Research Article

Study on the Low Temperature Cracking Mechanism of Steel Slag Asphalt Mixture by Macroscale and Microscale Tests

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Steel slag’s physical and mechanical properties are close to natural gravel, which can replace natural aggregate with paving asphalt mixture pavement. Based on macro- and microscales, it is necessary to study the low-temperature cracking characteristics of steel slag asphalt mixture (SAM). This paper aims to study the low-temperature cracking characteristics and influence mechanism of steel slag asphalt mixture by macro- and microscale tests. This article analyzes the strain field distribution and cracks propagation law of SAM at low temperatures by the three-point bending test combined with digital image correlation (DIC). The microscopic pore characteristics of SAM were studied by nuclear magnetic resonance (NMR). Based on fracture mechanics and weight function theory, the variation law of the stress intensity factor at the crack tip of the asphalt mixture with crack propagation is derived. The correlation between microscopic pores and low-temperature cracking characteristics of asphalt mixture was analyzed based on the grey correlation theory. The results show that SAM has more small and less large pores, and its total porosity is lesser than that of the basalt asphalt mixture (BAM). The initial elastic stage of SAM resisting bending deformation is longer than that of BAM, the bending strain energy density (dW/dV) is larger, and the crack penetration is slower. The horizontal strain energy density (Dh) of SAM is greater than BAM, and the crack tip stress is greater. The porosity correlates well with the low-temperature crack resistance of the asphalt mixture.

1. Introduction

Steel slag is a solid waste produced in the process of steel smelting. It can be used as an asphalt mixture aggregate in road engineering [1–3]. Pasetto and Baldo [4] studied the physical and chemical properties of steel slag and the mechanical properties of SAM. The results showed that steel slag had good adhesion to asphalt and better mechanical properties than natural aggregate. Wu et al. [5, 6] compared the interfacial bonding properties of SAM. The results showed that the steel slag fine aggregate was alkaline and could avoid the gelation of silicate minerals, with a high absorption rate and good adhesion to asphalt. However, there are few attempts to apply SAM in severe cold areas at home and abroad, and the research on its low-temperature crack resistance is still in its infancy [7]. Currently, standard evaluation methods for the low-temperature performance of asphalt mixture include the stiffness modulus method, low-temperature shrinkage coefficient method, and low-temperature creep rate method, which are macroevaluation methods [8]. Cannone Falchetto et al. [9–11] studied the low-temperature performance of the asphalt mixture. The results showed that the macroscopic mechanical properties of materials were determined by their inherent mesostructure. The macroscopic failure behaviour results from damage accumulation and fractures at the mesoscale. Jacob et al. [12] analyzed the fracture of asphalt mixture by using the Paris criterion, and the results showed that the crack propagation behaviour of asphalt mixture under load could be understood as the interaction of asphalt mortar, aggregates, and pores under load.
Kim and Hussein [13–15] used DIC technology to study the influence of the polyester mesh layer on the initiation and propagation of cracking of asphalt mixture. The results showed that the polyester mesh layer could improve the anticracking performance of the asphalt mixture. Wang et al. [16] applied DIC technology to the crack resistance test of asphalt mixture and proposed new indexes (horizontal strain $D_h$ and horizontal strain toughness $J_g$) for evaluating mesocracking characteristics of asphalt mixture. Mamlouk and Mobasher [17] analyzed the variation rule of stress intensity factor at the crack tip of asphalt mixture under different temperatures and loads by the three-point bending test. Studies showed that the lower the temperature, the higher the stress intensity factor, and the higher the load rate, the higher the stress intensity factor. Chell [18, 19] studied the stress intensity factor at the tip of pavement cracks using fracture mechanics combined with weight function theory. They deduced the calculation method of SIF for continuous pavement crack. Carpinteri et al. [20] analyzed the influence of cracks’ formation and propagation process in fibre asphalt mixture by studying the change rule of fractal dimension. Studies showed that the fractal dimension gradually increased with damage evolution and crack propagation, and micro-cracks became more chaotic. Jeager and Hoskins [21] studied the fracture of the asphalt mixture from a macroscopic perspective. They found that the cracking of the asphalt mixture began at the peak load point, and the material was continuously damaged in the subsequent process. Through the analysis of CT images of asphalt mixture, Wang et al. [22] found that the permanent deformation of asphalt mixture is significantly correlated with its internal structure, and the weakness of the internal structure is the main factor of permanent deformation. Quan et al. [23] observed and counted the microscopic images, pore types, and content of asphalt mixture specimens. Their studies showed that the closed pores in the asphalt mixture had an essential impact on the damaged evolution of materials. Wu et al. [24] used X-ray Computed Tomography (X-ray CT) and Mercury Intrusion Porosimetry (MIP) to study the effects of salt content, soaking time, and freeze-thaw cycles on pore characteristics. The results showed that the pore content increased sharply with the increase in salt content, water bath time, and freeze-thaw cycles. Asphalt mixture is a porous material with many internal pores. The essential cause of the deformation and destruction of asphalt mixture under the low-temperature environment are the development of internal defects, such as the pores and cracks of the mixture.

In this paper, the three-point bending test obtained the stress-strain curve, and the horizontal strain field distribution during cracking was analyzed with Video Image Correlation (VIC-3D). The low-temperature cracking performance of SAM was studied from macro- and microscales with bending strain energy density and horizontal strain energy density as indexes, respectively. There are two reasons for the failure rate of the beam in the three-point bending test. One is the bending strain energy of the beam, which is related to the flexure-tension-resistant performance of the asphalt mixture. The other is the distribution of potential stress concentration points, which is related to the heterogeneity of the beam; the size, and distribution of the pores influence the asphalt mixture's heterogeneity. The DIC obtained the crack length, and the variation of the stress intensity factor of the crack tip is derived. The effect of pore parameters on the low-temperature anticracking performance of SAM was studied.

2. Materials and Tests

2.1. Materials. The asphalt used in this study was SBS-modified asphalt. Two kinds of aggregate are used for asphalt mixtures, one is 100% steel slag aggregate and the other is 100% basalt aggregate. The aggregates fall into four grades of 10–20 mm, 5–10 mm, 3–5 mm, and 0–3 mm particle size. The mineral powder is made of limestone. The basic indexes of SBS-modified asphalt and aggregates are listed in Tables 1–3. The SAM and BAM gradation types are AC-16, designed by the Marshall method [4, 25]. The optimum grading, asphalt dosage, and porosity are shown in Table 4. The steel slag and basalt surface morphology was observed using the Laser Scanning Microscope (CLSM), as shown in Figure 1. Figure 1(a) is steel slag, and Figure 1(b) is basalt. It can be seen from the figure that the surface of the steel slag has a large contrast of light and dark color, indicating that the surface elevation difference of the steel slag has more pits and protrusions. From the three-dimensional steel slag surface elevation map in the lower right corner, the surface of steel slag is rougher than basalt, with many pits protruding; therefore, it is conducive to asphalt adhesion.

2.2. Tests

2.2.1. Nuclear Magnetic Resonance (NMR) Test. In order to study the effect of internal pore characteristics on material strength, the pore structure of SAM and BAM was tested through NMR. The asphalt mixture trabecular was cut into 40 mm ∗ 30 mm ∗ 35 mm cube specimens by a precision cutting machine, as shown in Figure 2(a). The specimens with vacuum saturation for 24 hours were placed in a MesoMR23-060H-I nuclear magnetic resonance spectrometer for testing, as shown in Figure 2(b). The pore parameters of SAM and BAM were calculated by the $T_2$ spectrum, which is obtained by the NMR test, and the relationship between pore structure and low-temperature crack resistance of the asphalt mixture was established [26, 27].

2.2.2. Three Point Bending Test of Beam Based on DIC. In order to study the low-temperature anticrack performance of SAM, using UTM, the load speed is 1 mm/min for a three-point bending test. The standard specimen (300 mm × 300 mm × 50 mm) is made by an LH-2 rut forming machine. A 3 mm × 1 mm prenotch is set in the middle of the beam bottom. Grind the sample surface and apply matte white paint. A matte black paint was applied to form uniform spots on the specimen surface. SAM and BAM experimented with three sets of parallel pieces. The Digital Speckle Correlation Method (DSCM) test system collected digital speckle images of beams, and horizontal strain analysis was performed by the VIC-3D technique, as shown in Figure 3.
Table 1: Basic indexes of SBS-modified asphalt.

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Specification</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration, 25°C, 100 g/5 s</td>
<td>0.1 mm</td>
<td>T 0604-2011</td>
<td>39.8</td>
</tr>
<tr>
<td>Softening point</td>
<td>°C</td>
<td>T 0606-2011</td>
<td>71.0</td>
</tr>
<tr>
<td>Ductility, 5°C</td>
<td>cm</td>
<td>T 0606-2011</td>
<td>14.0</td>
</tr>
<tr>
<td>Viscosity at 135°C</td>
<td>Pa·s</td>
<td>T 0606-2011</td>
<td>4.03</td>
</tr>
</tbody>
</table>

Table 2: Aggregate of SAM test results.

<table>
<thead>
<tr>
<th>Mineral specification</th>
<th>Apparent density (g/cm³)</th>
<th>Bulk density (g/cm³)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–20 mm</td>
<td>3.697</td>
<td>3.624</td>
<td>0.75</td>
</tr>
<tr>
<td>5–10 mm</td>
<td>3.647</td>
<td>3.592</td>
<td>1.12</td>
</tr>
<tr>
<td>3–5 mm</td>
<td>3.678</td>
<td>3.503</td>
<td>1.90</td>
</tr>
<tr>
<td>0–3 mm</td>
<td>3.499</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mineral powder</td>
<td>2.628</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3: Aggregate of BAM test results.

<table>
<thead>
<tr>
<th>Mineral specification</th>
<th>Apparent density (g/cm³)</th>
<th>Bulk density (g/cm³)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–20 mm</td>
<td>2.813</td>
<td>2.765</td>
<td>1.04</td>
</tr>
<tr>
<td>5–10 mm</td>
<td>2.956</td>
<td>2.700</td>
<td>1.00</td>
</tr>
<tr>
<td>3–5 mm</td>
<td>2.918</td>
<td>2.860</td>
<td>1.02</td>
</tr>
<tr>
<td>0–3 mm</td>
<td>2.881</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mineral powder</td>
<td>2.628</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 4: Optimum gradation, asphalt content, and porosity.

<table>
<thead>
<tr>
<th>Aggregate</th>
<th>Optimum gradation</th>
<th>Optimum asphalt</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAM (%)</td>
<td>BAM (%)</td>
<td>SAM (%)</td>
</tr>
<tr>
<td>0–0.75 mm</td>
<td>3</td>
<td>4</td>
<td>—</td>
</tr>
<tr>
<td>0.75–3 mm</td>
<td>24</td>
<td>33</td>
<td>4.56</td>
</tr>
<tr>
<td>3–5 mm</td>
<td>8</td>
<td>11</td>
<td>—</td>
</tr>
<tr>
<td>5–10 mm</td>
<td>35</td>
<td>22</td>
<td>—</td>
</tr>
<tr>
<td>10–20 mm</td>
<td>30</td>
<td>30</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 1: Mesosurface topography of aggregates: (a) mesosurface topography of steel slag; (b) mesosurface topography of basalt.
3. Results and Analysis

3.1. The Total Porosity. Figure 4 shows the total porosity of three groups of SAM and BAM. The figure shows that the total porosity (P) of SAM is smaller than that of BAM.

3.2. Pore Size Distribution (PSD). During the deformation of the material, the holes will squeeze and penetrate. Pore size and diversity affect material strength. Figure 5(a) shows the pore size distribution curve of SAM, and Figure 5(b) shows the pore size distribution curve of BAM. The pore size distribution curve is in a three-peak state. The curve is divided into three parts. The pore size of Part I is 10,000 nm, and the peak of SAM in this part is lower than BAM, accounting for a minor proportion of the total porosity. The pore diameter of Part II is 1000 nm~10000 nm, and the wave peak of BAM in this part is lower than BAM, accounting for a minor proportion of the total porosity. The pore size of Part III is 10000 nm~100000 nm. The wave peaks of BAM in this Part are higher than SAM. The peak porosity of Part II and Part III is higher in the two asphalt mixtures, and the peak porosity of SAM is lower than BAM. The numerical statistics of partial porosity ($P_A$) and peak porosity ($P_M$) in Figure 5 are given in Table 5.

3.3. The Fractal Dimension of Aperture $D_N$. In this paper, NMR pore structure analysis is based on the assumption that the internal pores of asphalt mixture are ideal spheres of different sizes. However, the pore structure inside the asphalt mixture is complex and randomly distributed, so the fractal dimension of pore size is used to analyze its complexity. Based on the Mengersponge model, the fractal dimension is calculated according to the literature [28], as shown in the following equation:

$$\lg V_L \propto (3 - D_N)\lg r,$$

where $V_L$ is the percentage of relaxation time less than $T_2$ pore cumulative volume in total porosity, $T_2$ is the transverse relaxation time, $T_{2\text{max}}$ is the maximum relaxation time, $D_N$ is a fractal dimension. $r$ is the aperture.
In the case of the SAM specimen, the lgV and lgR relation curves of the NMR fractal dimension model are drawn as shown in Figure 6. The curve presents two distinct phases on either side of the 98 nm. The point correlation $R^2$ of curve samples were all greater than 0.85, indicating that the SAM pore structure characterized by NMR has fractal characteristics. According to equation (1), $D_N$ is calculated from the slope $k_a$ and $K_b$ of the curve. The characteristic pore parameters of Part II and III of SAM and BAM in Figure 6, such as porosity $P_A$ and wave peak porosity $P_M$, as well as the calculated pore fractal dimension $D_N$, are summarized in Table 5. From the data analysis in the table, the fractal dimensions of BAM pore structure $D_{Na}$ and $D_{Nb}$ were larger than those of SAM. The larger the fractal dimension is, the smaller the effective bearing area of the mixture is, and the more complex the pore structure, the tubular or irregular pore structure [29]. Such asphalt mixture has strong heterogeneity, which is unfavourable to the cracking resistance of the material. Therefore, after being stressed, BAM will enter the damage stage earlier, and the cracking resistance is poor.

3.4. Stress and Strain. The stress-strain curves of SAM and BAM asphalt mixtures under load are shown in Figure 7. The cracking process of SAM can be divided into the initial elastic stage ($OA_1$), linear viscoelastic stage ($A_1A_2$), and nonlinear damage stage ($A_2A_3$). The cracking process of BAM can be divided into the initial elastic stage ($OB_1$), nonlinear viscoelastic stage ($B_1B_2$), and nonlinear damage stage ($B_2B_3$). The initial elastic stage of SAM and BAM almost coincide ($0 < \varepsilon < 0.0014 \text{ mm}^{-1}$). BAM is a typical nonlinear viscoelastic failure, and its nonlinear viscoelastic stage is short ($0.0014 \text{ mm}^{-1} < \varepsilon < 0.0097 \text{ mm}^{-1}$). It soon enters the nonlinear damage stage ($0.0039 \text{ mm}^{-1} < \varepsilon < 0.0039 \text{ mm}^{-1}$). SAM has a quasi-brittle failure and long linear viscoelastic stage ($0.0014 \text{ mm}^{-1} < \varepsilon < 0.0089 \text{ mm}^{-1}$). SAM has the property of delaying the damage of specimens. In the bending deformation of two asphalt mixtures, the lower pores of the specimen are deformed by tension, and the upper pores are deformed by compression. Because BAM has more internal pores, BAM beam heterogeneity is more serious. In the process of deformation, there are more stress concentration points caused by the internal pores, so the deformation stability of BAM material is poor, and it enters the nonlinear damage stage earlier. SAM has fewer pores and fewer stress concentration points caused by the internal pores of the
material. The deformation resistance stage is more linear, and the deformation time of the material is longer than BAM. There are more micropores of Part I in SAM than in BAM. The micropore deformation of the material is earlier than the strain response of the material at the initial stage of loading, and the viscoelastic deformation of SAM is linear after that. In the process of deformation, there are more stress concentration points caused by the internal pores, so the deformation stability of BAM material is poor, and it enters the nonlinear damage stage earlier. SAM has fewer pores and fewer stress concentration points caused by the internal pores of the material. The deformation resistance stage is more linear, and the deformation time of the material is longer than BAM. There are more micropores of Part I in SAM than in BAM. The micropore deformation of the material is earlier than the strain response of the material at the initial stage of loading, and the viscoelastic deformation of SAM is linear after that.

3.5. Bending Strain Energy Density. Bending strain density is an important macro indicator of the anticrack performance of asphalt mixture:

\[
\frac{dW}{dV} = \int_0^{\varepsilon_0} \sigma d\varepsilon = \int_0^{\varepsilon_0} f(\varepsilon) d\varepsilon, 
\]

where \(dW/dV\) is the bending strain energy density of asphalt mixture, \(\varepsilon_0\) is the strain value under the maximum stress. The bending strain energy density and peak stress of the two asphalt mixtures obtained by equation (2) [30] are listed in Table 6. The bending strain energy of SAM is 16.4% higher than that of BAM, indicating that SAM has better crack resistance at low temperatures than BAM. The peak stress of SAM is 17.2% higher than BAM, and the peak stress point is the stress at the crack tip when the asphalt mixture cracks [31]. SAM can withstand greater stress in the anticrack process.

3.6. Strain Field and Strain Analysis. Figure 8 shows the full-field strain cloud diagram when the beam is about to crack in the three-point bending test under DIC high-speed photography. Figures 8(a) and 8(b) are the strain states of SAM and BAM in the nonlinear damage stage during the bending deformation process, respectively. SAM and BAM beam specimens show a state of tension at the bottom and compression at the top. At this stage, SAM and BAM strains are concentrated, and nucleation is obvious in the red region in the middle. The reason is that with the increase of strain above the precut, the phenomenon of strain aggregation around it is significant. The adhesion between aggregate and mortar at the coarse aggregate interface near the strain concentration point gradually fails under a high-stress state. The original microcracks in the specimen are deformed and expanded more rapidly, thus forming macrocracks. The span from the minimum horizontal strain value to the maximum value for SAM is 0.0059–0.0154, and the span from the minimum horizontal strain value to the maximum value for BAM is 0.0046–0.0141. It indicates that the strain gradient of SAM is larger when the crack initiation point is formed, which further indicates that SAM has better flexural and tensile resistance.

3.6.1. Horizontal Strain. The accumulation of horizontal strain with time near the pre-cut of the beam specimen at the crack bottom is the most significant. As shown in Figures 8(a) and 8(b), seven points \((A_1, A_2, A_3, A_4, A_5, A_6\) and \(A_7)\) at the bottom of the crack are selected. The point with the most significant change in horizontal strain with time is taken as the research object, and the change rule of horizontal strain with time near the precut of the beam specimen at the crack bottom is analyzed, as shown in Figure 9. Between 400 s before loading, SAM and BAM are at the initial elastic deformation stage. The horizontal strain growth trends are the same, and the curves almost coincide. At 418 s, BAM first enters the nonlinear damage stage, and the horizontal strain increases rapidly with time. The horizontal strain of BAM reaches its peak earlier than...
that of SAM. The strain growth rate of BAM is higher than that of SAM.

### 3.6.2. Horizontal Strain Energy Density

The accumulation of the maximum horizontal strain at the crack bottom of the asphalt mixture over time from the beginning of loading to the formation of macroscopic cracks (horizontal strain energy density $D_{Eh}$) can characterize the material’s ability to store strain energy in the process of low-temperature cracking. The low-temperature cracking resistance of SAM was quantitatively and accurately described at a mesoscale.

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending strain energy density ($\text{KJ/m}^2$/dW/dV)</td>
<td>0.052</td>
<td>0.046</td>
<td>0.043</td>
<td>0.040</td>
<td>0.039</td>
<td>0.039</td>
</tr>
<tr>
<td>Average ($\text{KJ/m}^2$)</td>
<td>0.047</td>
<td>0.040</td>
<td>0.040</td>
<td>0.040</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure stress (MPa) $\sigma_0$</td>
<td>7.62</td>
<td>7.33</td>
<td>6.51</td>
<td>6.14</td>
<td>5.97</td>
<td>5.64</td>
</tr>
<tr>
<td>Average (MPa)</td>
<td>7.15</td>
<td>5.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$D_E$ is the $E_{XX} - t$ curve area before the maximum value of $E_{XX}$, as shown in Figure 10 in the color area ($S_A$ and $S_B$). The higher the $D_E$ value is, the better the crack resistance of the asphalt mixture is. The function expression is shown in the following equation (3), [16]:

$$D_E = \int_{0}^{t_d} E(t)dt,$$

where $E(t)$ is the $E_{XX} - t$ curve function, $t$ is the time value corresponding to the maximum value of $E_{XX}$, and $t_d$ is the differential of time. The calculation results of horizontal strain energy density $D_E$ of SAM and BAM are shown in Table 7. The horizontal strain energy density of SAM is 33.51% higher than BAM. SAM has better crack resistance at the mesoscale than BAM at low temperatures. Because SAM and BAM use the same asphalt mortar at the same temperature, SAM’s bending strain energy density and horizontal strain energy density are higher than BAM’s, indicating that this difference is influenced by the second reason mentioned above. It is affected by the difference in aggregate extrusion and adhesion between aggregate and asphalt mortar caused by different aggregate types.

3.7. Crack Length. The images of the specimens captured by the CCD high-speed camera were greyed, as shown in Figure 10(a), and the appropriate threshold was selected in Figure 10(b). Binarization images were obtained using the maximum interclass variance method [32]. Through the three links of fracture smoothing, skeleton, and fracture cutting, qualitative identification is carried out from the formation and propagation of microcracks to the main cracks. Sezer et al. proposed a binary region thinning
algorithm based on deleting region boundary points to obtain the region skeleton [33].

\[
\begin{align*}
(a) & \; 2 \le N(p_1) \le 6, \\
(b) & \; T(p_1) = 1, \\
(c) & \; p_2 \times p_4 \times p_6 = 0, \\
(d) & \; p_4 \times p_6 \times p_8 = 0,
\end{align*}
\]

where \( N(p_1) \) is the number of nonzero pixels of \( p_1 \).

\[
N(p_1) = p_2 + p_3 + \cdots + p_8 + p_9,
\]

where \( p_i \) is 0 or 1, \( T(p) \) is the collating sequence. Repeated this calculation to generate a two-dimensional structure map of this region (a binary map of the crack), as shown in Figure 10(c). The crack length can be obtained.

In the crack skeleton diagram, the corresponding fracture length can be obtained by accumulating the distance of adjacent pixels diagonally is 21/2 units length. The spacing between adjacent pixels diagonally is denoted as one unit length. The horizontal strain energy density of SAM is 33.51% higher than BAM. SAM has better crack resistance at the mesoscale than BAM at low temperatures. Because SAM and BAM use the same asphalt mortar at the same temperature, SAM’s bending strain energy density and horizontal strain energy density are higher than BAM’s, indicating that this difference is influenced by the second reason mentioned above. It is affected by the difference in aggregate extrusion and adhesion between aggregate and asphalt mortar caused by different aggregate types. Based on the calculation method of fracture length of the skeleton, the total crack length \( y \) can be obtained, \( y_{SAM} = 23.74 \) mm, \( y_{BAM} = 20.61 \) mm, \( y_{SAM} > y_{BAM} \). It shows that SAM can bear more damage before instability. Origin fitting is used to obtain the equation of crack length with time as shown in the following equation:

\[
y = A + B \times \left( \exp \left( \frac{C \times t}{t} - 1 \right) \right). \tag{6}
\]

The material parameters \( A, B, \) and \( C \) of the two mixtures obtained after Origin fitting are shown in Table 8.

The derivative of equation (6) is applied to obtain the crack growth rate as shown in equation (7). Since the material parameters \( B \) and \( C \) of BAM are both larger than SAM, the crack growth rate of BAM after cracking is faster than SAM.

\[
\frac{dy}{dt} = B \times \exp \left( \frac{C \times t}{t} \right). \tag{7}
\]

### Table 7: Horizontal strain energy density \( D_e/(KJ/m^2) \).

<table>
<thead>
<tr>
<th>Test specimen</th>
<th>Asphalt mixtures</th>
<th>SAM</th>
<th>BAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_e ) (KJ/m²)</td>
<td>( A_1 )</td>
<td>( A_2 )</td>
<td>( A_3 )</td>
</tr>
<tr>
<td>Average</td>
<td>5.83</td>
<td>5.69</td>
<td>5.41</td>
</tr>
</tbody>
</table>

3.8. Stress Intensity Factor. In order to describe the stress intensity at the crack tip, the weight function method was introduced and combined with the total crack length obtained by the DIC data binary region thinning algorithm. As the crack length expands, the stress intensity factor at the crack tip is calculated. One of the key problems to be solved in fracture mechanics theory is the stress intensity factor, which characterizes the stress singularity of the crack tip. The stress intensity factor is defined in fracture mechanics to describe the stress field strength of the crack tip because the stress field near the crack tip appears in regularity. For the stress intensity factor under complex stress conditions, Bueckner proposed the weight function method of the stress intensity factor. That is, the stress intensity factor \( K \) at the crack tip of the cracked body under arbitrary load can be obtained through equations (8) and (9) [35]:

\[
K = \int_0^y \sigma_0 m(x, y) dx, \tag{8}
\]

\[
m(x, y) = \left[ \frac{2}{\sqrt{2\pi} (y-x)} \right] \times \left[ 1 + M_1 \left( 1 - \frac{x}{y} \right)^{1/2} \right] + M_2 \left( 1 - \frac{x}{y} \right)^{1/2}, \tag{9}
\]

where \( x \) is the variable of the crack length, \( y \) is the maximum crack length, \( \sigma \) is the stress component corresponding to the crack surface position when the crack develops to \( x \), \( m(x, y) \) is the weight function, the weight function is only related to the geometric form of the crack, \( M_i \) (i = 1, 2, 3) is the geometric parameter, and its value only depends on the geometric form of the crack.

At the crack beginning of the edge cracked \( x=0 \), the curvature of the crack surface was 0, and then equation (10) was derived:

\[
\frac{d^2 m(x, y)}{dx^2} \bigg|_{x=0} = 0. \tag{10}
\]

The three-point bending test is used as an additional condition for solving \( M_3 \), so only two reference stress solutions need to be found. The type of load in the three-point bending test is very complex and is simplified to the superposition of two load types, i.e., uniform load and trapezoidal load, as shown in Figure 11. When the crack length develops to \( x \), the stress components corresponding to the crack surface position are shown in equation (11), respectively, uniformly distributed and trapezoidal loads, where \( W \) is the height of the beam specimen.

\[
\begin{align*}
(a) \; & \sigma_{t1} (x) = \sigma_0, \\
(b) \; & \sigma_{t2} (x) = \sigma_0 \left[ 1 - \left( \frac{2}{W} \right) x \right]. \tag{11}
\end{align*}
\]
In equation (11), the reference stress intensity factors corresponding to the two loads are as follows:

\[(a)\ K_{r1} = F_1 \sigma_0 \sqrt{\pi Y},\]
\[(b)\ K_{r2} = F_2 \sigma_0 \sqrt{\pi Y},\]  

where \(F_i (i = 1, 2)\) is the geometric correction coefficient of the reference stress intensity factor, which can be found in the stress intensity factor manual [36]:

\[(a)\ F_1 = 1.12 - 0.231 \left( \frac{Y}{W} \right) + 10.55 \left( \frac{Y}{W} \right)^2 - 21.72 \left( \frac{Y}{W} \right)^3 + 30.39 \left( \frac{Y}{W} \right)^4,\]
\[(b)\ F_2 = 1.122 - 1.4 \left( \frac{Y}{W} \right) + 7.33 \left( \frac{Y}{W} \right)^2 - 13.08 \left( \frac{Y}{W} \right)^3 + 14 \left( \frac{Y}{W} \right)^4.\]  

Substituting equation (9) into equations (10) and (13) into (12), three equations about \(M_i (i = 1, 2, 3)\) can be obtained as follows:

\[(a)\ F_1 \sigma_0 \sqrt{\pi Y} = \int_0^a \sigma_0 \left[ \frac{2}{\sqrt{2\pi}(Y-x)} \right] \left[ 1 + M_1 \left( 1 - \frac{X}{Y} \right)^{1/2} + M_2 \left( 1 - \frac{X}{Y} \right) + M_3 \left( 1 - \frac{X}{Y} \right)^{3/2} \right] dx,\]
\[(b)\ F_2 \sigma_0 \sqrt{\pi Y} = \int_0^a \sigma_0 \left[ 1 - \frac{2}{W} X \right] \left[ 1 + M_1 \left( 1 - \frac{X}{Y} \right)^{1/2} + M_2 \left( 1 - \frac{X}{Y} \right) + M_3 \left( 1 - \frac{X}{Y} \right)^{3/2} \right] dx,\]
\[(c)\ \frac{\partial^2}{\partial x^2} \left[ \frac{2}{\sqrt{2\pi}(Y-x)} \right] \left[ 1 + M_1 \left( 1 - \frac{X}{Y} \right)^{1/2} + M_2 \left( 1 - \frac{X}{Y} \right) + M_3 \left( 1 - \frac{X}{Y} \right)^{3/2} \right] \bigg|_{x=0} = 0.\]

Then, it is deduced that

---

**Table 8: Material parameters of SAM and BAM.**

<table>
<thead>
<tr>
<th></th>
<th>SAM</th>
<th>BAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00813 ± 0.03779</td>
<td>2.11497 ± 0.02491</td>
</tr>
<tr>
<td>B</td>
<td>1.05367E - 23 ± 4.44531E - 24</td>
<td>2.39411E - 23 ± 5.37298E - 24</td>
</tr>
<tr>
<td>C</td>
<td>0.33353 ± 0.00262</td>
<td>0.510394 ± 0.00441</td>
</tr>
</tbody>
</table>

**Figure 11: Reference load.**

---

In equation (11), the reference stress intensity factors corresponding to the two loads are as follows:

\[(a)\ K_{r1} = F_1 \sigma_0 \sqrt{\pi Y},\]
\[(b)\ K_{r2} = F_2 \sigma_0 \sqrt{\pi Y},\]  

where \(F_i (i = 1, 2)\) is the geometric correction coefficient of the reference stress intensity factor, which can be found in the stress intensity factor manual [36]:
\[(a) M_1 = \left( \frac{\sqrt{2}}{2} \right) \left( \frac{3W}{y^2} - 2 \right) F_1 \pi - \left( \frac{3\sqrt{2}}{2} \right) \left( \frac{W}{y} \right) F_2 \pi - \frac{24}{5}, \]
\[(b) M_2 = 3, \]
\[(c) M_3 = \left( 3\sqrt{2} \right) \left( 1 - \frac{W}{y} \right) F_1 \pi + 3\sqrt{2} \left( \frac{W}{y} \right) F_2 \pi + \frac{8}{5}. \]

Substituting equation (15) into equations (8) and (9), the stress intensity factor \( K \) at the crack tip is

\[
K = \int_0^{\alpha_0} \left[ 2 \frac{1}{\sqrt{2\pi(\gamma-x)}} \right] \left[ 1 + 3 \left( 1 - \frac{X}{\gamma} \right) + \left[ 2.1\sqrt{2} - 1.683\sqrt{2} \left( \frac{W}{\gamma} \right) - 10.995\sqrt{2} \left( \frac{W}{\gamma} \right) + 52.17\sqrt{2} \left( \frac{W}{\gamma} \right)^2 - 110.025\sqrt{2} \left( \frac{W}{\gamma} \right)^3 + 60.78\sqrt{2} \left( \frac{W}{\gamma} \right)^4 \right] \pi + \frac{16}{5} \left( 1 - \frac{X}{\gamma} \right)^{1/2} \right] dx.
\]

The total crack length \( y \) obtained was substituted into equation (16) to obtain the crack tip stress intensity factor of the two asphalt mixtures at different crack propagation depths, as shown in Figure 12. It can be seen that the stress intensity factor at SAM’s crack tip is always greater than BAM, with the crack length increasing. The stress intensity factor at SAM’s crack tip decreases more slowly than BAM with the increase of crack depth, and the residual stress intensity factor is larger than that at BAM. It indicates that SAM has higher deformation resistance strength and better crack resistance strength.

### 4. Discussion and Analysis

#### 4.1. Correlation Analysis between Pore Characteristic Parameters and Macro- and Microevaluation Indexes of Low-Temperature Crack Resistance of Asphalt Mixture

Correlation analysis was conducted on pore characteristic parameters (\( P, P_{II}, P_{III}, P_{II}, P_{II}, D_{Na}, \) and \( D_{Nb} \)) of the two asphalt mixtures with \( dW/dV \) and \( D_{Eb} \) macrocrack resistance indexes at low temperature, respectively, as shown in Figure 13. The left axis is \( dW/dV \), the right axis is \( D_{Eb} \), and the horizontal axis is characteristic pore parameters. The order of fitting effect of pore parameters was \( P_{II} > P_{III} > D_{Na} > D_{Nb} > P_{M} > P_{II} > P_{M} \), and the fitting relationships were all negatively correlated. It indicates that the total porosity \( P \) has the most significant negative influence on the low-temperature cracking resistance of the asphalt mixture. In contrast, \( P_{II} \) and \( P_{M} \) of Part III have a tremendous negative effect on the low-temperature crack resistance of the asphalt mixture. The linear dependence between \( P_{II} \) and \( P_{M} \) of Part II and \( dW/dV \) and \( D_{Eb} \) is not apparent, indicating that \( P_{II} \) and \( P_{M} \) of Part II have little influence on the crack resistance of asphalt mixture at low-temperature. It has been shown above that \( P_{SAM} > P_{BAM}, P_{III}SAM > P_{III}BAM, D_{Na}SAM > D_{Na}BAM, D_{NbsAM} > D_{NbsBAM} \), and SAM have better crack resistance at low-temperature than BAM. Besides, SAM has better crack resistance than BAM at low temperatures. In summary, \( P, P_{II}, D_{Na}, D_{Nb} \), and \( P_{M} \) have a good linear correlation with macroscopic and microscopic indexes of low-temperature crack resistance of asphalt mixture.

#### 4.2. Grey Correlation Analysis between Total Porosity and Horizontal Strain Energy Density

The grey relational analysis method analyzes and determines the degree of mutual influence among the factors of the system or the degree of the elements on the primary behaviour of the system through the grey relational degree. The basic idea is to judge whether the sequence of different factors is closely related to each other according to the similarity degree of the geometric shape of the sequence curve of each element. The closer the relationship is, the greater the correlation degree will be. Before the correlation degree analysis, if the characteristic behavioural sequence of the system and the dimensions and meanings of the related factors are entirely the same, the relationship between them can be directly analyzed. The system behaviour characteristic sequence and related factors are appropriately processed into dimensionless data with similar orders of magnitude through the operator function. The negative correlation factors are transformed into positive ones. In this chapter, two operators are used for dimensionless data sequence processing. The initial evaluating operator is used for positive correlation processing, and the reciprocal operator is used for negative correlation processing. The definitions of the initial evaluating operator and reciprocal operator are as follows [37]:

\[
X_i = (x_i(1), x_i(2), \ldots , x_i(n)).
\]

(1) Initial valuating operator is
Among them, $x_i(h) = \left[ \frac{x_i(k)}{x_i(1)} \right]$, $x_i(1) \neq 0, k = 1, 2, 3 \ldots n$. (19)

$H_1$ is the initial valuating operator. $X_iH_1$ is the image of $X_i$ in the initial valuating operator $H_1$, referred to as the initial value image.

(2) The reciprocal sequence is

$X_iH_2 = (x_i(1)h_2, x_i(2)h_2, \ldots, x_i(n)h_2)$. (20)

Among them,

$x_i(k)h_2 = \left[ \frac{1}{x_i(k)} \right] x_i(k)x_i(1) \neq 0, k = 1, 2, 3 \ldots n$ (21)

Then $H_2$ is the reciprocal operator. $X_iH_2$ is the image of $X_i$ in the reciprocal form operator $H_2$, abbreviated as the reciprocal form image.

Since the total porosity is negatively correlated with the horizontal strain energy density, the reciprocal operator calculation of the total porosity is first carried out according to equations (20) and (21). Then, according to equations (18) and (19), the initial valuation operator is calculated, and the results are listed in Table 9.

After operator processing, the original data sequence is transformed into the dimensionless sequence, and then grey correlation degree analysis is carried out. According to the grey correlation theorem, the correlation degree between the sequence of related factors and the sequence of system characteristic behaviour is determined by the following equation:

\[
(a) \gamma(x_i(1), x_i(k)) = \frac{\min_{k<k_k} |x_i(k) - x_i(k)| + \xi \max_i \max_k |x_i(k) - x_i(k)|}{|x_i(k) - x_i(k)| + \xi \max_i \max_k |x_i(k) - x_i(k)|},
\]

\[
(b) \gamma(X_j, X_i) = \left( \frac{1}{n} \right) \sum_{k=1}^{n} \gamma(x_i(1), x_i(k)) (k = 1, 2, 3 \ldots m, i = 2, 3, \ldots, n),
\]

where $\gamma(X_j, X_i)$ is the correlation degree between the sequence of related factors and the sequence of system behavior characteristics. The higher the correlation degree of the two sequences is, the closer the correlation degree is to 1. $\xi$ is resolution coefficient, $\xi \in (0, 1)$, usually 0.5.

Then, grey correlation degree analysis is conducted according to equation (22). It can be seen that the correlation degree between horizontal strain energy density and total porosity of asphalt mixture is as high as 0.9014. The total porosity $P$ is the main factor affecting the low-temperature cracking resistance of asphalt mixture and the critical reason leading to the superior low-temperature cracking resistance of steel slag asphalt mixture.
Figure 13: Fitting relationship between porosity and macrocrack resistance index of asphalt mixture at low-temperature.
### Table 9: Initial evaluating operator of SAM and BAM.

<table>
<thead>
<tr>
<th></th>
<th>Strain energy density</th>
<th>The total porosity</th>
<th>Data Availability</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>The test data (KJ/m²)</td>
<td>Initial image</td>
<td>The test data (%)</td>
</tr>
<tr>
<td>SAM₁</td>
<td>0.052</td>
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<tr>
<td>SAM₂</td>
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<td>SAM₃</td>
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</tr>
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<td>BAM₁</td>
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<tr>
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</tr>
<tr>
<td>BAM₃</td>
<td>0.039</td>
<td>0.7016</td>
<td>0.02799</td>
</tr>
</tbody>
</table>

### 5. Conclusion

1. Taking strain energy density (dW/dV) and horizontal strain energy density (DE) as evaluation indexes, it is found that the steel slag asphalt mixture has excellent crack resistance at low temperatures from the macroscopic and mesoscale analysis. It is characterized by delayed cracking, slow crack propagation, and high crack tip strength. The damage cracking process of SAM can be divided into an initial elastic stage, linear viscoelastic stage, and nonlinear damage stage.

2. Based on the theory of weight function, the stress intensity factor at the crack tip of the asphalt mixture with crack depth was calculated, and it was concluded that the SAM had the properties of slowing down crack propagation and high crack strength.

3. The total porosity of SAM is less than BAM, and the porosity of Part I, Part II, and Part III, and wave peak of SAM is less than BAM. The total porosity Pₚ, Part III porosity Pₚ₃, wave peak porosity Pₚ₄, and pore fractal dimension Dₙ₆ and Dₙ₇ are negatively correlated with dW/dV and Dₖ, which are the key factors affecting the low-temperature crack resistance of asphalt mixture.

4. Based on the grey system theory, it is found that the total porosity measured by the mesoscopic test has the highest correlation with the horizontal strain energy density, and the total porosity is the main factor affecting the low-temperature crack resistance of the asphalt mixture.

### Data Availability

The datasets used and analysed during the current study are available from the corresponding author upon reasonable request.

### Conflicts of Interest

The authors declare that there are no conflicts of interest.

### Acknowledgments

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