Pavement performance of environmentally friendly asphalt modifier in hot and humid environment

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Abstract. The modified asphalt binders and mixtures were prepared by SBP directed vat set modifier with recycled polyethylene as the main component. The effect of SBP modifier on the high-temperature characteristics of asphalt was characterized and analyzed by dynamic shear rheometer and differential scanning calorimeter. Thus, the pavement performance of SBP modified asphalt mixture was evaluated, and the test road was paved. The results show that the high-temperature rheological characteristics of asphalt were significantly improved with the SBP modifier. The high-temperature performance grade (PG) can be increased by 2-3 classes, but the improvement in high-temperature sensitivity was not noticeable. The SBP modifier can improve the low-temperature performance of asphalt to a certain degree, but this is not enough to change the low-temperature performance grade of asphalt. The high-temperature and water stability of SBP modified asphalt mixture are better than that of SBS modified asphalt mixture, which is more suitable for high-temperature and rainy areas.

1. Introduction
The rise in the social economy and the continuous adverse climatic conditions like high-temperature and precipitation have resulted in massive traffic flow and vehicle loads on the pavements. These conditions have put forward higher requirements on the performance of asphalt pavement in Southern China [1].

As a result, polymer modified asphalt has been widely used to improve the pavement performances like high-temperature and fatigue resistance, water stability performance, etc. [2-4]. Polyethylene (PE) is a kind of commonly used polymer in the modifier, it can increase the viscosity of asphalt, and improves the high-temperature stability of asphalt pavement [2]. In the view of the economy and environment, the recycled and low-price polyethylene can be used as a modifier for asphalt in road engineering. This can reduce not only the cost of construction but also achieve the recycling of resources. Further, it reduces the pollution to the environment, which is the worldwide concern for the usage of PE.
Panda et al. [5] have studied the effect of recycled PE on the performance of asphalt mixture. The results show that the recycled PE can improve the rebound modulus of asphalt mixture, enhance the water stability and improve the fatigue life. García-Morales et al. [6] have investigated the effect of the four kinds of polymer waste including PE on the rheological properties of the modified asphalt, in which the modified polymer composite with PE and ethylene-vinyl acetate copolymer (EVA) can form a mesh structure, so high-temperature rheological properties of asphalt can be improved. The study of Punith et al. [7] has shown that the fatigue life of asphalt mixture can be increased by 2.5 times after adding the PE. Fang et al. [8] have studied the microstructure and pavement performance of modified asphalt with PE and organic montmorillonite. The study of Yu et al. [9] has shown that the basic performances (like the penetration) of the modified asphalt composite can be improved with the addition of waste powder and waste PE. At present, PE waste is mainly used to prepare modified asphalt, and the direct vatset (DVS) modifier, but the use of recycled PE is found less in research. The DVS modifier can directly be added to the aggregate together with base asphalt mixture, and the modified asphalt mixture can rapidly be produced. It can do away with the tedious procedure of processing, storage, and transportation of modified asphalt, which can save money and energy costs. By using PE waste as the DVS modifier, it will produce more environmentally friendly production and economic benefits. SBP is a novel DVS modifier of asphalt with the primary material of recycled PE.

In this paper, the effect of SBP modifier on the high-temperature and low-temperature rheological characteristics, temperature sensitivity, differential scanning calorimetry (DSC) analysis and the pavement performances of asphalt are characterized, and a test road was paved. It can provide a basis for the application of this novel environmental modifier in engineering.

2. Experimental

2.1. Materials

2.1.1. SBP modifier. DSV SBP modifier is a kind of flat black particles, mainly compounded of recycled PE, organic sealant and nano-polymer, and produced by the process of plasticizing production, water ring granulation, etc. It is provided by Zhejiang New Shuaibang Traffic Facilities Co, Ltd, with 14.0% ash ratio. The particle size, softening point, melting point, melt flow rate, and density are 4 mm, 130°C, 175 °C, 2.33 g·10min⁻¹, 1.067 g·cm⁻³, respectively. The microstructure of recycled PE is shown in figure 1(a). PE shows linear long chain molecular structure with more methyl branched chain and alkyl side chain, which formed a multi-branched dendritic structure [10]. The microstructure of SBP modifier is shown in figure 1(b). From figure 1(b), during the formation of SBP, the chain structure of PE changed and formed a more stable network structure.
2.1.2. Asphalt. The base asphalt is the grade used in the South Korean SK-70 road asphalt, while SBS(I-D) modified asphalt produced by Zhenhai Petrochemical Engineering Co, Ltd was used in the comparative test. The main technical indices, which meet all requirements [11], are shown in Table 1.

Table 1. Technical indices of SK-70 and SBS modified asphalts

| Test items                  | SK-70 asphalt | SBS modified asphalt |
|-----------------------------|---------------|----------------------|
| Penetration /0.1 mm 25°C    | 60~80         | 40~60                |
| Ductility /cm               | ≥20(10°C)     | ≥20(5°C)             |
| Softening point /°C         | ≥46           | ≥60                  |
| Dynamic viscosity /Pa.s     | ≥180(60°C)    | ≤3.0(135°C)          |
| Change of mass /%           | 0.8~0.8       | -1.0~1.0             |
| After TFOT 25°C penetration | ≥61           | ≥65                  |
| Ductility /cm               | ≥6(10°C)      | ≥15(5°C)             |

2.1.3. Preparation of SBP modified asphalt. SBP modified asphalt was prepared by a high-speed shearing method with a small indoor high-speed shear emulsifier, as shown in Figure 2. The base asphalt was heated at a constant temperature of 150 °C in a sand bath. The dried SBP modifier was added slowly to the base asphalt at the rate of 4%, 7%, 10% (mass ratio of the base asphalt). And the shearing was carried out at a rate of 500 r·min⁻¹ for 15 min to make the SBP modifier dispersed in base asphalt uniformly. Then the temperature is raised to 180 °C, and shearing was carried at high speed of 4 000 r·min⁻¹ for 60 mins; then developed at a low speed of 500 r·min⁻¹ for 30 mins and the bubbles are removed which are generated during the high-speed shearing.
Figure 2. Preparation of SBP modified asphalt

2.1.4. Aggregate and Mineral powder. The coarse aggregate used the basalt gravel procured from Shengzhou in Zhejiang P.R. China, with the crushing value of 12.5%, the polished value of 47PSV, Los Angeles wear loss of 7.3% and apparent relative density of 2.908. The fine aggregate has used artificial sand. The mineral powder used limestone fillers procured from Lanxi in Zhejiang P.R. China, and the apparent relative density is 2.768.

2.2. Methods

2.2.1. Dynamic shear rheological test (DSR). The ADS fully automatic dynamic shear rheometer (Malvern Co, Ltd, UK) was used to carry out the DSR tests. Both the base asphalt and the asphalt after RTFOT short-term aging were used including SBP modified asphalt with three modifier dosages, SK-70 base asphalt, and SBS modified asphalt. The samples were poured into round cakes with 25 mm in diameter and 1 mm in thickness. The test was using strain control mode, and the loading frequency was 10 rad/s, with the initial temperature of 64 °C, and increased at 6 °C level until the rutting factor was not satisfied. The test was carried out under ASTM D7175[12].

2.2.2. Bending beam rheological test (BBR). The low-temperature BBR tests were performed using a bending beam rheometer (RHE-102, ATS Co, Ltd, US). Both the asphalt after RTFOT short-term aging and PAV long-term aging were used including SBP modified asphalt, SK-70 base asphalt, and SBS modified asphalt. The test temperatures were -12 and -18 °C. The tests were carried out under ASTM D6648[13].

2.2.3. Differential scanning calorimetry test (DSC). The DSC tests were performed using a Q100DSC analyzer (TA Co, Ltd, US). SK-70 base asphalt and 7% SBP modified asphalt were used. The samples were heated from -40 to 100 °C at a heating rate of 10 °C·min⁻¹, in the nitrogen atmosphere.

2.2.4. Pavement performance test of the asphalt mixture. Asphalt mixtures (AC-13 median gradation) with SBP, SK-70 and SBS asphalt were tested. SBP asphalt mixture was prepared by directed vat set method with SBP modifier. The best dosage of SBP modifier is 0.35% of the mass of asphalt mixture. The high-temperature performance was evaluated by rutting test under two additional harsh conditions (60 °C, wheel pressure of 0.7 MPa, immersion and 70°C, 0.8 MPa), along with the standard test condition (60°C, 0.7 MPa). The low-temperature performance was evaluated by beam bending test with
the standard test condition: -10 °C, a loading rate of 50 mm·min⁻¹. The water stability was tested by freeze-thaw split test under the standard test condition with a freeze-thaw cycle. The pavement performance test was carried out according to JTG E20 [14].

3. Results and Discussion

3.1 Analysis of SBP modified asphalt properties

3.1.1. High-temperature rheological property. The rutting or permanent deformation of the asphalt pavement is the result of the irreversible, partial accumulation of the deformation of the shear flow under the repeated load of the asphalt mixture at high-temperature, which is closely related to the viscoelastic characteristics of the asphalt at high-temperature. Therefore, it has been an effective method to evaluate the high-temperature performance of asphalt by studying the rheological property of asphalt under high-temperature by DSR test [15-17]. The complex shear modulus G* and phase angle δ can be obtained from DSR test. G* indicates the ability of shear deformation resistance, and this is enhanced with the increase of G*. δ reflects the ratio of viscosity and elasticity of asphalt. The greater the value of δ, the greater the viscosity ingredient of asphalt is. The proportion of irreversible asphalt is increased with the value of δ. SHRP is planned to take the rutting factor G*/sinδ as the evaluation indicator of high-temperature stability. At the condition of high-temperature, if G* increases, δ reduces. And hence the resistance of shear rheological deformation improves along with the high-temperature stability. It’s specified in SHRP specification that the G*/sinδ of base asphalt should not be less than 1.0 kPa, the G*/sinδ of residual asphalt after RTFOT should be no less than 2.2 kPa on the designated high-temperature.

(1) Complex modulus G* and phase angle δ

The results of the DSR test of SBP modified asphalt are shown in table 2. It can be seen from table 2 that the complex modulus G* of asphalt at different temperatures is significantly higher than that of base asphalt after the modification of SBP modifier, and resistance of the shear deformation of asphalt is enhanced. The effect of G* is related to the amount of SBP modifier. At the same temperature, G* is improved with the amount of modifier. But the addition of SBP modifier decreases the phase angle of asphalt, and the decrease is attributed to the amount of modifier. δ is the measure of the ratio of the loss modulus G'' to the storage modulus G'. SBP modifier increases the storage modulus G' above the loss modulus G''. Elasticity component of asphalt increases, loss of viscosity component decreases, that is, the part of recoverable deformation increases and the permanent deformation resistance is improved.

| Asphalt | Complex modulus G*/Pa | Phase angle δ/° |
|---------|------------------------|-----------------|
|         | 64°C | 70°C | 76°C | 82°C | 64°C | 70°C | 76°C | 82°C |
| SK-70   | 1923.4 | 774.7 | 500.0 | - | 87.9 | 89.0 | 89.8 | - |
| 4%SBP   | 5661.7 | 2689.8 | 1295.6 | 698.3 | 82.1 | 83.8 | 85.0 | 85.9 |
| 7%SBP   | 10795.6 | 4977.9 | 2398.5 | 1216.4 | 77.7 | 79.7 | 80.8 | 81.2 |
| 10%SBP  | 20009.9 | 9366.2 | 4679.8 | 2393.0 | 71.2 | 74.6 | 76.0 | 76.9 |

(2) Rutting factor G*/sinδ

The results of the rutting factor of the base asphalt and RTFOT short-term aged asphalt are shown
in table 3. At the same temperature, after adding the SBP modifier, the rutting factor of asphalt increases, the high-temperature stability is improved, and the high-temperature stability is increased with the amount of modifier. As shown at 64°C, after the modification of 7% SBP modifier, the rutting factor is improved to 11 050 Pa from 1 925 Pa, the high-temperature stability is improved by 4.74 times, which is 2.64 times higher than that of SBS modified asphalt. Five kinds of asphalt were classified by the high-temperature performance according to SHRP specification. Under three dosage types (4%, 7%, 10%), the high-temperature classification temperature of SBP modified asphalt is improved to 70, 76, 82°C, respectively. The high-temperature performance classification of 7% SBP modified asphalt can achieve that of SBS modified asphalt. The high-temperature performance classification of 10% SBP asphalt is higher than that of SBS modified asphalt. That is because the cross-linked network structure acts as a constraint on the flow of asphalt at high-temperatures after the addition of SBP modifier. Then, the viscosity and the resistance of shear rheological deformation at high-temperature of asphalt are increased, and the cross-linked network structure is improved. Hence, the modification is enhanced by the amount of modifier. Considering the high-temperature stability, the sufficient amount of SBP modifier should be above 7%.

### Table 3. The rutting factors of SBP modified asphalt

| Asphalt | Base asphalt ($G^*/\sin\delta$) /Pa | Short-term aged binder($G^*/\sin\delta$) /Pa | PG high-temperature range /°C |
|---------|-----------------------------------|------------------------------------------|-------------------------------|
|         | 64°C | 70°C | 76°C | 82°C | 64°C | 70°C | 76°C | 82°C | 88°C | 64°C | 70°C | 76°C | 82°C | 88°C | 64°C | 70°C | 76°C | 82°C | 88°C | 64°C | 70°C | 76°C | 82°C | 88°C |
| SK-70   | 1925 | 775  | 500  | ---  | 2483 | 1185 | 602  | ---  | ---  | 2483 | 1185 | 602  | ---  | ---  | 64  |
| SBS     | 4179 | 2581 | 1725 | 1287 | 6446 | 3778 | 2336 | 1526 | ---  | 6446 | 3778 | 2336 | 1526 | ---  | 76  |
| 4%SBP   | 5716 | 2705 | 1301 | 700  | 7981 | 3814 | 1794 | ---  | ---  | 7981 | 3814 | 1794 | ---  | ---  | 70  |
| 7%SBP   | 11050| 5060 | 2430 | 1231 | 15371| 7384 | 3689 | 1916 | ---  | 15371| 7384 | 3689 | 1916 | ---  | 76  |
| 10%SBP  | 21135| 9717 | 4823 | 2457 | 31800| 14980| 7493 | 3994 | 2134 | 31800| 14980| 7493 | 3994 | 2134 | 82  |

3.1.2. Temperature sensitivity in the high-temperature range. The temperature sensitivity of high-temperature range directly affects the pavement performance of high-temperature of the asphalt mixture. If the sensitivity towards the temperature is strong, with the increase of temperature, the viscosity of asphalt decreases significantly, and the resistance of the shear rheological deformation is reduced. And it is easy to prepare high-temperature permanent deformation such as rutting. At the high-temperature range of 64 ~82 °C, asphalt rutting factor and temperature have a linear relationship in the semi-logarithmic coordinates, so we can use the ($k$) of this linear relationship to evaluate the temperature sensitivity of asphalt. As the absolute value of the slope increases, the change of the rutting factor with temperature is increased, and hence the temperature sensitivity of asphalt is enhanced. The corresponding fitting results are shown in figure 3. It can be seen from figure 3 that SBS modified asphalt has the least sensitivity towards the temperature, SK base asphalt has the strongest, and SBP modified asphalt is better than the base asphalt, but it is still sensitivity towards the temperature. The reason may be due to the degradation of recycled PE performance. With the rise in temperature, the SBP network structure is gradually deformed and lost the constraints to asphalt. Therefore, it reflects that the rutting factor declines rapidly with the increasing temperature, but in the range of high-temperature, the high-temperature stability of the amount of SBP asphalt above 7% is still better than that of SBS modified asphalt.
3.1.3. DSC analysis. DSC test results of asphalt are shown in figure 4 and 5. In the temperature range of 30 ~ 60 °C, there is an apparent endothermic peak in the DSC curves of the two kinds of asphalt. In the high-temperature range, the asphalt enters from the viscoelastic state into the viscous state. Some asphalt components show a change in solid-liquid phase. The more significant the solid-liquid phase shift, the more is the significant effect on the macroscopic properties of asphalt. And the temperature range is just the range of high-temperature permanent deformation of asphalt pavement like rutting [1]. Therefore, the study of heat absorption property of asphalt in this temperature range is instrumental in evaluating the macroscopic high-temperature stability performance of asphalt. The amount of heat absorption corresponding to the endothermic peak can be calculated by integrating the endothermic peak curve over time in the temperature range.

![Graph showing the DSC analysis results.](image)

**Figure 3.** The rut factor-temperature relationships of asphalt

**Figure 4.** The DSC curve of SK-70 asphalt  **Figure 5.** The DSC curve of SBP modified asphalt

It can be seen from figures 4 and 5 that within the high-temperature range of the asphalt from the viscoelastic state into the viscous state, the average heat absorption of SK base asphalt is more than that of SBP asphalt. The more heat absorption indicates more change of the aggregation state of the asphalt component and the more change in solid-liquid phase observed. After the addition of a modifier, in this temperature range, the aggregation state of the asphalt component prone to change is decreased, the multiphase system of asphalt is more stable than that of base asphalt, the thermal stability is improved, and high-temperature stability is enhanced. But the temperature range reflects the change of the aggregation state of the asphalt component. The temperature range of the endothermic peak of SBP
modified asphalt is narrower than base asphalt. It indicates that the temperature range of the aggregated state is small, and the range of effect of temperature is reduced. The temperature range of the stable asphalt multiphase system is decreased, and the temperature sensitivity of the asphalt is diminished. The result is consistent with the DSR test.

3.1.4. Low-temperature rheological property. The effect of the BBR test is shown in table 4. In the BBR test, the bending creep stiffness modulus \( S \) and the rate of creep stiffness change \( m \) is taken as the evaluation indexes of the low-temperature rheological properties of asphalt. The higher the creep stiffness modulus \( S \), the more is brittleness, and the easier is cracking. However, larger \( m \) values result in lower tensile stresses, and the less the possibility of low-temperature cracking. It can be seen from table 4 that the stiffness modulus \( S \) of asphalt becomes smaller, the \( m \) value increases, the stress relaxation ability is improved, and the low-temperature performance is improved when the SBP modifier is added. The asphalt shows the best performance when the dosage is 7%. The requirement of PG low-temperature grade in SHRP specification is \( S<300 \) MPa, \( m>0.3 \). According to this standard for low-temperature classification, the temperatures of SBP modified asphalt and SK-70 base asphalt are both -22°C. That is because of low-temperature PG classification at intervals of -6°C; the temperature interval is too large to describe the differences of the low-temperature property of asphalt effectively. Simultaneously, it indicates that SBP modifier can improve the low-temperature property of asphalt, but the effect is limited, it cannot improve the low-temperature property grade of base asphalt.

|        | \(-12^\circ C\) | \(-18^\circ C\) |
|--------|----------------|----------------|
| asphalt| \( S/\text{MPa} \) | \( m \)       | \( S/\text{MPa} \) | \( m \)       |
| SK-70  | 246            | 0.305          | 444            | 0.241          |
| SBS    | 186            | 0.314          | 358            | 0.240          |
| 4%SBP  | 193            | 0.307          | 370            | 0.259          |
| 7%SBP  | 173            | 0.310          | 323            | 0.271          |
| 10%SBP | 191            | 0.305          | 326            | 0.236          |

3.2 SBP modified asphalt mixture property analysis

3.2.1. High temperature stability. The result of rutting test is shown in table 5. It can be seen from table 5 that the dynamic stability of SBP asphalt mixture is 8.1 times higher than that of base asphalt mixture, 1.5 times higher than that of SBS modified asphalt under the standard conditions. The SBP modifier significantly improves the anti-rutting performance of asphalt mixture. The dynamic stability is decreased by 2.6 and 23.6% under the terms of immersion and 70 °C with the wheel pressure of 0.8 MPa. The anti-rutting performance of SBP modified asphalt and under the two harsh conditions is still better than that of SBS modified asphalt mixture under the standard requirements. The result of the high-temperature test of asphalt mixture is consistent with the result of the DSR test of asphalt, SBP modified asphalt shows excellent high-temperature stability.
3.2.2. Low temperature crack resistance. The results of the low-temperature bending test are shown in Table 6. The flexural strength and the maximum flexural strain of SBP mixtures are both increased, but the amplitude is limited. The low-temperature performance of SBP mixture is better than the base asphalt but not as good as SBS modified asphalt mixture. The result is consistent with the result of the BBR test. The improvement of low-temperature performance of asphalt mixture by SBP modifier is not as significant as that of high-temperature performance.

| Asphalt mixture | Dynamic stability /cycles·mm⁻¹ | Rut depth /mm |
|-----------------|-------------------------------|--------------|
| SK-70           | 1136                          | 3.608        |
| SBS             | 6169                          | 1.584        |
| SBP standard    | 9232                          | 1.175        |
| SBP immersion   | 8996                          | 1.245        |
| SBP (70°C, 0.8MPa) | 7050                      | 1.179        |

3.2.3. Water stability. The results of freezing and thawing split test are shown in Table 7. On comparing with the base asphalt, the tensile strength of SBP asphalt mixture at 25 °C is improved by 49.1%, which is higher than that of SBS modified asphalt. The mechanical properties of the mix could be improved by SBP modifier. The freeze-thaw splitting strength is 10.5% higher than that of the base asphalt, which indicates that the SBP modifier can adjust the water stability of the asphalt mixture. That is because of SBP modifier modified the interface of the aggregate. With the addition of SBP modifier in the heated aggregate, the high-temperature heat transfer of the aggregate and the mutual friction and shearing action of the mixture during the mixing process are carried out. The modifier is rapidly melted, dispersed and adhered to the aggregate surface, forming a layer of modifier film that can diffuse into the micro-void of the aggregate surface. After adding the asphalt, the modified asphalt is well wrapped around the aggregate surface to form a good aggregate asphalt interface. The cohesive force between the aggregate and the asphalt is greatly enhanced, and the water resistance of the mixture is improved.

| Asphalt mixture | Flexural tensile strength/MPa | Maximum bending strain/με |
|-----------------|------------------------------|---------------------------|
| SK-70           | 7.783                        | 2091                      |
| SBS             | 9.231                        | 2969                      |
| SBP             | 8.804                        | 2561                      |

3.3. Engineering application. The experimental results show that the SBP modifier can improve the high-temperature and water stability of asphalt and mixture. To further verify the practical application of SBP modifier in the high-temperature and rainy areas, a test road was paved to verify it. The test road
is in Jiaojiang Bridge, Taizhou City, Zhejiang Province. The AC-13C SBP asphalt mixture was used in the upper layer of K65+400–K65+600 (right), K65+600–K65+700 (left). The usage of SBP modifier is 0.35%, directed vat set, dry mixing time 15s, wet mixing time 40s. In addition to 15 s dry mixing time, there are no special requirements during the construction process of SBP mixture like transport, paving, rolling, etc. It shows good construction characteristics. From the field sampling, the pavement performance tests under the standard conditions were performed, the results are shown in table 8. All the performance can meet the requirements. It should be pointed out that it is necessary to observe the test road for a long time for the long-term performance of SBP asphalt mixture.

| Test items                               | Technical requirement | Test results |
|------------------------------------------|-----------------------|--------------|
| Immersed residual stability /%           | ≥85                   | 91.1         |
| Freeze-thaw splitting strength ratio /%   | ≥80                   | 92.9         |
| Dynamic stability /cycles·mm⁻¹           | ≥2 800                | 8 012        |

4. Conclusions

✓ With the addition of SBP modifier, the complex modulus of asphalt increases, and the phase angle decreases. The high-temperature performance is improved with the amount of SBP. However, the improvement of temperature-sensitive property in the high-temperature range is not as significant as the high-temperature stability.

✓ From the view of thermal analysis, the average heat absorption of the asphalt in the high-temperature range is reduced, and the temperature range of the endothermic peak is narrow down after the modification of SBP modifier. The high-temperature stability is improved, which is in good agreement with the DSR test.

✓ Concerning the low-temperature performance of asphalt, the best usage is 7%, it can improve the low-temperature performance of asphalt to a certain degree, but not enough to improve the low-temperature property grade of base asphalt.

✓ SBP modifier can significantly improve the high-temperature and water stability of asphalt mixture and shows a better effect than SBS, and the improvement of the low-temperature performance of asphalt mixture is limited. It can be concluded that the performance characteristics of SBP can meet the requirements of high-temperature rutting and water damage resistance of asphalt mixture in south China, which is more suitable for the high-temperature and rainy areas.

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