan [28] and Wang [29] due to the differences in the treatment methods of steel slag.

3.2.3. Aggregate Loss

The aggregate retention property of the chip seal samples is presented in Figure 11. It shows that ALR can be given in the order of FER, BOF and BS, from the lowest to highest, with average values of 5.3%, 7.5% and 11.0%, which means that FER slag has the best aggregate retention performance. The reason is that the FER particles are closer to the sphere compared with BOF slag, which reduces the friction force between the Hobart mixer and the sample surface. Although there is no widely accepted criterion of ALR, 10% is often used for newly constructed chip seals [15]. Therefore, the BOF slag and FER slag meet the reference value, but basalt exceeds. Careful consideration is needed when basalt is used as the aggregate for chip seal. The conclusions of Kumbargeri [21] and Wasiuddin [15] show that the ALR of chip seal made of natural gravel and modified binder ranges from 4 to 15% based on the aggregate application rate, which is consistent with the result in this study. Meanwhile, the result that the aggregate retention performance of BOF is better than that of BS should be attributed to the alkaline surface of steel slag. Therefore, the interface bond strength between asphalt and BOF is greater than that between asphalt and BS.

![Figure 11. Aggregate loss rate of different chip seal samples.](image)

4. Conclusions

This study explored the characteristics of steel slag and the effect of steel slag on the thermal exchange and aggregate retention performance of chip seal. Furthermore, the surface features, including texture depth and skid resistance, of chip seal were also examined. The following conclusions can be summarized:

1. The relative ranking of aggregate types according to thermal conductivity places BOF slag as the lowest and FER slag as the highest, with the basalt falling in between. The differences in thermal behavior can be attributed to the various chemical compositions.

2. The morphologies of FER slag are more rounded and circular than those of the BS and BOF slag due to the air-granulated treatment methods, and BOF slag has the most abundant morphological features among the aggregates.

3. The thermal exchange performances of chip seal made of FER slag are better than those of BOF slag and basalt. The recycling of FER slag as aggregate in chip seal can allow the chip seal to resume traffic about ten minutes earlier than original samples.
4. The BPN and MTD values of chip seal made of FER slag are the worst among the three kinds of aggregate. However, they still meet the requirements of the specification, although they are less than those of ordinary aggregates.

5. FER slag offers the best aggregate retention performance due to its spherical particles and alkaline surface. It can reduce the friction force and strengthen the interface bond between aggregate and asphalt.

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