Analysis of High Temperature Stability and Water Stability of SMA Mixture using Orthogonal Experiments
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ABSTRACT

The influence of three material factors, namely asphalt-aggregate ratio, fiber-aggregate ratio and mineral filler-aggregate ratio (filler-aggregate ratio) on Marshall indexes of the lignin fiber SMA mixture are investigated in this study. To achieve this goal, orthogonal experiment design and implementation of Marshall stability test, residential stability test and rutting test were used to analyze the material factors on the high temperature stability and water stability of the established SMA mixture. The results show that these three factors have prominent influences on Marshall indexes of the SMA mixture. The optimum asphalt-aggregate ratio, fiber-aggregate ratio and mineral filler-aggregate ratio values were found to be 6.1%, 0.31% and 10%, respectively. With these ratios, the high temperature stability and water stability of the lignin fiber SMA-16 are optimal.

Keywords: SMA mixture; Marshall indexes; Residual stability; Rutting; Orthogonal Experiments.

1. Introduction

Stone Mastic Asphalt (SMA) mixture is made up of asphalt, fiber stabilizer, mineral filler and less fine aggregate consisting of mastic asphalt binder. This mixture fills in the gap of coarse aggregate skeleton gradation in the formation of fibrous SMA mixture (Qin Jun et al. 2008, Ou La et al. 2009, Ibrahim M. Asi. 2006, and Dong Xianlin et al. 2008). SMA mixture has a strong anti-rutting capacity and is capable of resisting deformation in low temperature. SMA mixture can also significantly improve the water stability of mixture, and has the performance of good anti-slide, anti-aging and anti-high temperature performance and consequently can extend the life of the pavement (Dong Xianlin et al. 2008, Richardson JTG. 1997, Brown ER et al. 1997, Bellin P. 1997, Cooley LA et al. 2003, Scherocman JA. 1991, Askeri Karakus. 2011, Xue Yongjie et al. 2009 and Cooley Jr Allen et al. 2010). In recent years, the application of SMA mixture has been increasingly extensive (F. Moghadas Nejad et al, 2010). The charisteristics of the composition of SMA mixture, mix optimization and its road performance improvement have received considerable attention from the research community. However, asphalt is a composite material and thus using different constituent materials lead to different properties of SMA mixture. The specific performance requirements also vary depending on the climate conditions in different countries. Therefore, prior to SMA mixture usage, its characteristics and indicators need to be investigated. In certain construction conditions, constituent materials of SMA mixture and their volume fractions or contents are particularly important. The main material contents of SMA are mineral aggregate gradation, asphalt content and fiber content. The effect of each of these three contents or factors on SMA mixture performance is proven to be significant. So far, some authors have studied this
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problem (Ou La et al. 2009, Zhang Zhixiang et al. 2006, Wang Jun et al. 2010, Lai Hongbin et al. 2010, Liang Juan. 2009 and Ge Liang. 2010) but none have considered the three factors, namely mineral aggregate gradation, asphalt content and fiber content on SMA mixture at the time. Using orthogonal test methodology (Zheng Shaohua, Jiang Fenghua ed, 2003) and the SMA test program, this paper analysed the influences of three factors, namely asphalt-aggregate ratio, fiber-aggregate ratio and filler–aggregate ratio on Marshall indexes of the lignin fiber SMA mixture and the high temperature stability of this mixture in order to determine the reasonable amount of each asphalt, lignin fiber and mineral filler.

2. Materials and Method

2.1 Materials

Asphalt was used styrene butadiene styrene polymer (SBS) modified asphalt, made in China with a penetration of 67 (0.1 mm at 25°C, 100 g & 5 s), ductility of 95.2 cm (at 5°C) and softening point of 76.5°C.

Aggregate and mineral filler: Aggregate used crushed basalt mineral, with a specific gravity of 2.84 g/cm³ and maximal size of 16 mm; mineral filler used limestone type, with a specific gravity of 2.78g/cm³, with 87.7% by mass smaller than 0.075 mm. The passing quality percentage of aggregates and mineral filler is shown in Table 1.

Table 1: Passing quality percentage of mineral aggregate (%)

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>19</th>
<th>16</th>
<th>13.2</th>
<th>9.5</th>
<th>4.75</th>
<th>2.36</th>
<th>1.18</th>
<th>0.6</th>
<th>0.3</th>
<th>0.15</th>
<th>0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed stone (10-20mm)</td>
<td>100</td>
<td>88.9</td>
<td>29.0</td>
<td>0.7</td>
<td>0.1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crushed stone (5-10mm)</td>
<td>100</td>
<td>98.8</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crushed stone (3-5mm)</td>
<td>100</td>
<td>70.5</td>
<td>0.2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregate (&lt; 3mm)</td>
<td>100</td>
<td>90.3</td>
<td>63.0</td>
<td>35.9</td>
<td>21.9</td>
<td>11.2</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mineral filler</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>96.6</td>
<td>87.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fiber: less than 6 mm length of lignin fiber, fibre diameter 46 μm, with a density of 1.6g/cm³.

All physical and mechanical properties of the materials were checked and proven to satisfy China’s standard requirements (JTG F40-2004, JTJ 052-2000).

2.2 Test program

2.2.1 Orthogonal experimental design

There are a lot of factors that affect the properties and performance of SMA mixture. If all materials that form this mixture are qualified and mineral aggregate gradation conforms to the standard requirements, the main three factors are asphalt-aggregate ratio (L), fiber-aggregate ratio (X) and filler–aggregate ratio (K). Asphalt-aggregate ratio (L) is the percentage ratio of asphalt to mineral aggregate (coarse aggregate, fine aggregate and mineral filler). Fiber-aggregate ratio (X) is the percentage ratio of lignin fiber to mineral aggregate
and similarly filler-aggregate ratio (K) is the percentage ratio of mineral filler to mineral aggregate.


<table>
<thead>
<tr>
<th>Levels</th>
<th>Asphalt-aggregate ratio L (%)</th>
<th>Fiber-aggregate ratio X (%)</th>
<th>Filler-aggregate ratio K (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.8</td>
<td>0.28</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>6.2</td>
<td>0.32</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>0.36</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>0.40</td>
<td>12</td>
</tr>
</tbody>
</table>

Based on the results of the mineral aggregate sieving test and SMA-16 gradation requirements (JTG F40-2004), by trial calculation one can obtain that 10-20 crushed stone ratio is 57%, 5-10 crushed stone ratio is 18%, 3-5 crushed stone ratio is 5%, and fine aggregate and mineral filler is 20%. Corresponding to four different filler ratios there are four SMA-16 mineral aggregate gradations as shown in Table 3 and Table 4.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Gradation 1</th>
<th>Gradation 2</th>
<th>Gradation 3</th>
<th>Gradation 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed stone (10-20mm)</td>
<td>57</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Crushed stone (5-10mm)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Crushed stone (3-5mm)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Fine aggregate (&lt;3mm)</td>
<td>11</td>
<td>10</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Mineral filler</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>19</th>
<th>16</th>
<th>13.2</th>
<th>9.5</th>
<th>4.75</th>
<th>2.36</th>
<th>1.18</th>
<th>0.6</th>
<th>0.3</th>
<th>0.15</th>
<th>0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradation 1</td>
<td>100</td>
<td>95.1</td>
<td>81.9</td>
<td>53.7</td>
<td>25.3</td>
<td>18.2</td>
<td>15.8</td>
<td>13.4</td>
<td>11.3</td>
<td>9.9</td>
<td>8.6</td>
</tr>
<tr>
<td>Gradation 2</td>
<td>100</td>
<td>95.1</td>
<td>81.9</td>
<td>53.7</td>
<td>25.3</td>
<td>18.4</td>
<td>16.2</td>
<td>14.0</td>
<td>12.1</td>
<td>10.8</td>
<td>9.4</td>
</tr>
<tr>
<td>Gradation 3</td>
<td>100</td>
<td>95.1</td>
<td>81.9</td>
<td>53.7</td>
<td>25.3</td>
<td>18.6</td>
<td>16.5</td>
<td>14.6</td>
<td>12.9</td>
<td>11.6</td>
<td>10.2</td>
</tr>
<tr>
<td>Gradation 4</td>
<td>100</td>
<td>95.1</td>
<td>81.9</td>
<td>53.7</td>
<td>25.3</td>
<td>18.7</td>
<td>16.9</td>
<td>15.2</td>
<td>13.7</td>
<td>12.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Upper limit</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>65</td>
<td>32</td>
<td>24</td>
<td>22</td>
<td>18</td>
<td>15</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Lower limit</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>65</td>
<td>32</td>
<td>24</td>
<td>22</td>
<td>18</td>
<td>15</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Middle limit</td>
<td>100</td>
<td>95</td>
<td>75</td>
<td>55</td>
<td>26</td>
<td>19.5</td>
<td>18</td>
<td>15</td>
<td>12.5</td>
<td>11.5</td>
<td>10</td>
</tr>
</tbody>
</table>
From Table 3 and 4, it is seen that the four-level specifications meet SMA-16 gradation requirements. The difference is due to the amount of fine aggregate and mineral filler. Other mineral aggregates are kept with the same volume. Orthogonal array L_{16}(4^5) (Zheng Shaohua, Jiang Fenghua ed, 2003) is used to design sixteen groups of experiments of Marshall test. The specific orthogonal experiment scheme is shown in Table 5.

### 2.2.2 Marshall test

For the Marshall test (JTJ 052-2000), specimens are manufactured following Marshall standard. Four replicates of the specimens for each group (101.6 mm in diameter and 63.5 ± 1.3 mm in height) were produced with 75 blows compacting energy per side. The test measures include determining the specimen bulk specific gravity (MD), Marshall stability (MS- Marshall stability at 60°C, 30 min water immersion) and Marshall flow value (FL) and calculating the air void (VV), voids in mineral aggregate (VMA ) and voids filled asphalt (VFA).

### 2.2.3 Water stability test

Residual stability test was used to evaluate the water stability of the SMA mixture. The moisture susceptibility of asphalt mixture was also measured through laboratory performance test. Two groups of duplicate specimens (three specimens for each group, 101.6 mm in diameter and 63.5 ± 1.3 mm in height) were prepared. The first group of the specimens was submerged in water at 60°C for 30 min, and the second group of the specimens was submerged in water at 60°C for 48 h. Consequently, the residual stability is determined as follows (JTJ 052-2000):

\[
MS_0 = \frac{MS_2}{MS_1} \times 100\%
\]

Where MS2 is Marshall stability at 60°C, after 48 h water immersion ; MS1 is Marshall stability at 60°C, 30 min water immersion and MS0 is residual stability at 60°C, after 48 h water immersion.

### 2.2.4 High temperature stability test

To evaluate the high temperature stability of the SMA mixture the rutting test was conducted. The wheel tracking test was utilized to measure rutting resistance of the specimens. The square slab specimen with 300 mm long, 300 mm wide and 50 mm thick was immersed in dry atmosphere at 60 ± 0.5°C for six hours. Subsequently a wheel pressure of 0.7 MPa ± 0.05 MPa was applied onto the specimen. The traveling distance of the wheel was 230 ± 10 mm. The traveling speed of the wheel was 42 ± 1cycles/min. The wheel was loaded to test for 60 minutes. The dynamic stability (cycle/mm) was determined as follows (JTJ 052-2000):

\[
DS = \frac{42 \times 15}{d_{60} - d_{45}}
\]

Where DS is the dynamic stability (cycle/mm); d60 and d45 is the rutting depth (mm) at 60 min and 45 min; 42 is the speed (cycle/min) and 15 is the time difference (min).
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3. Results and discussion

3.1 Marshall test results and orthogonal analysis

Each index is determined from the average of the four specimens. The test results are shown in Table 5.

Table 5: Marshall orthogonal test results

<table>
<thead>
<tr>
<th>No.</th>
<th>L (%)</th>
<th>X (%)</th>
<th>K (%)</th>
<th>MD (g/cm³)</th>
<th>MS (kN)</th>
<th>FL (mm)</th>
<th>VV (%)</th>
<th>VMA (%)</th>
<th>VFA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1(5.8)</td>
<td>1(0.28)</td>
<td>1(9)</td>
<td>2.42</td>
<td>8.58</td>
<td>2.62</td>
<td>5.48</td>
<td>18.50</td>
<td>69.73</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2(0.32)</td>
<td>2(10)</td>
<td>2.42</td>
<td>8.87</td>
<td>2.76</td>
<td>5.51</td>
<td>18.57</td>
<td>69.60</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3(0.36)</td>
<td>3(11)</td>
<td>2.41</td>
<td>8.81</td>
<td>3.34</td>
<td>6.13</td>
<td>19.15</td>
<td>67.13</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>4(0.4)</td>
<td>4(12)</td>
<td>2.40</td>
<td>8.49</td>
<td>3.46</td>
<td>6.19</td>
<td>19.26</td>
<td>66.89</td>
</tr>
<tr>
<td>5</td>
<td>2(6.2)</td>
<td>1</td>
<td>2</td>
<td>2.44</td>
<td>10.19</td>
<td>3.50</td>
<td>4.21</td>
<td>18.16</td>
<td>76.30</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2.44</td>
<td>10.85</td>
<td>3.32</td>
<td>4.44</td>
<td>18.40</td>
<td>75.25</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>2.43</td>
<td>9.40</td>
<td>3.74</td>
<td>4.58</td>
<td>18.57</td>
<td>74.62</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>2.44</td>
<td>8.99</td>
<td>3.39</td>
<td>4.44</td>
<td>18.50</td>
<td>75.24</td>
</tr>
<tr>
<td>9</td>
<td>3(6.6)</td>
<td>1</td>
<td>3</td>
<td>2.44</td>
<td>9.20</td>
<td>4.20</td>
<td>3.82</td>
<td>18.56</td>
<td>78.98</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2.43</td>
<td>9.10</td>
<td>4.40</td>
<td>4.03</td>
<td>18.79</td>
<td>78.00</td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2.43</td>
<td>7.98</td>
<td>4.38</td>
<td>4.10</td>
<td>18.90</td>
<td>77.71</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2.44</td>
<td>8.26</td>
<td>4.61</td>
<td>3.81</td>
<td>18.61</td>
<td>79.00</td>
</tr>
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<td>13</td>
<td>4(7.0)</td>
<td>1</td>
<td>4</td>
<td>2.43</td>
<td>8.72</td>
<td>4.89</td>
<td>3.81</td>
<td>19.28</td>
<td>79.85</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2.43</td>
<td>7.78</td>
<td>4.36</td>
<td>3.67</td>
<td>19.22</td>
<td>80.45</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2.43</td>
<td>8.00</td>
<td>4.60</td>
<td>3.65</td>
<td>19.24</td>
<td>80.51</td>
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<tr>
<td>16</td>
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<td>4</td>
<td>3</td>
<td>2.42</td>
<td>8.47</td>
<td>4.80</td>
<td>3.88</td>
<td>19.49</td>
<td>79.48</td>
</tr>
<tr>
<td>Requirement (JTG F40-2004)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

The Statgraphics software is used to analyse the variance of the tests and the results are obtained in Table 6.

Table 6: F values of the variance analysis of Marshall indexes
(Note: * significant at 95% probability; ** significant at 99% probability).

<table>
<thead>
<tr>
<th>Factor</th>
<th>MD</th>
<th>MS</th>
<th>FL</th>
<th>VV</th>
<th>VMA</th>
<th>VFA</th>
<th>F₀.₀₅</th>
<th>F₀.₀₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>8.58**</td>
<td>4.38**</td>
<td>3.42*</td>
<td>9.22**</td>
<td>11.29**</td>
<td>9.72**</td>
<td>2.53</td>
<td>3.78</td>
</tr>
<tr>
<td>L</td>
<td>59.81**</td>
<td>11.61**</td>
<td>56.92**</td>
<td>362.88**</td>
<td>85.66**</td>
<td>677.77**</td>
<td>2.53</td>
<td>3.78</td>
</tr>
<tr>
<td>X</td>
<td>11.69**</td>
<td>2.32</td>
<td>3.09*</td>
<td>7.91**</td>
<td>17.76**</td>
<td>8.55**</td>
<td>2.53</td>
<td>3.78</td>
</tr>
</tbody>
</table>

As can be seen from Table 6, all three factors, namely asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio have significant influences on the mixture of the six Marshall indexes. Of these three ratios, asphalt-aggregate ratio has the most significant influence.

Analysis of variance and using regression gives six correlation equations of bulk specific gravity, Marshall stability, Marshall flow value, air void, voids in mineral aggregate, voids filled asphalt to asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio:

\[
MD = 0.48131 + 0.0140272K + 0.617252L - 0.574025X - 0.000781676K^2 - 0.0474636L^2 + 0.72239X^2 \quad (3)
\]

\[
MS = -115.224 + 5.63727K + 30.7166L - 7.03336X - 0.257646K^2 - 2.45013L^2 + 2.25221X^2 \quad (4)
\]

\[
F = -7.71917 + 0.138642K + 1.43879L + 2.79645X \quad (5)
\]

\[
VV = 13.4216 + 0.100161K - 1.67457L + 2.14347X \quad (6)
\]
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VMA = 84.6364 − 0.893983K − 20.8562L + 17.0589X + 0.0465446K^2 + 1.6618L^2 − 21.1245X^2 (7)
VFA = 21.6628 − 0.409003K + 9.56582L − 8.95205X (8)

The parameters and variables in these correlation equations were defined in Subsection 2.2. These six regression correlation equations above express the relationship of bulk specific gravity, Marshall stability, Marshall flow value, air void, voids in mineral aggregate, voids filled asphalt with three factors of asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio.

Analysis of variance also gave P-values of six correlation equations. All P-values obtained were less than 0.05, so it can be concluded that there are statistically significant relationships among the variables at the 95.0% confidence level.

As can be seen from Table 5, when asphalt-aggregate ratio is 6.2%, fiber-aggregate ratio is 0.28~0.32% and filler-aggregate ratio is 10~11% the mixture of all six indexes all meet the requirements. Thus, according to the analyses of the orthogonal test results, the optimum asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio are 6.2%, 0.30% and 10%, respectively.

3.2 Impact analysis of SMA mixture performance

Based on the optimum values of asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio determined from the orthogonal test results, it is seen that the filler-aggregate ratio is found to be optimal at 10% which is equal to the average value of the passing percentage according to China’s standard requirements (see Table 4). Therefore, filler-aggregate ratio is kept constant at 10% in this study whereas asphalt-aggregate ratio and fiber-aggregate ratio are varied to investigate their effects on the properties of the SMA mixture. The Marshall test, residual stability test and rutting test were conducted to investigate the degree of influence of asphalt-aggregate ratio and fiber-aggregate ratio on the high temperature stability and water stability of the SMA mixture.

3.2.1 The influence of asphalt-aggregate ratio

In order to study the influence of asphalt-aggregate ratio, fiber-aggregate ratio is kept fixed at 0.3% and filler-aggregate ratio is 10%. Asphalt-aggregate ratio, 6.2%, is varied with ±0.2% to obtain two different ratios to investigate the influence of this ratio. Marshall test, residual stability test and rutting test are conducted. The result is shown in Table 7 and in Figures 1 to 4.

### Table 7: Different asphalt-aggregate ratio test results

<table>
<thead>
<tr>
<th>L (%)</th>
<th>X (%)</th>
<th>K (%)</th>
<th>MD (g/cm³)</th>
<th>MS (kN)</th>
<th>FL (mm)</th>
<th>VV (%)</th>
<th>VMA (%)</th>
<th>VFA (%)</th>
<th>MS₀ (%)</th>
<th>DS (cycle/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.80</td>
<td>0.30</td>
<td>10</td>
<td>2.414</td>
<td>8.88</td>
<td>2.60</td>
<td>5.53</td>
<td>18.85</td>
<td>69.44</td>
<td>81.56</td>
<td>5865</td>
</tr>
<tr>
<td>6.00</td>
<td>0.30</td>
<td>10</td>
<td>2.430</td>
<td>9.74</td>
<td>3.12</td>
<td>4.63</td>
<td>18.44</td>
<td>73.84</td>
<td>83.03</td>
<td>6900</td>
</tr>
<tr>
<td>6.20</td>
<td>0.30</td>
<td>10</td>
<td>2.437</td>
<td>10.09</td>
<td>3.53</td>
<td>4.07</td>
<td>18.34</td>
<td>76.85</td>
<td>83.35</td>
<td>6790</td>
</tr>
<tr>
<td>6.40</td>
<td>0.30</td>
<td>10</td>
<td>2.433</td>
<td>8.75</td>
<td>4.12</td>
<td>3.97</td>
<td>18.63</td>
<td>77.77</td>
<td>82.43</td>
<td>4977</td>
</tr>
<tr>
<td>6.60</td>
<td>0.30</td>
<td>10</td>
<td>2.432</td>
<td>7.91</td>
<td>4.80</td>
<td>3.77</td>
<td>18.82</td>
<td>79.15</td>
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<tr>
<td>Requirement</td>
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<td>2-5</td>
<td>3-4.5</td>
<td>≥16.5</td>
<td>70-85</td>
<td>≥ 80</td>
<td>≥3000</td>
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</tbody>
</table>

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Analysis of high temperature stability and water stability of SMA mixture using Orthogonal experiments
Dang Van Thanh, Cheng Pei Feng, Liu Hai Long

(JTG F40-2004) 11

6 5.8 6.0 6.2 6.4 6.6 MS, kN

\(MS = -9.0982L^2 + 111.35L - 330.84\)
\(R^2 = 0.9128\)

Figure 1: Asphalt-aggregate ratio and Marshall stability relation

7 7.8 8.0 8.2 8.4 8.6 8.8 9.0

76 78 80 82 84 86 88 90 MSo,%

\(MSo = -32.565L^2 + 399.53L - 1137.4\)
\(R^2 = 0.9873\)

Figure 2: Asphalt-aggregate ratio and residual stability relation

3.0 3.5 4.0 4.5 5.0 5.5 6.0

VV,%

\(VV = 3.3132L^2 - 43.173L + 144.44\)
\(R^2 = 0.9865\)

Figure 3: Asphalt-aggregate ratio and air void relation
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Of the Marshall indexes, air void and Marshall stability of asphalt mixture are the most important indexes. They have significant influences on high temperature stability and other road properties. If air void is too big, the mixture of asphalt is fast aging and less durable, but if air void is too small, the stability of the mixture is reduced. Therefore, air void of SMA mixture should be strictly controlled; otherwise the significance of SMA structure is lost. The permanent deformation of high-temperature asphalt pavement is mainly caused by the shear deformation of asphalt mixtures. At high temperatures, if the asphalt content of mixture is small, it will cause the mixture segregation, but if asphalt content is too large it will cause high-temperature rutting phenomenon.

As can be seen from Table 7, if asphalt-aggregate ratio is below 5.8%, the air void is too large, voids filled asphalt and residual stability is small, but if asphalt-aggregate ratio higher than 6.4%, the flow values (Marshall flow) is large and residual stability is low. From Figures 1 to 4 it can be seen that with the increase of asphalt-aggregate ratio, the air void of the mixture is reduced, Marshall stability, dynamic stability and the residual stability first increases and then decreases. The average value of asphalt-aggregate ratio which corresponds to maximum Marshall stability, maximum residual stability, maximum dynamic stability and the middle value of the allowable range of air void is 6.1%. Based on these four important indexes, the optimum asphalt-aggregate ratio is determined to be 6.1%. This result is consistent with the result from the orthogonal experiment.

3.2.2 The influence of fiber-aggregate ratio

In order to study the influence of lignin fiber amount on the mixture properties, asphalt-aggregate ratio is kept fixed at 6.1% and filler-aggregate ratio is 10%. Fiber-aggregate ratio 0.3% as a central value is varied to obtain 0.26%, 0.34% and 0.38%. With these four different fiber-aggregate ratios Marshall test, residual stability test and rutting test are conducted. The results are shown in Table 8 and Figures 5 to 8.

**Table 8: Different fiber-aggregate ratio test results**

<table>
<thead>
<tr>
<th>L (%)</th>
<th>X (%)</th>
<th>K (%)</th>
<th>MD (g/cm³)</th>
<th>MS (kN)</th>
<th>FL (mm)</th>
<th>VV (%)</th>
<th>VMA (%)</th>
<th>VFA (%)</th>
<th>MS₀ (%)</th>
<th>DS (cycle/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.10</td>
<td>0.26</td>
<td>10</td>
<td>2.439</td>
<td>8.25</td>
<td>3.28</td>
<td>4.14</td>
<td>18.15</td>
<td>76.29</td>
<td>84.73</td>
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<tr>
<td>6.10</td>
<td>0.30</td>
<td>10</td>
<td>2.434</td>
<td>9.52</td>
<td>3.69</td>
<td>4.32</td>
<td>18.37</td>
<td>75.46</td>
<td>89.53</td>
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</table>
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<table>
<thead>
<tr>
<th>Requirement (JTG F40-2004)</th>
<th>≥ 6</th>
<th>2-5</th>
<th>3-4.5</th>
<th>≥16.5</th>
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<th>≥ 80</th>
<th>≥3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.10</td>
<td>0.34</td>
<td>10</td>
<td>2.430</td>
<td>9.12</td>
<td>3.90</td>
<td>4.45</td>
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<td>6.10</td>
<td>0.38</td>
<td>10</td>
<td>2.414</td>
<td>7.58</td>
<td>4.86</td>
<td>5.02</td>
<td>19.09</td>
</tr>
</tbody>
</table>

**Figure 5:** Fiber-aggregate ratio and Marshall stability relation

**Figure 6:** Fiber-aggregate ratio and residual stability relation

**Figure 7:** Fiber-aggregate ratio and air void relation
The results from Table 8 show that if the fiber-aggregate ratio is greater than 0.38%, the Marshall flow value and the air void are large and Marshall stability and voids filled asphalt is smaller. The reason is that when fiber-aggregate ratio is different, fiber dispersion in the mixture, the effective surface area and the reinforced effect of the fiber to the mixture is different. When the fiber-aggregate ratio is larger the total surface area of the fiber is greater and consequently the adsorption capacity of asphalt is higher. However, when fiber-aggregate ratio is too large the fiber dispersion on the asphalt mixture is limited, pellet bundle phenomenon appears which lead to undesirable impacts to the mixture. On the other hand, the added fibers are also the same as filler, but the fiber density is much smaller than the density of mineral aggregate and fibers are separated. Furthermore, since added fibers occupy certain spaces and fibers have a certain rigidity, compacting asphalt mixture is more difficult to process with the same compaction work. Therefore, the density of mixture decreases, air void and voids in mineral aggregate increase. These cause an adverse effect on water stability. Thus when fiber-aggregate ratio is more than 0.3%, the residual stability MS0 does not increase but decreases slowly. The higher the fiber-aggregate ratio is, the lower the bulk specific gravity of the mixture will be, especially in the case of uneven fiber dispersion. Fiber-aggregate ratio increases often results in the mixture with the "strength weakness" fluctuation phenomena (Wang Jun, Lu Xuefeng, 2010).

Figure 5 to 8 show that when fiber-aggregate ratio increases, the air void of the mixture increases, Marshall stability, residual stability and dynamic stability first increases, reaches a maximum and then begins to decrease. The increase of lignin fiber-aggregate ratio causes the variation of the dynamic stability of the asphalt mixture. This indicates that lignin fiber portion has a great influence on mixture dynamic stability. In the asphalt mixture, asphalt and fiber have a good adhesion. Fibers absorb and stabilize free asphalt, so asphalt viscosity and cohesive strength increase. In addition, the fiber has "connection", "bridge" role that criss-crosses to the external envelope in the aggregate and thus form an effective fiber frame structure. This frame structure establishes the integrity within the asphalt mixture and consequently enhances rutting resistance and shear capacity. When the fiber-aggregate ratio is too large, voids are easily formed during mixing and compacting process. Particularly, when asphalt-aggregate ratio is constant, if the fiber-aggregate ratio is too large, part of the fibers can not absorb asphalt so they are in the mixture as loose bodies. These loose fibers not
only do not contribute anything to the mixture but also take a certain mixture volume which cause adverse effects to the mixture dynamic stability and other road properties.

The mean-value of the fiber-aggregate ratio which coresponds to maximum Marshall stability, maximum residual stability, maximum dynamic stability within allowable scope of air voids value is 0.31%. Based on the four important indexes the optimum fiber-aggregate ratio is determined to be 0.31%. With this ratio, fibers best contribute to the stabilizing effect of the asphalt and the reinforcement effect of the mixture. The results are vastly consistent with those of the orthogonal experiment.

4. Conclusion

Three factors, namely asphalt-aggregate ratio, fiber-aggregate ratio and filler-aggregate ratio have significant influence on Marshall indexes of SMA mixture. Based on the results of the orthogonal tests the relationship equations of these three factors with respect to bulk specific gravity, Marshall stability, Marshall flow, air void, void in mineral aggregate, voids filled asphalt of SMA-16 mixture have been established.

With the increases of the asphalt-aggregate ratio and the fiber-aggregate ratio, all Marshall stability, residual stability and dynamic stability increase, reach a maximum and subsequently decrease. This shows that there exists an optimum asphalt-aggregate ratio and fiber-aggregate ratio value for high temperature and water stability of the SMA mixture.

Combination of Marshall stability, residual stability, dynamic stability, air void and other indexes indicates that when filler-aggregate ratio is 10%, the optimum asphalt-aggregate ratio of SMA-16 mixture is 6.1% and the optimum fiber-aggregate ratio is 0.31%. With these optimum ratios, lignin fibers best contribute to the stability of the asphalt and as "reinforcement" function to the mixture.

Acknowledgement

The laboratory tests were performed at the Highway Testing Center of Civil Engineering College of Northeast Forestry University, China.

5. References


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