Study on High-Temperature Property Parameters of Polymer Modified Bitumen Based on Rheology

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ABSTRACT: This paper investigates the evaluating parameters on high temperature performance of polymer modified bitumen (PmB). Six bitumen were adopted in this paper and its high temperature performance was researched by rheology method and phenomenology method. Softening point, rutting factor $G^*/\sin(\delta)$ and non-recovery creep compliance $J_{nr}$ are tested and the mutual relationship is analyzed. Results indicated $J_{nr}$ is better than rutting factor for evaluating high temperature performance of PmB.

INTRODUCTION

After past 20 years of rapid development, total road mileages continuously have increased in China. However, because of extreme climate phenomena and heavy load traffic, rutting became the main pavement distress, especially in crossing, bus lane, climbing sections and so on (John et al, 2010). The high temperature performance of bitumen directly influences the rutting resistance of asphalt pavement. So the high temperature property parameters are evaluated as the most critical indexes.

The penetration grading system is adopted for road bitumen in China. Phenomenological parameters, penetration, softening point and ductility, are the three key indexes of this system. Softening point is the high temperature property parameter, and ductility is the low temperature property parameter of road bitumen. The viscosity grading system is also adopted by some countries, based on dynamic viscosity standard at 60 °C (John et al, 2007). But in 1990s, US’s strategic highway research plan (SHRP) developed a rheological evaluating parameter and a performance grading system (PG) to describe scientifically mechanical behavior of road bitumen. The high temperature grade is determined by dynamic shear modulus $G^*$ and phase angle $\delta$ (D’Angelo and Dongre, 2004).

At present, the high temperature performance is evaluated by phenomenological parameter softening point in China, but by rheological parameter in US and Europe. In the beginning of this century, the non-recoverable creep compliance $J_{nr}$ from multi-stress creep and recovery test is used to evaluate the high temperature property of base bitumen or polymer modified bitumen. Although rheological parameters haven’t been adopted in current technical specification for construction of highway asphalt pavement in China, rheological testing methods have been written in standard test methods of bitumen and bituminous mixture for highway engineering (JTG E20-2011). So the rheological parameters will become the better choice for road bitumen, as the evaluating parameters with scientific basis.
However, it is worth investigating which parameter of bitumen is more relevant to rutting resistance of bituminous mixture. This will be an important condition for using the parameter. Based on this focus, this paper carried out a research on the choice of high temperature property parameters of polymer modified bitumen (PmB).

**MATERIALS**

Six PmB were investigated, including Styrene-Butadiene-Styrene (SBS) modified bitumen, and crumb tire rubber modified bitumen. Four of them (A/B/C/D) are SBS modified bitumen. One of them (F) is crumb tire rubber modified bitumen and another (E) is complex modified bitumen. The polymer contents can be seen in the table 1.

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS content (%)</td>
<td>3.0</td>
<td>4.1</td>
<td>4.7</td>
<td>8.6</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>Crumb rubber content(%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

**LABORATORY TESTING**

There are three grading systems for road bitumen in different countries and regions, including penetration grading, viscosity grading, and performance grading. Currently, penetration grading system is used in China. At the same time, performance grading system is also favored because of its obvious rationality. The methods of two systems are adopted to investigate the high temperature property of PmB in this paper.

**Conventional Test**

The conventional tests in this research are penetration, softening point, ductility, viscosity and elastic recovery tests for penetration grading system. The first three are the central indexes for this grading system. Although they are useful and convenient, their rationality is debatable because of describing the phenomenological behavior.

**Rheological Test**

Dynamic shear rheology test and multi-stress creep recovery test are used to evaluate the high temperature property of PmB in this research. The two tests can be executed by the dynamic shear rheometer DHR-2 in laboratory. Complex modulus $G^*$ and phase angle $\delta$ can be obtained from dynamic shear test and non-recoverable creep compliance $J_{nr}$ can be obtained by multi-stress creep and recovery test.

Initial strain value at the beginning of the creep portion of each cycle shall be denoted as $\varepsilon_0$. The strain value at the end of the creep portion (after 1.0 s) of each cycle shall be denoted as $\varepsilon_c$. The strain value at the end of the recovery portion (after 10.0 s) of each cycle shall be denoted as $\varepsilon_r$. The adjusted strain value at the end of creep portion (after 1.0 s) of each cycle: $\varepsilon_1=\varepsilon_c-\varepsilon_0$. The adjusted strain value at the end of recovery portion (after 10.0 s) of each cycle $\varepsilon_{10}=\varepsilon_r-\varepsilon_0$. Average percent recovery $R$ and the non-recoverable creep compliance $J_{nr}$ can be calculated as the following formula:

$$R = \frac{(\varepsilon_1 - \varepsilon_{10})}{\varepsilon_1} \times 100$$

(1)
The different stress levels 0.1kPa, 3.2kPa are usually adopted for \( R \) and \( J_{nr} \). But when \( J_{nr} \) is used to evaluate the high temperature property of PmB, 3.2kPa stress level is generally adopted. To improve the accuracy of the test, ten cycles are tested.

ANALYSIS OF RESULTS

The six bitumen samples were studied using the test described in the previous section. The presentation of results in this section will be divided into three parts. First, the results relative to phenomenological behavior, as tested by conventional equipment, will be provided. Second, the results relative to rheological behavior, as measured by rheological equipment, will be obtained. Afterwards, results concerning the relationship between different parameters will be given.

Phenomenological Parameters of PmB

According to the current testing methods of penetration grading system of China, six polymer modified bitumen are evaluated by phenomenological parameters including penetration, softening point, ductility and elastic recovery. They are shown in the following table 2.

Table 2. Conventional parameter of penetration grading system.

<table>
<thead>
<tr>
<th>Samples No.</th>
<th>Penetration (5s,100g, 25°C, 0.1mm)</th>
<th>Ductility (5°C, cm)</th>
<th>Softening point (°C)</th>
<th>Rotational viscosity (135°C, Pa·s)</th>
<th>Elastic recovery (25°C, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70</td>
<td>46</td>
<td>60.5</td>
<td>1.0</td>
<td>89</td>
</tr>
<tr>
<td>B</td>
<td>65</td>
<td>30</td>
<td>63.0</td>
<td>1.5</td>
<td>94</td>
</tr>
<tr>
<td>C</td>
<td>51</td>
<td>29</td>
<td>77.5</td>
<td>2.3</td>
<td>100</td>
</tr>
<tr>
<td>D</td>
<td>90</td>
<td>68</td>
<td>89.0</td>
<td>3.3</td>
<td>100</td>
</tr>
<tr>
<td>E</td>
<td>43</td>
<td>15</td>
<td>72.5</td>
<td>2.6 (180°C)</td>
<td>95</td>
</tr>
<tr>
<td>F</td>
<td>57</td>
<td>22</td>
<td>65.0</td>
<td>1.2 (180°C)</td>
<td>93</td>
</tr>
</tbody>
</table>

Because six bitumens are produced for heavy-duty traffic, the softening points of them are high over 60°C, as table 2 shows. Softening point of D with the higher SBS content is the highest and over 80 °C. The sequences of high temperature property is : D>C>E>F>B>A based on softening point. The elastic recovery of six bitumens all are high, related to polymer content. Rotation viscosity is measured to evaluate the workability and polymer content higher, viscosity is higher. Especially, SBS modified bitumen F and CRM bitumen E are tested at 180 °C, and mixing and compaction all need the higher temperature.

Rheological Parameters at high temperature of PmB

Dynamic Shear Rheological Parameters

Dynamic modulus \( G^* \) and phase angle \( \delta \) results of six polymer modified bitumen
are obtained by dynamic shear test. And rutting factor $G^*/\sin(\delta)$ is calculated as follow in table 3.

### Table 3. $G^*/\sin(\delta)$ results before and after RTFOT aging.

<table>
<thead>
<tr>
<th>T ℃</th>
<th>A bef</th>
<th>A aft</th>
<th>B bef</th>
<th>B aft</th>
<th>C bef</th>
<th>C aft</th>
<th>D bef</th>
<th>D aft</th>
<th>E bef</th>
<th>E aft</th>
<th>F bef</th>
<th>F aft</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
<td>2.44</td>
<td>4.25</td>
<td>3.29</td>
<td>4.46</td>
<td>7.46</td>
<td>11.85</td>
<td>5.91</td>
<td>6.77</td>
<td>5.61</td>
<td>9.67</td>
<td>6.47</td>
<td>8.85</td>
</tr>
<tr>
<td>70</td>
<td>1.36</td>
<td>2.22</td>
<td>1.90</td>
<td>2.39</td>
<td>4.30</td>
<td>7.06</td>
<td>3.67</td>
<td>4.37</td>
<td>3.37</td>
<td>5.84</td>
<td>4.06</td>
<td>5.40</td>
</tr>
<tr>
<td>76</td>
<td>0.78</td>
<td>1.19</td>
<td>1.11</td>
<td>1.32</td>
<td>2.55</td>
<td>4.32</td>
<td>2.62</td>
<td>2.79</td>
<td>2.07</td>
<td>3.63</td>
<td>2.63</td>
<td>3.37</td>
</tr>
<tr>
<td>82</td>
<td>0.47</td>
<td>0.68</td>
<td>0.67</td>
<td>0.76</td>
<td>1.61</td>
<td>2.72</td>
<td>2.26</td>
<td>2.03</td>
<td>1.32</td>
<td>2.32</td>
<td>1.73</td>
<td>2.15</td>
</tr>
<tr>
<td>88</td>
<td>0.30</td>
<td>0.40</td>
<td>0.41</td>
<td>0.46</td>
<td>1.04</td>
<td>1.74</td>
<td>2.16</td>
<td>1.61</td>
<td>0.87</td>
<td>1.51</td>
<td>1.17</td>
<td>1.40</td>
</tr>
</tbody>
</table>

According to SUPERPAVE system of USA in SHRP, high temperature standard of performance grading (PG) system are over 1.0 kPa and 2.2 kPa of $G^*/\sin(\delta)$ for before and after RTFOT aging. Therefore, PmB A and B belong to PG70 level. D and F is PG76 level. C and E is PG 82 level.

### Multi-Stress Creep Recovery Parameters

The non-recoverable creep compliance $J_{nr}$ and percent recovery $R$ of bitumen after RTFOT aging can be obtained by mulita-stress creep and recovery test. Three testing temperatures are used with 70, 76, 82℃ and test results are shown in table 4.

### Table 4. Test results of multi-stress creep and recovery test.

<table>
<thead>
<tr>
<th>Samples No.</th>
<th>70℃</th>
<th>76℃</th>
<th>82℃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R/%</td>
<td>$J_{ur}$/kPa$^{-1}$</td>
<td>R/%</td>
</tr>
<tr>
<td>A</td>
<td>29.8</td>
<td>2.77</td>
<td>10.5</td>
</tr>
<tr>
<td>B</td>
<td>45.5</td>
<td>1.62</td>
<td>10.9</td>
</tr>
<tr>
<td>C</td>
<td>79.0</td>
<td>0.20</td>
<td>65.6</td>
</tr>
<tr>
<td>D</td>
<td>97.6</td>
<td>0.03</td>
<td>94.5</td>
</tr>
<tr>
<td>E</td>
<td>55.6</td>
<td>0.38</td>
<td>29.7</td>
</tr>
<tr>
<td>F</td>
<td>47.1</td>
<td>0.63</td>
<td>26.1</td>
</tr>
</tbody>
</table>

$J_{nr}$ lower, the high temperature property is better. So the sequence of high temperature property is converse of $J_{nr}$. It can be seen that the rutting resistance of SBS modified bitumen is better than one of crumb rubber modified bitumen. Dr. Yusuf Mehta provided a proposed range of $J_{nr}$ (Guo et al, 2012; Cai, 2013), separately $J_{nr} \leq 0.5$ k/Pa for extremely heavy traffic, $J_{nr} \leq 1.0$ k/Pa for very heavy traffic, $J_{nr} \leq 2.0$ k/Pa for heavy traffic, $J_{nr} \leq 4.0$ k/Pa for standard traffic. According to the above standard, high temperature level of PmB can be differentiated again. PmB A belongs to PG70-S level. PmB B is PG70-H level. PmB D is PG76-E level. PmB F is PG 76-H level. PmB C is PG82-H level. But PmB E is outside the range because of more than 4 k/Pa $J_{nr}$, so the high temperature property of PmB E is poor based on MSCR standard. Otherwise, Mike Anderson proposed the reasonable interval between $J_{nr}$ and $R$ (Wasage et al, 2011), as the following table 5 shows.
Table 5. The corresponding range between $J_{nr}$ and $R$.

<table>
<thead>
<tr>
<th>$J_{nr}$ @ 3.2 kPa</th>
<th>2.0~1.01</th>
<th>1.0~0.51</th>
<th>0.50~0.251</th>
<th>0.25~0.125</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Percent recovery(%)</td>
<td>$R_{\text{min}}$</td>
<td>30</td>
<td>35</td>
<td>45</td>
</tr>
</tbody>
</table>

As can be seen in the above table, the three B, C, D among six polymer modified bitumen conform to the relationship range. Their high temperature performance is better than the other three A, E, F because of the lower $J_{nr}$ and the higher $R$.

**Relationship of Different High Temperature Property Parameters**

Softening point, rutting factor $G^*/\sin (\delta)$, non-recoverable creep compliance $J_{nr}$ and percent recovery are adopted to evaluate the high temperature property of six polymer modified bitumen in this paper. The different conclusions are obtained for the same bitumen by different parameter. The softening point is the earliest evaluating parameter for the high temperature performance of bitumen, based on phenomenological method. However, the other three are based on rheological method. $J_{nr}$ and $R$ based on multi-stress creep and recovery test are the latest achievement of SHRP plus. The relationship between them is essential to investigating.

**Softening Point and Rheological Parameters**

![Figure 1. Relationship between softening point and $J_{nr}$.

First, the relationship between softening point and $J_{nr}$ is described in figure1. For the three different temperatures, exponential function can be used to fit their relationship by testing data. Correlation coefficient of fitting curve all are over 90%. With softening point increasing, non-recoverable creep compliance $J_{nr}$ decreases. Second, the relationship between softening point and rutting factor is described in figure2. For $G^*/\sin (\delta)$ before and after aging, relationship curves are shown in figure2.
As can be seen in figure 2, with softening point increasing, rutting factor curve appears saw-tooth fluctuated. So there is no reliable correlation both of them. The height of saw-tooth is different with testing temperature.

**Different Rheological Parameters**

At the same temperature, the relationship between $G'/\sin(\delta)$ and $J_{nr}$ can be described in figure 3.

![Graph](image1)

Figure 3. Relationships between $J_{nr}$ and rutting factor.

As the above figure 3 shows, relationship curves are saw-tooth and falling. The obvious correlation of $J_{nr}$ and $G'/\sin(\delta)$ is difficult to find. D and F have the same PG 76 high temperature level. C and E have the same PG 82 high temperature level. However, $J_{nr}$ of them have the huge difference. So it is not accurate to evaluate the high temperature property only by rutting factor. $J_{nr}$ can precisely characterize the property of PmB. The sequence of $J_{nr}$ value at 76 °C and 82 °C are shown in figure 4.

![Graph](image2)

Figure 4. $J_{nr}$ at 76 °C, 82 °C.

At 76 °C, the sequence of high temperature property evaluated by $J_{nr}$ is the same with one by softening point. At 82 °C, this sequence is also relatively close. So it can be seen that it is consistent to evaluate the high temperature performance of PmB by softening point and $J_{nr}$. According to research results of Asphalt Institute (AI), there is linear relationship with the correlation coefficient more than 85% between $J_{nr}$ and rutting depth of accelerating load facility (ALF) test and I-55 of Mississippi State in six year (Golalipour, 2011). The rutting factor has no relationship with rutting depth of ALF and actual pavement. So the MSCR test is used to evaluate fully the high temperature property of bitumen (Wasage et al, 2011; Cristian et al, 2012).
CONCLUSIONS

The high temperature property of six polymer modified bitumen is investigated by rheological and phenomenological method. And the relationship among different parameters is also analyzed in this paper. The following conclusion can be obtained.

(1) With SBS content increasing, softening point monotonously rise. PG high temperature grade based on $G^/\sin(\delta)$ is not similar.

(2) There are the Exponential relationship between softening point and $J_{nr}$, and the correlation coefficient is over 90%. However, there is no correlation of softening point and $G^/\sin(\delta)$, $J_{nr}$ and $G^/\sin(\delta)$.

(3) $J_{nr}$ of bitumen with the same PG high temperature grade is very different. The rutting factor $G^/\sin(\delta)$ cannot characterize accurately the high temperature performance of PmB. But $J_{nr}$ has certain advantage.

(4) It is effective and convenient to evaluate the high temperature performance of bitumen by softening point in Chinese standard. At the same time, it is more comprehensive and accurate for polymer modified bitumen to characterize rutting resistance by multi-stress creep and recovery test.

REFERENCES


