REVIEW PAPER

X. Gu,1 X. Zhang,2 J. Lv,1 Z. Huang,1 B. Yu,1 and X. Zou3

Laboratory Performance Evaluation of Reinforced Basalt Fiber in Sealing Asphalt Chips

Reference

ABSTRACT
This study investigated the laboratory performance of basalt fiber (BF) used as an asphalt-chip seal. Specimens of the basalt fiber asphalt-chip seal (BFACS) at various contents of styrene–butadiene–rubber (SBR)-modified emulsified asphalt (EA) and BF were prepared. These were subjected to a series of tests, including plate impact, sweeping, pull-out, and direct shear tests, to inspect their bond performances. The results indicate that BF can significantly improve the performances of the aggregate retention and the interlayer bond of asphalt-chip seal. This study evaluated the performance of BFACS in terms of the low-temperature anti-cracking, interlayer bond, and skid resistance. Specimens with different EA and BF contents and lengths were fabricated to quantify their respective impacts. The findings suggest the optimal BFACS design at 1.8 kg/m² EA and 70 g/m² BF with a length of 70 mm. The BF fiber was proven to substantially enhance the performance of asphalt-chip seal compared to the controlled specimens (0 % BF). Specifically, the tensile strength, shear strength, and surface texture depth for the optimal design were increased by 29.2 %, 51.6 %, and 14.2 %, respectively.

Keywords
basalt fiber asphalt-chip seal (BFACS), wearing course, optimal contents, bond performance, aggregate loss

Introduction
Chip seal is a preventive maintenance treatment used for asphalt pavements. This treatment is formed by spreading well-graded aggregate over an asphalt-binder membrane as a thin wearing course. The unique advantages of chip seal compared to other types of pavement surface treatment include its low initial cost and rapid construction [1,2]. However, issues such as aggregate loss, low-temperature cracking, and bleeding are still frequently observed with the increasing application of chip seal in China [3–5].

Basalt fiber (BF), which consists of natural basalt rock, is produced by melting raw materials in a furnace at a temperature of 1450°C–1500°C, followed by manufacturing with platinum-and-rhodium-alloy wire-drawing bushing [6]. Basalt fiber includes many merits, such as natural compatibility and
outstanding high-temperature performance, as well as superior mechanical and stable chemical properties [7,8]; this is one of the four major high-tech fibers used in China [9].

The applications of BF in asphalt mixture and cement concrete have triggered abundant research interests [10]. Sim and Park [11] investigated BF in concrete structures, which improved the overall performance of concrete. The tensile strength and ductility were increased by 0.5–1.0 and 3–5 times, and the bearing capacity was also enhanced compared to the other fiber concretes. Zielinski and Olszewski [12] determined the optimal content of BF by testing its physical and mechanical properties using the modified cement mortar specimens after curing for 28 days. Dias and Thaumaturgo [13] studied the effects of BF on the fracture toughness of inorganic polymer cement concrete and Portland cement concrete mixed with BF. Li et al. [14] reported that the addition of 0.1 % (volume fraction) of BF into the cement concrete increased its compressive strength and toughness at about 26 % and 14 %, respectively. Yang et al. [15] concluded that the best BF volume content to enhance the toughness of concrete is 0.2 %. Fan et al. [16] investigated the properties of BF-reinforced concrete through a laboratory test and found that the BF-reinforced concrete has a higher compression strength and deformation capacity compared to the controls (concrete without fiber). Xu et al. [17] and Wang et al. [18] investigated the performances and mechanical properties of the BF-reinforced asphalt concrete and found that fiber positively influenced the performance of asphalt mixture in terms of high-temperature deformation resistance, low-temperature cracking resistance, and fatigue behavior. Morova [6] investigated the effect of BF in hot mix asphalt (HMA) concrete using the Marshall stability test. The results indicate that the optimum asphalt content (5 %) and fiber ratio (0.50 %) led to better stability values compared with other asphalt contents.

Considering its outstanding physical and mechanical properties, BF is becoming a research hotspot in civil and road engineering. However, there is limited knowledge on the use of BF as additives in asphalt-chip seal. In this study, the application rate and length of BF used in chip seal is investigated to enhance the performance of asphalt-chip seal in terms of aggregate retention, interlayer bond, low-temperature anti-cracking, and skid resistance. For this purpose, the specimens of basalt fiber asphalt-chip seal (BFACS) at various contents of the modified emulsified asphalt (EA) and BF were prepared and evaluated by a series of laboratory tests to determine the optimum BFACS design.

Materials

MATERIAL PROPERTIES

In this study, SBR-modified EA was used in BFACS. The properties of EA binders satisfied the requirements of JTG E20-2011 [19], as given in Table 1. The BF characteristics are presented in Table 2. Basalt rock was used as an aggregate for the BFACS with a particle size of 5–10 mm, that is, overall gradation is one size or uniformly graded with fractured faces of 70 %. The physical test results of the aggregates are listed in Table 3 [20]. The BFACS structure is shown in Fig. 1.

### MATERIAL APPLICATION RATES

The fiber asphalt-chip seal (FACS) and ordinary asphalt-chip seal (OACS) are similar in material design. The FACS solely uses fiber as an additive to design a procedure of FACS, which can refer to the OACS theoretically and empirically [21]. The theoretical method (such as the Kearby and McLeod methods) has different versions in different countries or regions, without a unified standard design [22–26]. Thus, the empirical method is frequently used to determine the range of suitable material contents according to the field condition in the construction process [27,28].

Meanwhile, the test specification for the FACS is not well established, and the rates in chip seal application are mainly

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>EA binder properties.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
<td>Values</td>
</tr>
<tr>
<td>Evaporated residue</td>
<td>Evaporated residual content (%)</td>
</tr>
<tr>
<td>Penetration (25°C, 0.1 mm)</td>
<td>70</td>
</tr>
<tr>
<td>Softening point (°C)</td>
<td>55</td>
</tr>
<tr>
<td>Ductility (15°C, 5 cm/min)</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Solubility (Trichloroethylene) (%)</td>
<td>98.5</td>
</tr>
<tr>
<td>Adhesive with mine materials</td>
<td>&gt;2/3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>BF characteristics.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Values</td>
</tr>
<tr>
<td>Physical and mechanical</td>
<td></td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.78</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>4,100–4,840</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>93.1–110</td>
</tr>
<tr>
<td>Ductility at break (%)</td>
<td>3.1–3.2</td>
</tr>
<tr>
<td>Filament diameter (μm)</td>
<td>13–20</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td></td>
</tr>
<tr>
<td>H₂O (%)</td>
<td>1.5</td>
</tr>
<tr>
<td>2 n NaOH (sodium hydroxide) (%)</td>
<td>2.8</td>
</tr>
<tr>
<td>2 n HCl (hydrochloric acid) (%)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Aggregate properties.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity (g/cm³)</td>
<td>Moisture Absorption (%)</td>
</tr>
<tr>
<td>Moisture</td>
<td>Los Angeles Abrasion (%)</td>
</tr>
<tr>
<td>Crushing Values (%)</td>
<td>Flakiness Index (%)</td>
</tr>
<tr>
<td>2.946</td>
<td>1.017</td>
</tr>
<tr>
<td>15.60</td>
<td>14.33</td>
</tr>
<tr>
<td>3.5</td>
<td></td>
</tr>
</tbody>
</table>
determined by an empirical method. In this study, the initial material application rates were determined based on the empirical method as follows [29]: (1) the aggregates are well graded with a size of 5–10 mm. The aggregate content was set to 9.5–12.5 kg/m² in BFACS so that the wearing course can form a compact configuration as a thin layer of even particle distribution. (2) The EA content range was set to 1.4–2.2 kg/m² with an interval of 0.2 kg/m². (3) The BF content range was set to 50–110 g/m² to investigate the effect of BF on asphalt-chip seal.

Test Methods of Bond Performances and Results

The distresses of OACS in the field occur because of the insufficient bond between the binder and the aggregate or between the chip seal layer and the beneath layer. Therefore, it is important to assure the bond performance between the component materials in chip seal design and the engineering application. The bond performance of BFACS was investigated using different test methods, including plate impact, sweeping, pull-out, and direct shear tests. The plate impact test was conducted at a low temperature, whereas the sweeping test was performed at natural temperature to inspect the adhesion properties between the EA and the aggregates. The oblique load between the chip seal layer and the original pavement can be decomposed into the normal and shear forces. Thus, the pull-out and direct shear tests were carried out to evaluate the pull and shear strengths upon the interlayer. To determine the optimum content of each component, this study used five EA and four BF contents. At this stage, the BF measured at a length of 70 mm. Three replicated specimens were prepared and tested in this study.

PLATE IMPACT TEST

The plate impact test (PIT) was used to test the adhesive performance between the asphalt and the aggregates under impact load in chip seals. This can evaluate the aggregate retention performance by computing the aggregate loss [30,31]. The test temperature was −18. The developed procedure for the plate impact test is as follows:

1. Wash and dry the aggregates of 5–10 mm sizes and prepare the specimen mold with dimensions of 180 × 180 mm, maintaining the aggregate and mold at a constant temperature of 60°C.
2. Take and spray half of the mass of the designed EA content onto the mold, and then scatter the BF evenly onto the mold.
3. Take and spray the other half of the designed EA content onto the specimen mold, and then scatter it evenly at about 100 aggregates on the asphalt binder surface to form a surface abrasion layer, as shown in Fig. 2a.
4. Cure the specimens at 60°C for 8 h, and then store them at −18°C for 2 h.
5. Directly invert a specimen mold on the testing apparatus for 10 s after being cured in the freezer, as shown in Fig. 2b, then it is dropped to a stainless steel ball thrice from a 50-cm height on the back of the specimen mold.
6. Count the number of residual aggregates in the mold to calculate the percentage of aggregate loss using Eq 1.

\[
\text{Aggregate loss rate (\%)} = \frac{N_{T,\text{aggregate}} - N_{R,\text{aggregate}}}{N_{T,\text{aggregate}}} \times 100
\]

where:

- \(N_{T,\text{aggregate}}\) and \(N_{R,\text{aggregate}}\) = the number of aggregates on the chip-seal specimen before and after the test, respectively.

SWEEPING TEST

Sweeping test (ST) was also used to examine the bond performance between the asphalt and the aggregate under friction loads by calculating the off-aggregate mass for the BFACS. In general, the more off-aggregate weight in the specimens, the lower the adhesion between the asphalt and the aggregate, and vice versa. The test procedure follows ASTM D7000-11 [32] (Marshall et al. [33]). The test temperature was 25°C. The specimens and apparatus of the ST test are presented in Fig. 3a–c. The aggregate loss was calculated using Eq 2.

\[
\text{Aggregate loss mass (\%)} = \frac{W_{R,\text{aggregate}} - W_{A,\text{aggregate}}}{W_{R,\text{aggregate}}} \times 100
\]
where:

\[ W_{BA_{\text{aggregate}}} \text{ and } W_{A_{\text{aggregate}}} \] = the weights of the aggregate on the BFACS specimen before and after the test, respectively.

**PULL-OUT TEST**

Aside from the bond behavior of chip seal components, it is also important to evaluate the adhesive property between the chip seal and the original pavement [34]. The pull-out test was carried out to investigate the effects of the EA and BF contents on the pull-out strength between the abrasion course and the original asphalt surface course. The specimen fabrication and test procedure are as follows:

1. Prepare the base-plates of the asphalt concrete with a height of 50 mm and a cross section of 300 \( \times \) 300 mm, referring to the test methods of JTG E20-2011 [19].
2. Fabricate a BFACS layer on the base-plate, and then compress the specimens.
3. Cure the specimens on the over at 60°C for 16 h, and then cool them at room temperature (25°C).
4. Cut the specimens into a square dimension of 50 × 50 mm and paste the pull head on the specimen using an epoxy resin adhesive, as shown in Fig. 4a.
5. Keep the specimens flat, and then install the pull-out instrument on the pull head and perform the pull-out loading at a load rate of 100 mm/min [35].
6. Record the pull-out loading value and the size of the BFACS failure area at the interface to obtain the pullout strength.

**DIRECT SHEAR TEST**

Direct shear test (DST) was performed to determine the shear strength and to evaluate the bond performance between the layers of the tangent direction under shear loads. Through the DST test, the influence of the EA and BF contents on the bond performance between the fiber asphalt-chip seal (abrasion course) and the original pavement course were investigated.

The test was conducted at 25°C in a 50 × 50 mm loading area. The test model is shown in Fig. 4b. The specimen preparation and test procedure are similar with the pull-out test.

**TEST RESULTS**

The four set of test results are plotted in Figs. 5–8. The PIT test in Fig. 5 shows that the aggregate loss rate in the BFACS gradually decreases as the EA content increased under the constant BF content. However, for the same EA content, the value decreases first and then increases as the BF content increases. The minimum aggregate loss rate is obtained at 70 g/m² BF contents and 2.2 kg/m² EA contents. Similar findings are obtained for the ST test, as shown in Fig. 6. The minimal aggregate loss values achieved for the BF and EA contents are 90 g/m² and 2.2 kg/m², respectively. This finding also suggests that the increase of asphalt content positively influence the adhesion performance between the aggregate and the asphalt at low and medium temperatures. The fiber can significantly improve the aggregate retention performance, but this improvement effect decreases with excessive fiber. This result can be attributed to the mixture with BF, which adsorbs the existing redundant oil in the EA to effectively stop the flow of the free asphalts and to form a dense network structure among the fiber, asphalt, and aggregates. However, as the amount of fiber increases continuously, it absorbs the useful oil content to decrease the adhesive force between EA and aggregate and to increase the aggregate loss.
The pull-out test indicates that, under the same BF dosage, the strength generally increases as the EA content rose. However, the strength rises first and then drops with increasing BF dosages at the same EA dosage. As shown in Fig. 7, the peak strength value occurs at 90 g/m² BF and 2.2 kg/m² EA contents under pull-out loading. The DST test result indicates that the shear strength increases first and then reduces with the increase of the EA and BF contents. Fig. 8 shows that the maximum shear strength is obtained at 70 g/m² BF and 1.8 kg/m² EA contents under shear loading.

Based on the above results and analyses, the aggregate retention and the strength of the BFACS specimens significantly improved compared to those of the control specimens. Furthermore, the optimum contents for BF and EA are 70 g/m² and 1.8 kg/m², respectively.
Pavement Performances Evaluation

This section further inspects and analyzes the performances of BFACS in terms of low-temperature anti-cracking, interlayer bond, and skid resistance. Specimens at varying EA contents (1.4, 1.6, 1.8, 2.0, and 2.2 kg/m²), BF contents (0 [control], 50, 70, 90, and 110 g/m²), and BF lengths (30, 70, and 110 mm) were fabricated to quantify the individual impact. The test matrix is presented in Table 4.

### ANTI-CRACKING AT LOW TEMPERATURE

Cracking is a common distress that occurs in asphalt pavement, especially in cold regions. The plate tension test (PTT) was used to obtain the tensile strength of BFACS to further evaluate the BF-reinforced effect on chip seal. The specimen fabrication and test procedure are as follows:

1. Prepare a dusting agent of specimens coated by glass base-plates with a length of 300 mm and breadth of 60 mm, and then place the glass base-plates into a 60°C oven to a constant temperature.
2. Fabricate a BFACS layer on the base-plate, and then compress the specimens.
3. Cure the specimens at a 60°C oven for 8 h; then cool them at a −10°C for 2 h.
4. De-mold the specimens and measure their thicknesses; and then place the specimens quickly on the testing machine (see Fig. 9), where the loading rate is 20 mm/min under −10°C [35].
5. Record the tensile loading value and calculate the tensile strength using Eq 3.

\[
\sigma_t = \frac{P}{h \times 60}
\]

where:
- \(\sigma_t\) = the tensile strength,
- \(P\) = the maximum tensile load, and
- \(h\) = the thickness of the specimen.

### Effect of EA Content

In the Group A specimen, the developing curve of the tensile strength and the EA content (see Fig. 10a) show that the tensile strength of the specimens increases first and then decreases when the EA content rises at a constant BF content and length. Furthermore, the low temperature anti-cracking performance has similar rules and the peak value occurs at 1.8 kg/m² EA content. When the EA content is lower than 1.8 kg/m², it is absorbed by the fiber so that the asphalt content that binds the aggregates is insufficient. This explains the reduced anti-cracking performance. With the EA content is increasing, the BF absorbs the redundant asphalt to form a network structure system and enhances the bond performance. However, once the EA content is excessive, the free flow of the asphalt binder in the mixture does not completely contact with the BF, which develops a weak interface in fiber composites. Thus, the anti-cracking performance at a low temperature is weakened.

### Effect of BF Content

In the Group B specimen, Fig. 10b indicates the developing rule for tensile strengths, which is similar to that of Group A. The fiber possesses a high elastic modulus and an excellent tensile strength, which forms a network system after absorbing the asphalt binder to effectively prevent an initial cracking extension, thereby enhancing the crack resistance performance. However, with the continuous increase of BF content, an excessive BF content may produce an uneven distribution and even bundle together resulting in a weak structure interface. The peak strength of the curve is between 70 and 90 g/m² BF contents. The peak value of the tensile strength for BFACS is increased by 32.6 % compared to the control.

### Effect of BF Length

For the Group C specimen, Fig. 10c suggests that the tensile strength of the specimen increases as the BF’s length extends from...
30 to 110 mm. Furthermore, the difference in strength at 70 and 110 mm BF length is limited.

**ADHESIVE PERFORMANCE AT THE INTERLAYER**

Pushing and lumping are frequently observed in the asphalt pavement under hot temperature, where the former can result in pavement cracking and the latter influences surface course smoothness. One of the main causes of these distresses is the lack of an effective adhesion between the asphalt pavements under repeated horizontal vehicle loads resulting in the sliding at the interlayer [34]. The chip seal placed as the surface abrasion layer above the pavement course is thinner than the other pavement courses. Thus, these distresses can more easily occur on the interlayer. In this study, the results of the interlayer shear strength are obtained based on the DST, which further discusses and evaluates the bond performance of different EA content, as well as BF content and length.

**Effects of EA and BF Contents**

In the Group A specimen, Fig. 11a shows that the shear strength first increases and then decreases with increased EA content when the peak strength corresponds to 1.8 kg/m² EA content. This result can be attributed to the enlarging aggregates on the contact areas of the asphalt with aggregates given the same BF content and the increasing EA content. This condition increases the adhesive force, thereby improving the shear strength. However, if the EA content is excessive, the additional asphalt binder increases the asphalt film thickness to weaken the interlock between the aggregates and to degrade the bond performance at the interlayer in BFACS.

Fig. 11b indicates that, with the increase of BF content, the shear strength changes for the Group B specimen is similar with that of Group A, and its peak strength increased by 51.6 % compared to the result of the control specimen with a corresponding BF content of 70 g/m². This is because after mixing with fiber, BF adsorbs the EA asphalt to increase the viscosity and to form a dense network structure among the fiber, asphalt, and aggregates. In addition, the partial fibers inserted into the asphalt concrete course connect the surface abrasion layer of the chip seal and the asphalt concrete course to improve shear strength. When the amount of fiber increases continuously, the fiber may lump together to form a weak layer to reduce shear strength.

**Effect of BF Length**

Fig. 11c indicates the limited change of the interlayer shear strength for the Group C specimen. This result explains that the BF length is not the main factor influencing the adhesive property of the interlayer under constant contents of EA and BF.
SKID-RESISTANCE PERFORMANCE

The surface abrasion layer of pavements directly contacts with the vehicle tires; thus, the performance of skid resistance needs to be assured. The pavement surface texture based on micro- and macro-textures is strongly related to skid-resistance and tire-pavement friction, which are important to minimize traffic accidents [36]. In this study, the depth of the surface texture as an indicator was measured by conducting a texture depth test to evaluate the effects of the BF on the skid-resistance performance of the pavement. This test was performed with reference to the testing method T0731-2000 for JTG E20-2011 of China [19], wherein sand in the cylinder is initially poured on the surface of the BFACS specimen, and then spread out into a round shape from inside to outside using a pushing flat-plate. The diameter of the round shape is finally measured. The calculated equation of the surface texture depth is as follows:

\[
TD = \frac{1000 \times V}{\pi \times D^2 / 4} = \frac{31.831 \times D^2}{D^2}
\]

where:
- \(TD\) = the surface texture depth value (mm),
- \(V\) = the volume of sand at 25 cm\(^3\), and
- \(D\) = the average diameter of the flatted sand (mm).

Effect of EA Content

Fig. 12a suggests that the texture depth gradually decreases as the EA content increased for the Group A specimen; thus, the skid resistance performance also decreases as the EA content rose. As the EA content becomes larger than 1.8 kg/m\(^2\), the change rate of the texture depth quickens. For this reason, the rising effect of asphalt increases along the surface of the aggregates with increased EA content, hence the surface texture depth decreased at the constant BF content and length of BFACS.

Effect of BF Content

Fig. 12b shows that the skid resistance remarkably increases as the BF content rises for the Group B specimen. For this reason, the amount of EA absorbed in the fiber increases as the BF content increased to reduce the free asphalt content; thus, the rising effect of EA is diminished. Eventually, the surface texture depth is increased at the same EA content and BF length in BFACS.

Effect of BF Length

Fig. 12c indicates that the texture depth is nearly identical despite the increased BF length for the Group C specimen. Thus, the BF length has a limited impact on the skid resistance performance for the surface abrasion course.
Conclusions

In this study, the basalt fiber additive was used as a surface abrasion layer in asphalt-chip seal and its performances were evaluated using a series of laboratory tests. Based on the experiment results obtained in this paper, the following conclusions can be drawn:

1. Results of the bond performance testing showed that the BF added in the asphalt-chip seal can remarkably enhance the adhesion performance among the aggregate, asphalt, the pull-out strength, and the shear strength at the interlayer compared to the control specimen. However, it should also be noted that this reinforcement effect may decrease given excessive fiber. Based on the above results, the optimum BF and EA contents were obtained as 70 g/m² and 1.8 kg/m², respectively.

2. Based on the performance analysis of BF-reinforced asphalt-chip seal in terms of low temperature anti-cracking, interlayer bond, and skid resistance, the findings confirmed that the ultimate optimal chip seal is composed of 1.8 kg/m² EA and 70 g/m² BF at a length of 70 mm.

3. The basalt fiber was demonstrated to significantly improve the asphalt-chip seal performance, including low temperature anti-cracking, interlayer bond, and skid resistance as opposed to the control specimens (0 % BF), wherein the tensile strength, the shear strength, and the surface texture depth (the optimal content) were increased by 29.2 %, 51.6 %, and 14.2 %, respectively. The usage of BF in asphalt-chip seal has a substantial positive impact on the BFACS performances.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the support of the National Natural Science Foundation of China (No. 51108082). All of the authors of the works cited herein are much appreciated.

References


