Study on Bending Resistance and Self-healing Property of SBS Modified Asphalt Mortar under Thermal Aging

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Abstract: At present, there are many studies on asphalt mixtures in China, but the research on asphalt mortar is not enough. In this paper, through trabecular bending tests of base asphalt mortar and SBS modified asphalt mortar under different aging degrees, and the change rules of mechanical properties of two kinds of asphalt mortar under different aging degrees were studied. By designing self-healing experiments of asphalt mortar specimens. The test results show that SBS modified asphalt mortar has better deformation resistance and load-bearing capacity than base asphalt mortar, SBS modified asphalt has better pavement performance, and the deformation resistance and stress relaxation performance of SBS modified asphalt mortar are greatly affected by short-term aging, which is the main factor affecting the healing degree. Therefore, controlling the short-term thermal aging of SBS modified asphalt mixture during paving and transportation is of great significance to the improvement of pavement service life.

1. Introduction
With the development of the 13th Five-Year Plan of Expressway in China, Scientific researchers have carried out multi-level and multi-angle research work around asphalt pavement and asphalt materials. Asphalt concrete is mainly composed of asphalt, fine aggregate and coarse aggregate. Analyzing the performance of asphalt mortar is of great significance for studying the mechanical behavior of asphalt concrete [1,2]. Huang studied the influence of asphalt to mineral powder ratio, fine aggregate gradation and asphalt mortar ratio on pavement performance of asphalt mixtures with anti-cracking, water stability and anti-rutting performance as indicators [3]. Pang through the compressive strength, direct tension and beam bending tests of asphalt mortar, analyzed the influence of different fine aggregate content and different particle size of aggregate on the basic performance of asphalt mortar [4].

Asphalt pavement is often in a hot and high temperature environment, and asphalt pavement is affected by short-term thermal aging in the process of paving and transportation. Therefore, it can be seen that thermal aging has a great influence on the performance of road materials. Zhang studied the high and low temperature properties of several SBS modified asphalts under different aging conditions. It was concluded that long-term aging had a great influence on the performance of asphalt binder. The performance of short-term aging could not be used to predict the performance of asphalt binder after long-term aging [5]. Ma used dynamic modulus test and indirect tensile fatigue test to compare the mechanical properties of asphalt mixture before and after aging. It was concluded that the dynamic modulus of modified asphalt mixture increased and the anti-deformation ability increased compared with the matrix mixture. After aging, the anti-rutting ability of asphalt mixture at high temperature increased and the anti-deformation ability at low temperature weakened [6].
2. Considering the unavoidable thermal aging of asphalt pavement during paving and operation, the short-term thermal aging and long-term thermal aging tests of matrix and SBS modified asphalt mortar were carried out respectively. Then the bending failure tests are carried out to test the changing rules of flexural performance of the two kinds of asphalt mortars after aging, and the differences of flexural performance and pavement performance between the two kinds of asphalt mortars are compared and analyzed. Finally, through the orthogonal design of four factors and three levels, the significant influencing factors are selected, and then the single damage self-healing test is carried out to analyze the self-healing of two kinds of asphalt mortars.

2. Test Materials And Methods

2.1 Test Materials
In this paper, base asphalt Panjin 90 and SBS modified asphalt were used. The basic indexes of the two asphalts are shown in Table 1. Basalt is used as aggregate in asphalt mortar, and the technical index of aggregate is shown in Table 2; the specific technical index is shown in Table 3; the ratio of asphalt mortar is shown in Table 4.

| Technical Index                              | Matrix Asphalt | SBS Modified Asphalt |
|----------------------------------------------|----------------|----------------------|
| Penetration value (25°C, 5s, 100g) (0.1mm)   | 90             | 65                   |
| PI                                           | -1.78          | -0.2                |
| Ductility (5°C, 5cm/min) (cm)                 | 38.5           | 33                   |
| Softening point (°C)                         | 51             | 70                   |
| Relative density (25°C)                      | 1.033          | 1.02                |
| Flash point (COC) (°C)                       | 290            | 269                  |

Table 2. Mineral material technical index.

| Aggregate specification          | 4.75-2.36 | 2.36-1.18 | 1.18-0.6 | 0.6-0.3 | 0.3-0.15 | 0.15-0.075 |
|----------------------------------|-----------|-----------|----------|--------|---------|-----------|
| Apparent relative density        | 2.91      | 2.825     | 2.824    | 2.835  | 2.846   | 2.857     |

Table 3. Technical index of mineral filler.

| Apparent density /g·cm⁻³ | Hydrophilic coefficient | Less than 0.075mm content % |
|--------------------------|------------------------|-----------------------------|
| 2.770                    | 0.92                   | 85                          |

Table 4. Asphalt mortar ratio.

| Project | 0~0.075 | 0.075~0.15 | 0.15~0.3 | 0.3~0.6 | 0.6~1.18 | 1.18~2.36 | 2.36~4.75 | Powder | Oil sand ratio |
|---------|---------|------------|----------|--------|---------|-----------|-----------|--------|---------------|
| Mass ratio % | 39.61 | 13.62 | 8.287 | 6.589 | 2.896 | 3.172 | 7.207 | 8.125 | 10.5           |

2.2 Test Method

2.2.1 Preparation of Asphalt Mortar Specimens
Asphalt mortar specimens are made by cutting method using T0703 asphalt mixtures wheel rolling test method of "Test Rules for Asphalt and Asphalt Mixture in Highway Engineering (JTG E20-2011)" , and the size of the specimens is 250 mm x 30 mm x 35 mm [7]. The aging of asphalt mortar adopts the aging method of asphalt mixture, referring to the accelerated aging method of T0734-2000 hot mix asphalt mixture. Short-term aging is to spread the asphalt mortar evenly on the enamel plate, loosen the pavement by about 21-22 kg/m³, heat the mixture in an oven at 135 °C, under forced ventilation condition for 4 h +3 min, and mix the mortar once an hour with a shovel in the sample plate. After heating for 4 hours, the mortar was removed from the oven and rolled. Long-term aging is to cut short-term aging moulded asphalt mortar rutting board into 250 mm x 30 mm x 35 mm standard trabecular specimens by cutting machine, put them into high and low temperature alternating box at 85 ℃, and heat them continuously for 5 days under forced ventilation conditions(120h±0.5h)。

In order to unify the bending failure modes of two kinds of asphalt mortar under different aging degrees, the standard trabecular specimens of non-aging, short-term aging and long-term aging asphalt mortar were prefabricated with pre-notches of uniform location and size. The pre-notches were reserved at the midpoint of the trabecular specimens of asphalt mortar. The width and depth of the pre-notches were 2 mm and 6 mm.

2.2.2 Bending Test of Asphalt Mortar Trabecula
Referring to the "Test Rules for Asphalt and Asphalt Mixture in Highway Engineering (JTG E20-2011)" T 0715-2011 asphalt mixture bending test [7], the test temperature of asphalt mortar bending is selected as 15 ℃, which ensures that the temperature of loading box is within the test temperature error of (+0.5 ℃) and the loading rate is 12 mm/min. The same loading mode is adopted for the two kinds of asphalt mortar under different aging degrees. The formulas for calculating the maximum flexural-tensile strain at the bottom of the beam and the modulus of flexural stiffness at failure are as follows:

\[ R_B = \frac{3 \times L \times P_B}{2 \times b \times h^2} \]  
\[ \varepsilon_B = \frac{6 \times h \times d}{L^2} \]  
\[ S_B = R_B \]  

Above formula: \( R_B \) - Bending Tensile Strength (MPa) of specimens under failure; \( \varepsilon_B \) —Maximum flexural-tensile strain of specimens under failure (\( \mu\varepsilon \ )); \( S_B \) - bending stiffness modulus (MPa) of specimens under failure; \( B \) - The width (mm) of the cross-interrupt interview piece; \( H \) - The height (mm) of the cross-interruption interview; \( L \)-span (mm); \( P_B \) - Maximum load (N) of specimen under failure; \( D \) - The mid-span deflection (mm) when the specimen is destroyed.

2.2.3 Self-healing Test and Healing Index of Asphalt Mortar
Two kinds of asphalt mortar bending damage healing tests were carried out by UTM-1 universal testing machine. The following steps were taken: 1) loading at a rate of 0.1mm/s until the pre-determined damage displacement of each specimen stopped; 2) taking out the specimen and the pasted soft rubber block together with the upper hard rubber gasket and putting them into the curing box, and restoring the specimen at the corresponding temperature and time; 3) Trabecular bending failure tests were carried out on the healed specimens. In this paper, the damage degree of asphalt mortar specimens is set by means of displacement control. By controlling the descending displacement of load-displacement sensor, the damage degree is controlled. The trabecular bending failure displacement of specimens is taken as the initial parameter \( S \). The displacement \( S \) values of two kinds
of asphalts under different aging degrees are measured, and the damage degree is defined as 30%, 45% and 60% S. Stop loading when the displacement reaches the preset damage level.

The maximum flexural-tensile strain of two kinds of asphalt mortars is calculated, and the healing degree of two kinds of asphalt mortars is analyzed by range analysis. The calculation table is as follows:

Table 5 Damage and self-healing properties orthogonal test table of asphalt mortar.

| Test label | Self healing temperature | Aging degree   | failover time | Damage degree |
|------------|--------------------------|----------------|---------------|---------------|
| 1          | 35°C                     | Non aging      | 1h            | 30%           |
| 2          | 35°C                     | Short term aging | 2h          | 45%           |
| 3          | 35°C                     | Long term aging | 4h          | 60%           |
| 4          | 50°C                     | Non aging      | 2h            | 60%           |
| 5          | 50°C                     | Short term aging | 4h          | 30%           |
| 6          | 50°C                     | Long term aging | 1h          | 45%           |
| 7          | 65°C                     | Non aging      | 4h            | 45%           |
| 8          | 65°C                     | Short term aging | 1h          | 60%           |
| 9          | 65°C                     | Long term aging | 2h          | 30%           |

In this paper, the maximum bending-tension strain ratio at the bottom of beams before and after asphalt mortar damage healing is taken as the healing index:

$$HI^1 = \frac{\varepsilon_{B1}}{\varepsilon_{B0}}$$  \hspace{1cm} (4)

$HI^1$ - Healing degree 1, $\varepsilon_{B1}$—The maximum bending-tension strain at the bottom of the beam under normal failure of the specimens. $\varepsilon_{B2}$—It is the maximum bending-tension strain at the bottom of the beam after damage healing.

3. Test Result

3.1 Variation Law of Bending Test Force of Trabecula with Time

The bending failure test of asphalt mortar trabecula was carried out. The force versus time curves of two asphalt mortars under different aging degrees are compared and analyzed, as shown in the following figure. In the figure, J-W indicates that the matrix asphalt mortar is not ageing, J-DL indicates that the matrix asphalt mortar is short-term ageing, J-CL indicates that the matrix asphalt mortar is long-term ageing, S-W indicates that the SBS modified asphalt mortar is not ageing, S-DL indicates that the SBS modified asphalt mortar is short-term ageing, S-CL indicates that the SBS modified asphalt mortar is long-term ageing, the same below.

Figure 1. The variation of two asphalt mortar forces with time under different aging degrees.
From figure (a), it is found that the peak load of matrix asphalt mortar increases with the deepening of aging degree, and the loading time to reach the peak load is shortened. Figure (b) shows that the peak load of SBS modified asphalt mortar is the largest after short-term aging, followed by long-term aging, while that of non-aging SBS modified asphalt mortar is the smallest.

3.1.1 Variation of Load and Displacement of Trabecular Bending Test under Different Aging Degrees

![Load and displacement curves](image1)

(a) Non aging  
(b) Short term aging  
(c) Long term aging

Figure 2. Load and displacement curves of two kinds of asphalt mortar under different aging degrees.

From the figure (a), (b), (c), it can be found that the peak load of matrix asphalt mortar increases gradually with the aging degree deepening. The peak load of matrix asphalt mortar is the largest after long-term aging, and the damage displacement of matrix asphalt mortar decreases with the aging degree deepening, and the damage displacement of matrix asphalt mortar is the smallest when long-term aging.

3.1.2 Bending Stiffness Modulus of Trabecular Beams Subjected to Bending Failure under Different Aging Degrees

When the modulus is higher, the deformation resistance of asphalt mortar is stronger and the plastic deformation is smaller. When the modulus is smaller, the cracking resistance of asphalt mortar is stronger and the ductility at low temperature is better [8,9].

![Modulus and strain](image2)

Figure 3. Bending stiffness modulus of two asphalt mortars under different degrees of aging

Figure 4. Maximum bending strain of two asphalt mortars under different degrees of aging.
As shown in Figure 3, the flexural modulus of SBS modified asphalt mortar is the largest after short-term aging, followed by long-term aging and the smallest after non-aging, and the flexural modulus of SBS modified asphalt mortar after aging is higher than that of non-aging, which indicates that the stress relaxation performance of SBS modified asphalt mortar after short-term aging is the worst and the deformation resistance is the worst.

3.1.3 Maximum Flexural-tensile Strain of Trabecular Beams under Different Aging Degrees During Bending Test Failure

From Figure 4, it can be seen that the flexural-tensile strain of both asphalt mortars shows the rule of non-aging > short-term aging > long-term aging. It shows that the deformation ability of the two asphalt mortars decreases with the deepening of aging degree, and the low-temperature cracking resistance becomes worse. Comparing the maximum flexural strain of two kinds of asphalt mortar under different aging degrees, it is found that the maximum flexural strain of SBS modified asphalt mortar is obviously larger than that of matrix asphalt mortar under the same aging degree.

3.2 Orthogonal Test Results of Single Injury Self-healing

3.2.1 Range Analysis of Single Damage Self-healing Orthogonal Test Based on Failure Strain

The orthogonal test data of two kinds of asphalt mortar are counted, and the range of two kinds of asphalt mortar under four factors is calculated based on the failure strain of healing index as shown in figure 5.

Figure 5 shows the healing degree of two kinds of asphalt mortar with failure strain as healing index under different factors. Range analysis of orthogonal test results shows that the self-healing temperature is the main factor affecting the healing degree of asphalt mortar. The healing degree of asphalt mortar changes greatly in the experiment, that is, the self-healing temperature is the main influencing factor. Secondly, the degree of aging. Figure 5 (b) shows that the order of the four factors affecting the healing degree of failure strain of SBS modified asphalt mortar is damage degree > aging degree > self-healing temperature > self-healing time.

3.2.2 Comparison of Healing Degree of Different Factors at Different Levels

Orthogonal test has comprehensive comparability. Four factors are analyzed by "comprehensive comparison". Under the comprehensive influence of the other three factors, because the other three factors have the same effect on each level of this factor, and each level of each factor is affected by the other three factors, so as to analyze the difference of healing degree of each factor at each level [10].

Through the method of "comprehensive comparison" in visual analysis of orthogonal test, the healing degree of two kinds of asphalt mortar after single damage self-healing orthogonal test under
different factors and levels is as follows:

Relevant experiments have found that the healing of crack surface can be divided into two steps: (1) strength recovery caused by surface adhesion between cracks; (2) This is due to the time-related degree recovery caused by polymer diffusion and reorganization in cracks of SBS modified asphalt mortar [11].

From Figure 6 (a), it can be seen that the healing degree of matrix asphalt mortar shows the following regularity with the deepening of aging degree: long-term aging > non-aging > short-term aging, and the healing degree of SBS modified asphalt mortar shows the following regularity with the deepening of aging degree: non-aging > long-term aging > short-term aging; It can be seen that the healing degree of base asphalt after medium and long-term aging is the highest, and the healing degree of SBS modified asphalt mortar after long-term aging is slightly less than that of non-aging.

Figure 6 (b) shows that the healing degree of the matrix asphalt mortar increases with the healing time: 1 h > 2 h > 4 h, the healing degree of the matrix asphalt mortar is close to that of the matrix asphalt mortar after 1 h and 2 h of healing, but the healing degree of the matrix asphalt mortar after 4 h of healing decreases. The healing degree of SBS modified asphalt mortar did not fluctuate significantly with the increase of healing time, which indicated that the damage strain healing of SBS modified asphalt mortar was smaller after 1 hour of healing.

From Figure 6 (c), it can be seen that the healing degree of matrix asphalt mortar at different healing temperatures presents as follows: 35% > 50% > 65% and SBS modified asphalt mortar at different healing temperatures presents as follows: 65% > 50% > 35%. This may be due to the fact that the matrix asphalt is more easily deformed at higher temperatures, and the flexural-tensile strain as a healing index can not accurately reflect its healing index. SBS modified asphalt mortar has stable deformation performance in this temperature range.

From Figure 6 (d), it can be seen that the healing degree of matrix asphalt mortar presents...
60%>30%>45% with the increase of damage degree, and the regularity of healing degree is not very good with the increase of damage degree, which also reflects the limitation of using damage strain to evaluate healing.

In summary, the failure strain as a healing index for different asphalt materials under the same experimental temperature and aging degree, due to the influence of viscoelasticity of materials, there are differences in the response of failure strain to load, so there are unreasonable rules for different levels of the same factor. Combining with the results of range analysis, it can be seen that the effect of healing temperature on the matrix asphalt mortar is most significant, and the temperature sensitivity of the matrix asphalt is greater, and the damage strain variability of the matrix asphalt mortar is also greater at different temperatures. The most important factor of SBS modified asphalt mortar healing is the degree of damage, so it is reliable to characterize deformation and self-healing ability by failure strain.

4. Conclusion
(1) Comparing and analyzing the force-displacement curve, failure strain, stiffness modulus and fracture toughness of the two asphalt mortars in bending test, it is found that the deformation resistance and load-bearing capacity of SBS modified asphalt mortar are better than those of base asphalt mortar.

(2) Failure strain can accurately reflect the deformation and cracking resistance of asphalt mortar, and the healing index established by failure strain is not very accurate for the evaluation of matrix asphalt mortar, but it is objective for the evaluation of the healing ability of SBS modified asphalt mortar, which has certain reference value.

(3) It is found that aging has a great influence on the performance of the two kinds of asphalt mortar through damage test and self-healing test. It is of great significance to control the deepening of aging degree in the construction and use process for the service life of asphalt pavement. The anti-deformation and self-healing ability of SBS modified asphalt mortar are most affected by short-term aging. Controlling the short-term aging of SBS modified asphalt pavement during paving and transportation is of great significance to improve the service life of SBS modified asphalt pavement.

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References
[1] HE F, TANG J, LIU Q T, et al. (2016). Thermally Activated Self-healing of Asphalt Mastic, Journal of Wuhan University of Technology. 40 (4): 701-704.
[2] YING R H WU Z T, WU T. (2011). Influence of Fine Aggregate Composition and Grade Matching on Bending Test of Asphalt Mortar[J], Journal of China & Foreign Highway.31 (6): 261-264.
[3] HUANG B T, TIAN W P. (2008) Asphalt mortar mix design method with long-term performance. [J] 4:149-150.
[4] PANG H F. (2009). Experimental Analysis of Viscoelasticity of Asphalt Mortar[D]. Changsha University of Technology.
[5] ZHANG Z Q, LI P, WANG B G. (2005) Performance of SBS Modified Asphalt and Influence of Aging[J]. HIGHWAY.9:151-155.
[6] MA L X. (2012). Study on viscoelastic properties of asphalt and asphalt mixture during aging[D]. Wuhan; Wuhan University of Technology.
[7] Research Institute of Highway Ministry of Transport(2011). Standard test methods of bitumen and
bitumen mixture for highway engineering: JTG E202011Is]. Beijing: China Communication Press.

[8] TIAN Y X, MA B, ZHOU X Y, HUANG W. (2016). Value of the Bending Stiffness Modulus of Asphalt Mixture in Surface Layer[J]. Bulletin of the Chinese Ceramic Society10 (35): 3281-3287.

[9] WANG M, ZHOU Q W, HU D Y, SHANG F. (2016) Research on the Fatigue Performance of Three Kinds of Steel Bridge Deck Pavement Material[J]. Highway Engineering 3(41): 41-42.

[10] MAO S S, ZHOU J X, CHEN Y. (2012). Experimental design[M].Beijing: Chin Statistics Press.

[11] SI Z M, LITTLE D, LYTTON R. (2002_) Evaluation of fatiguehealing effect of asphalt concrete by pseudostiffness [J]. Transportation Research Record, (1):73-79.