Research Article

Fatigue Performance of Steel Slag SMC Ultrathin Abrasive Layer Under Strain Controlling Mode

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Received 20 April 2022; Accepted 18 July 2022; Published 26 August 2022

1. Introduction

Road function decreases rapidly as the operational time of the highway continuously expands with the increasing phenomenon of heavily loaded and overloaded vehicles and exacerbating traffic environment. Plagued with insufficient attention to highway maintenance, especially preventive maintenance, there exists early breakage in most roads, accelerating the road deterioration and posing a great challenge to the maintenance and management of roads. In addition to increasing maintenance and protection investment, the maintenance and protection philosophy also must be transformed. That means the maintenance philosophy must shift to preventive maintenance from current corrective maintenance and maintenance according to need of the road. The systematic highway maintenance and protection system needs established to spontaneously make preventive maintenance based on the real road condition of highways [1–3].

At present, the common preventive maintenance technologies of asphalt road surface at home and abroad are fog seal, slurry seal, microsurfacing, synchronous surface dressing, and ultrathin overlay. Although the above technologies have their respective advantages, seal and surfacing-type technologies are not applicable to circumstances in which the road surface has obvious fatigue cracks or temperature cracks due to technical limitations. The ultrathin abrasive layer is the only solution to improve the road conditions [4, 5]. The ultrathin abrasive layer as the preventive maintenance treatment to the superficial abrasive layer of newly built roads and roads made from high-grade asphalt or cement and concrete, enjoying the advantages of high strength, good durability, rich surface texture, and excellent sliding resistance can restrain and improve road disease and prolong the service life of the road, which attracts the attention of a wide range of scholars [6–12].
Ary et al. utilized rubber powder particle to replace partly fine aggregate and applied it to ultrathin abrasive layer, discovering it could reduce the asphalt dose with better MLS stabilization in asphalt mixture [13]. Zhang et al. tested the road performance of asphalt mixture of ultrathin abrasive layer of rubber asphalt of four different types gradations and made a comparison, discovering that it possesses favorable high-temperature stability, low-temperature performance, and water stability performance but poor sliding resistance performance [14]. Zhou et al. applied rubber asphalt made from waste rubber powder and new type vita rubber asphalt with ultrathin abrasive layer, discovering that it possesses favorable road performance. However, the mixing and compaction temperatures of the mixture in the construction process are increased because of the larger viscosity [15, 16]. For the mix of cold-mix-cold-laid ultrathin abrasive layer, Li et al. found that the flow value and dynamic stability did not satisfy the technical index of hot-mix asphalt mixture. Consequently, it is not applicable to ultrathin abrasive layer of the upper surface of high-grade roads [17].

Through the analysis of the above research, high-temperature asphalt ultrathin abrasive layer mixture is found to possess good pavement performance, but because of its thin thickness and easy cooling, the construction compaction is not ideal, and the sliding resistance performance is rapidly reduced. In response to the call of “low carbon environmental protection” and “green energy conservation,” some progresses have been made in warm mixing technology, bringing out many novel road materials. The styrene methyl copolymers (SMC), derived from waste plastics, waste rubber, and other methyl styrene polymers, were used to modify the warm mixing asphalt accompanied with a certain proportion of epoxy resin, epoxy resin hardener, and other auxiliaries, which displayed excellent energy-saving and emission-reducing effects [18, 19]. Xie et al. have adopted SMC modifier in road regeneration and achieved normal road performance under room temperature mixing by using 60% of waste materials [20]. However, the application of SMC warm mixing modifier to the road foilum coat is still in the initial stage [15–18]. Through late tracking of these regenerated roads, many cracks were found due to the poor durability. In this work, the SMC room temperature asphalt modifier produced by Ningxia Rui Tai Tian Cheng New Material Science and Technology, (with waste tires, rubber oil made of plastic as the main ingredient, accounting for about 80% of the weight of the modifier, and other auxiliary chemical raw materials accounting for 20% of the weight) can be melted or dispersed in the asphalt to change the construction and ease of the asphalt bond under room temperature conditions, so that the asphalt and asphalt mixture at room temperature and subzero temperature conditions still have some mobility. [21] After a certain period of recuperation, room temperature modified asphalt mixture in the volatile solvent evaporation completely, the mixture gradually curing the formation of strength, the formation of a new type of modified asphalt ultrathin wear layer, the fatigue behavior was studied under strain controlling mode to get appropriate criteria.

2. Materials and Methods

2.1. Materials

2.1.1. Warm Mix Modifier. SMC warm mixing modifier was brown viscous liquid at room temperature, as shown in Figure 1, which was prepared by colloid mill and high speed shearing method. The technical specifications and test results are shown in Table 1.

2.1.2. Asphalt. SBS modified asphalt was heated at 135°C, then mixed with 12% SMC warm mix modifier, and stirred for 1 hour to obtain warm mix asphalt. The test results about SBS modified asphalt and SMC warm mix modified asphalt are shown in Tables 2 and 3, respectively.

2.1.3. Aggregate. The coarse and fine aggregate used in this paper are conventional basalt, and the mineral powder is conventional limestone, which meets the requirements of relevant specifications.

2.1.4. Design Gradation of Slag Asphalt Mixture. The aggregate gradations for SMC-10 and AC-16 are presented in Table 4. And 5% steel slag powder is added in SMC-10. Based on the Marshall mix design results, the optimum asphalt to aggregate ratios are both 5.3% for SMC-10 and AC-16 mixtures.

Plate specimens were prepared with the upper layer of 1.5 cm SMC-10 and under layer of 3.5 cm AC-16, as shown in Figure 2. According to the Chinese《Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering》(JTG_E20-2011) [22], the wheel pressure method was used to make the specimen, which was loaded in two layers and rolled into shape with a rut board and then placed for 72 hours at laboratory temperature. After that, the beam specimens were cut with 38 cm length, 5 cm height, and 6.5 cm width.

2.2. Test Methods. The fatigue behavior was tested by using a multifunctional dynamic testing system for road materials (UTM-100) developed by the Italian CONTROLS Company. 10 Hz is usually adopted in the asphalt mixture fatigue test for loading frequency, which corresponds to the time when the vehicle running speed is 60–65 km/h, relatively close to the loading state of the road under real traffic load. At the same time, the fatigue life is related to the loading waveform.

The strain loading control mode with four strain levels (400, 500, 600, and 700 με) was adopted. The test temperature was set as 10°C and 15°C, respectively. All tests were terminated until the bending stiffness modulus attained to 30% of the initial stiffness modulus (S₀).

3. Results and Discussion

3.1. Studies on the Characteristic Factors

3.1.1. Bending Stiffness Modulus (S) and Time Product

Normalized Stiffness (NM). Generally, the fatigue life is defined as cycle time when the initial stiffness modulus
attenuates to 50%, which can boast the advantage of quick test and convenient data analysis [23]. However, the collected data are insufficient and easily lead to unconvincing experimental conclusions. Herein, all tests in the present work were terminated until the bending stiffness modulus attained to 30% of the initial stiffness modulus. Meanwhile, the fatigue life of ASTM D746 was measured as cycle time when the time product of normalized stiffness (normalized modulus × cycles, NM) reached the maximum [12]. Figure 3 shows the bending stiffness modulus versus cycling time, and the initial bending stiffness modulus is listed in Table 5.

As shown in Figure 3, the curves of bending stiffness modulus (S) of SMC warm mixing modified ultrathin abrasive layer versus increased cycle time (N) can be divided into three stages. Mixture bending stiffness modulus attenuated rapidly with the increase in cycle time in the first stage. Attenuation of the mixture bending stiffness modulus came to a stability with the increase in cycle time in the second stage. Attenuation rate in the second stage was clearly lower than that of the first stage. Compared with the second stage, the attenuation rate of mixture bending in the third stage apparently increased with the cycle time when the cycle time reached a certain value. Besides, a distinct transition point (Nf) was found between the second and third stage, which was the characteristic fatigue cracking sign for the SMC warm mixing modified ultrathin abrasive layer.

For the tests under the same mode, the value of cycling time at the transition point (Nf) was almost the same, which means that the indices of bending stiffness modulus (S) and normalized stiffness time product (NM) can be regarded as the criterion of fatigue life.

The initial stiffness modulus S0 of this study was the bending stiffness modulus at the 100th cyclic loading time. It can be seen from Table 1 that the initial stiffness modulus of SMC warm mixing modified ultrathin abrasive layer was enhanced with lowered strain level at the same test temperature, while reduced with increased test temperature at the same strain level. The value of initial stiffness modulus (S0) at 10°C was about twice larger than that at 15°C.

3.1.2. Modulus Ratio of Residual Stiffness (Sr). In this study, the modulus ratio of residual stiffness (Sr) = the stiffness modulus under the loading cycles/initial stiffness modulus (S0). The variation of residual stiffness modulus ratio with the number of cycles is shown in Figure 4.

As shown in Figure 4, the Sr showed a similar tendency to S, which was decreased rapidly in the first stage, slowly in the second stage, and drastically in the third stage. Thus, the Sr can also be regarded as the criterion of fatigue life.

3.1.3. Phase Angle (θ). As shown in Figure 5, the phase angle (θ) fluctuated up and down with increased cycle time, while maintaining the growth tendency. In consistent with the other values (S, S0, Sr), three stages were also found with the same indication for the curves of phase angle (θ) versus cycle time. The value of cycle time corresponding to the turning point (Nf) was considered as the fatigue life of specimen. Furthermore, the phase angle at 15°C was larger than that at 10°C under the same strain condition, indicating that soft material was easy to generate larger recoverable deformation.

3.1.4. Accumulative Dissipated Energy (Qd). The dissipated energy was an essential factor which could reflect the cracking process of materials. As shown in Figure 6, the value of accumulative dissipated energy (Qd) increased constantly with elevated cycle time (N). Moreover, the Qd was enlarged with lowered strain level during the thorough test process. It should be noted that the three-stage as well as transition point (Nf) appeared in the curves of S, S0, Sr, and θ versus cycle times were not found for Qd. Therefore, we cannot determine the failure time from the curves of Qd versus cycle time, and the accumulative dissipated energy Qd should not be regarded as the direct criterion of fatigue life of specimens.

3.2. Fatigue Behavior of Asphalt Mixture Analyzed by Energy Method. As indicated by many researchers, the asphalt mixture was a viscoelastic material which exhibited a failure process accompanied with energy dissipation [16, 17]. Although the accumulative dissipated energy Qd was not the direct criterion of fatigue life of specimen, the relevant change law of dissipated energy was still of great significance to underline the fatigue behavior of asphalt mixture. The relationship between energy dissipation and fatigue life is shown as follows:

\[ W_f = AN_f^Z. \]  

\( W_f \)——accumulative dissipated energy; \( N_f \)——fatigue life; \( A, Z \)——test regression coefficient.

There was a time-induced hysteresis phenomenon for strain stress in viscoelastic materials (Figure 7). Carpenter et al. proposed the relative dissipated energy change ratio (RDEC) to depict the fatigue properties of materials [18].

The calculation formula for the RDEC is shown as
\[ RDEC = \frac{DE_j - DE_i}{DE_i(j-i)} \]  

where \( DE_i \) and \( DE_j \) represent the energy dissipation for the energy dissipation of the \( i \)th and \( j \)th cycle, respectively. \( j > i \), the difference between \( j \) and \( i \) is determined by fatigue life and instrument fatigue sampling. There exists a three-stage variation law of RDEC, and the corresponding fatigue time at the turning point between the second and third stages \( (N_f) \) is determined as the fatigue life. Thereby, the fatigue equation shown in formula (3) can be obtained by using the average \( \langle PV \rangle \) of RDEC in the second stage [19, 20].

\[ PV = cN_f^d. \]  

Table 1: The technical specifications and test results for SMC warm mixing modifier.

<table>
<thead>
<tr>
<th>Type</th>
<th>Test results</th>
<th>Technical specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.93</td>
<td>0.8 ~ 1.0</td>
</tr>
<tr>
<td>Rubber Hydrocarbon ≥</td>
<td>94</td>
<td>85</td>
</tr>
<tr>
<td>Viscosity (25°C) ≤</td>
<td>0.63</td>
<td>0.8</td>
</tr>
<tr>
<td>Flash point</td>
<td>93</td>
<td>90 ~ 110</td>
</tr>
<tr>
<td>Volatile organic compounds benzene ≤</td>
<td>0.01</td>
<td>0.1</td>
</tr>
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</table>

Table 2: Test results about SBS modified asphalt.

<table>
<thead>
<tr>
<th>Type</th>
<th>Test results</th>
<th>Technical specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration (25°C, 100 g, 5 s)</td>
<td>90</td>
<td>80 ~ 100</td>
</tr>
<tr>
<td>Softening point (R and B), ≥</td>
<td>47</td>
<td>44</td>
</tr>
<tr>
<td>Ductility (15°C, 5 cm/min), ≥</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>Density (15°C)</td>
<td>1.08</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3: Test results about SMC warm mix modified asphalt

<table>
<thead>
<tr>
<th>Type</th>
<th>Test results</th>
<th>Technical specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary viscometer (60°C), ≤</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Flash point, ≥</td>
<td>198</td>
<td>180</td>
</tr>
<tr>
<td>Loss of mass due to distillation, ≤</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Adhesion to coarse aggregate, ≥</td>
<td></td>
<td>7¾3/4</td>
</tr>
</tbody>
</table>

Table 4: Gradation composition.

<table>
<thead>
<tr>
<th>Gradation types</th>
<th>Through the mesh quality percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19</td>
</tr>
<tr>
<td>SMC-10 (35%)</td>
<td>—</td>
</tr>
<tr>
<td>AC-16</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2: Optical image of ultrathin abrasive layer.

\[ PV = cN_f^d. \]  

c, d are the fitting parameters.

Accordingly, the fatigue life of asphalt mixture of SMC warm mixing modified asphalt was predicted and analyzed with energy method in this work. The data of RDEC versus cycle time were obtained and calculated according to formula (2).

The curves of RDEC versus cyclic loading time \( N \) were divided into three stages (Figure 8–Figure 13). At the first stage (RDEC 1), the specimen possessed a relatively high RDEC value, which was gradually reduced with increased cyclic time. It was assumed that the native energy dissipation played an important role on the resistance of initially cycled loading. For the second stage (RDEC2), a low RDEC value was maintained, which implied a steady damage rate of RDEC. Finally, the RDEC value increased gradually at the third stage (RDEC 3), which resulted in an accelerated fatigue damage.

If the 50% initial stiffness was adopted in the tests, no obvious increased energy dissipation change ratio was found under either mode of strain control. The fatigue damage was in steady state, which provided the specimen enough residual energy to resist the external loadings. Thus, the transition point between the second and third stages \( (N_f) \)
Table 5: Initial stiffness modulus under different test conditions.

<table>
<thead>
<tr>
<th>Test temperature/°C</th>
<th>Strain level/με</th>
<th>Initial stiffness Modulus/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>400</td>
<td>7080.28</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>6882.92</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>5671.21</td>
</tr>
<tr>
<td>15</td>
<td>500</td>
<td>3619.96</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>3339.83</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>3108.26</td>
</tr>
</tbody>
</table>

Figure 3: Bending stiffness modulus of SMC warm mixing modified ultrathin abrasive layer mixture and normalized coefficient.

Figure 4: Variation of residual stiffness modulus ratio of SMC warm mixing modified ultrathin abrasive layer.
Figure 5: Phase angle of SMC warm mixing modified ultrathin abrasive layer.

Figure 6: Variation law of accumulative dissipated energy of SMC warm mixing modified ultrathin abrasive layer.
Figure 7: Lag time and lag curve.

Figure 8: Diagram of Relation between RDEC and cycle time at 10°C-400.

<table>
<thead>
<tr>
<th>Test temperature/°C</th>
<th>Strain level/με</th>
<th>PV</th>
<th>N/Cycle times</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>400</td>
<td>5.3E-5</td>
<td>1712340</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>7.5E-5</td>
<td>643243</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>1.3E-4</td>
<td>203435</td>
</tr>
<tr>
<td>15</td>
<td>500</td>
<td>1.25E-5</td>
<td>2823104</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>1.83E-5</td>
<td>1123433</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>4.51E-5</td>
<td>241223</td>
</tr>
</tbody>
</table>
Figure 9: Diagram of Relation between RDEC and cycle time at 10°C-500.

Figure 10: Diagram of Relation between RDEC and cycle time at 10°C-600.
Figure 11: Diagram of Relation between RDEC and cycle time at 15°C-500.

Figure 12: Diagram of Relation between RDEC and cycle time at 15°C-600.
was an appropriate factor to determine the fatigue life of the specimen.

The value of PV assigned to the relative change rate of energy dissipation was calculated from the RDEC data in the second stage and listed in Table 6, which was increased with the elevated strain level. The fatigue life of SMC warm mixing modified ultrathin abrasive layer asphalt mixture was fitted with (equation (4)). Through logging both sides of (4) simultaneously, the relationship between log (PV) and fatigue life ($N_f$) was established and shown in Figure 14. The PV and $N_f$ displayed a strong correlation with coefficient $R^2$ reached more than 0.98, indicating the RDEC value at the transition point of $N_f$ can be used as an appropriate criterion for predicting the fatigue cracking of SMC warm mixing modified ultrathin abrasive layer asphalt mixture.

$$\log(PV) = \log c + d \log(N_f).$$  \tag{4}

**4. Conclusions**

The study of the fatigue behavior of the SMC warm mixing modified ultrathin abrasive layer asphalt mixture was carried out under the strain controlling mode. All characteristic parameters (bending stiffness modulus, normalized times, product, and phase angle) showed a similar three-stage change process correlated with the stress cycle times, except for the accumulative dissipated energy. It is unreasonable to use 50% initial stiffness as the standard of fatigue failure of SMC warm mixing modified ultrathin abrasive asphalt mixture. However, The PV and $N_f$ displayed a strong correlation with coefficient $R^2$ reached more than 0.98, indicating the RDEC value at the transition point of $N_f$, considering the rest of the valid parameters for verification, and these can be used as appropriate criteria for predicting the fatigue cracking of SMC warm mixing modified ultrathin abrasive layer asphalt mixture.
Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Lingling Gao prepared the original draft; Shuyun He and Chaoyang Guo administered the project; Xianhu Wu curated the data. All authors have read and agreed to the published version of the manuscript.

Acknowledgments

This work was supported by National Natural Science Foundation, grant number 51308266. Science and technology research project of Higher education in Hebei Province, grant number ZD2021050. The authors would like to thank Feng Gan for critically reviewing the manuscript.

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