Investigating the Cracking Resistance of Asphalt Binder in the UAE using Styrene-Butadiene-Styrene Polymer

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Abstract. This research work focuses on investigating the fatigue and thermal cracking resistance of asphalt binder with different percentages of styrene-butadiene-styrene (SBS) utilizing rheological testing methods. The laboratory experimental program includes the Dynamic Shear Rheometer (DSR) test at intermediate temperature for fatigue cracking and Bending Beam Rheometer (BBR) at low temperature to assess thermal cracking. The polymer-modified asphalt binders were prepared using four different SBS contents of 2.5, 4.2, 4.8, and 6.1% by asphalt binder weight. The test results were then used to compare the performance of four different SBS modified binders and the control asphalt binder without SBS. The findings showed that the addition of the SBS to asphalt binder improved the fatigue resistance as it was noted that the fatigue parameter ($G^*\sin \delta$) was decreasing as the temperature decreases. The BBR results also showed that the addition of SBS enhanced the low-temperature performance by lowering the creep stiffness and increasing the m-values compared to the control asphalt binder. The best performance against fatigue cracking and thermal cracking was obtained using 6.1% SBS.

1. Introduction

Fatigue and thermal cracking are the two most common cracking types in asphalt pavements. Fatigue cracks start to appear slowly with the continuous propagation and formation of micro-cracks within the asphalt concrete (AC) layer, however the problem arises due to many different reasons such as moisture, temperature variation and repeated loading [1].
Thermal cracking mostly exists in regions or countries that have long periods of cold seasons [2]. From day to night and from season to season, repeated cooling and heating cycles can result in thermal related cracking within the AC layer due to expansion and contraction of the surface layer. This type of cracking occurs when pavements withstand tensile strains above its threshold for certain climate condition. Thermal cracking usually can be distinguished from other cracking types as they appear in a direction perpendicular to the road centerline, commonly known as transverse cracks [3-8]. There are many factors which contribute to the occurrence of thermal cracking. Temperature and aging are two main factors that accelerate thermal cracking development [9, 10].

The styrene-butadiene-styrene (SBS) polymer is a strong rubber-like material that has high durability and used for manufacturing various products. It is considered as type of copolymer which is called block polymer. Synthetically, it is a long chain consists of three parts. The first part of the chain is polystyrene, the second part which is located in the middle of the chain is polybutadiene, and the last part is another chain of polystyrene. Polystyrene is a hard plastic that gives durability to the SBS while the polybutadiene gives the rubber-like properties [11]. When these molecules combine with each other to form the SBS, they give the material the ability to retain its shape after being exposed to elongation. When the maltenes in the conventional asphalt binder interact with the SBS, it starts to swell making whole system gradually turning into a biphasic microstructure after it was in maltenes-swollen-polymer case [12-15]. This makes SBS one of the materials that can help the binders to become more resistant to cracking, permanent deformation and other distresses [16].

2. Literature review

During the past few decades, many researchers have studied the behavior of different modified asphalt binders under high and low temperature conditions using superpave tests. SBS was proven to be able to improve the performance of asphalt in terms of cracking and rutting resistance [17]. Zeiada et al. (2014) evaluated the fatigue performance of reference, polymer-modified gap-graded mixtures. The results showed that polymer-modified mixtures achieved higher loading cycles till failure compared to the unmodified mixture. In addition, the study demonstrated that the polymer-modified mixture yielded a slightly higher fatigue life than the rubber-modified mixture [18-20]. Khattak and Baladi (1998) studied the behavior and the effect of SBS-modified asphalt binder on the properties of AC mixtures. The findings showed increased fatigue life and tensile strength at temperature of 25 °C. The authors have noted also that there is no significant effect the polymer on the elastic properties under temperature of -5°C [21]. Khattak and Baladi (2001) studied the development of fatigue and permanent deformation models for polymer modified asphalt mixtures. The results showed that there is a strong relation between the laboratory fatigue life and permanent deformation and the rheological properties of polymer modified binders [22].

The use of SBS-modified asphalt binder have been investigated extensively, especially in regions that have long cold seasons to mitigate primarily thermal cracking. Zhang (2019) studied the performance of SBS modified-asphalt binders for different SBS dosages (4.5%, 5%, 5.5% and 6%) using Bending Beam Rheometer (BBR). It was found that the stiffness values at temperature of −18 °C were higher than those values measured at temperature of −12 °C. It can be concluded that SBS improved the low temperature performance of the asphalt binder [23]. Another research work by Wei Yang (2018) investigated the influencing factors on low temperature properties using different SBS polymer types at different SBS contents. The PG 64-16 control asphalt binder and two types of SBS modified-binders were used with SBS contents ranged from 3.0% to 6.0% of asphalt binder weight. BBR test was conducted at different low temperatures (-12, -18 and -24). It was found that the optimum content of SBS for asphalt binder is 6% and optimum SBS content for AC mixture is 4.5%. The study also concluded that the linear and radial SBS modified-asphalt binders have higher performance than the control (PG 64-16). This advantageous performance of SBS modified-asphalt binders was due to the increase in m-value as the SBS content increases. In addition, it was found that both linear and radial SBS have a similarly positive influence on the creep ability of asphalt binder [24].

Despite using the polymer modified asphalts worldwide, their uses in UAE is very limited and the research done using the local materials conditions in UAE is still behind. This research studies the behaviour of SBS modified binder which is locally manufactured materials in the UAE. SBS modified
asphalt binder is expected to offer more effective solutions to improve the resistance of asphalt binders and mixtures against fatigue and thermal cracking. The main objective of this research is to assess the fatigue and thermal cracking of asphalt binders when modified with different percentages of SBS in UAE.

3. Materials
A control (PG 64-10) asphalt binder along with four asphalt binders modified with different dosages of SBS (2.5, 4.2, 4.8 and 6.1%) was used in this study. The mixing of the polymer with the control binder was done at local asphalt binder facility operated by Mena Energy Company.

4. Testing methods
The testing plan is to assess the fatigue and thermal cracking of SBS-modified asphalt binders. The Dynamic Shear Rheometer (DSR) was used to assess the fatigue cracking performance, whereas the Bending beam Rheometer (BBR) was for the thermal cracking. For both tests, control and SBS-modified asphalt binders were long-term aged using both the Rolling Thin-Film Oven (RTFO) and the Pressure Aging Vessel (PAV). Figure 1 presents the experimental plan flowchart.

![Figure 1. Experimental Plan.](image)

4.1. Aging process:
RTFO (Figure 3) was used to simulate the short-term aging of asphalt binders during mixing and laydown. The procedure was conducted according to AASHTO T 240. 35 g of asphalt binder was poured in 8 preheated standard bottles then allowed to cool for 60 minutes at room temperature (Figure 2). The bottles were then placed in the RTFO oven for 85 minutes under temperature of 163 °C and constant air flow of 4000 ml/min [25].
PAV (Figure 4) was used to simulate the long-term aging of asphalt binders during the service life of the asphalt pavement. According to AASHTO R28, RTFO residues were poured in standard PAV pans, 50 g each. The pans were then loaded to a frame and placed in the aging vessel for exposure to a pressure of 2.1 MPa under a temperature of 110 °C for 20 hours. Degassing was used afterwards to free the samples from entrapped air [26].

4.2. Dynamic Shear Rheometer (DSR):
DSR covers the characterization of the linear viscoelastic behavior of asphalt binder using the parallel plate’s geometry. Dynamic Hybrid Rheometer (DHR III) by TA-Instruments shown in Figure 5 was used for fatigue testing. This test determines the dynamic shear modulus (|G*|) and phase angle (δ) values of asphalt binder at intermediate temperature range using an oscillatory shear loading frequency of 1.59 HZ (10 rad/sec). The test is conducted using 8 mm parallel-plate geometry (Figure 5) on PAV-aged specimens in accordance with AASHTO T315-06 [27].
4.3. **Bending beam Rheometer (BBR):**

BBR (Figure 6) provides a measure of the low temperature stiffness and relaxation properties of PAV-aged asphalt binders. The standard BBR test method according to AASHTO T 313 was adopted. The determination of Superpave performance grade (PG) specification involving the determination of binder’s low temperature PG and intermediate temperature range were calculated based on AASHTO PP42. The basic procedure of the BBR test includes pouring the binder in beam-shaped molds (125 x 12.5 x 6.25 mm). The sample was then left to cool for one hour then it was immersed in the BBR liquid bath for 1 hour at desired testing temperature. A contact pressure of 35±10 mN is applied at the beginning of the test. The test involves applying a load of 980 ± 50 mN to a two-point supported beam for 240 seconds. The instrument automatically measured the central deflection over time, δ (t), which is used then to calculates the m-value and creep stiffness S(t) according to Eq. 1 and Eq. 2 at loading times of 8.0, 15.0, 30.0, 60.0, 120.0 and 240.0 [28].
\[ m\text{-value} = \left[ \frac{d\left(\log[S(t)T]\right)}{d\left(\log t\right)} \right] \]  
(1)

\[ S(t) = \frac{PL^2}{4bh^3\delta(t)} \]  
(2)

where:
- \( m\text{-value} \) = logarithmic creep rate;
- \( S(t) \) = creep stiffness at time \( t \);
- \( P \) = applied load;
- \( L \) = distance between beam supports;
- \( b \) = beam width;
- \( h \) = beam height; and
- \( \delta(t) \) = deflection at time \( t \).

\[ \text{Figure 6. Bending Beam Rheometer (Controls Group-BBR3)} \]

According to AASHTO M 320, the determination of the low temperature (PG) for each asphalt binder is based on a limiting \( m\text{-value} \) 0.3 maximum and \( S(t) \) should of 300 MPa minimum at 60 seconds of loading time [29].

5. Results and discussion

5.1. Fatigue parameter \((G^*\sin \delta)\)

\( G^*\sin \delta \) can be considered as the viscous portion of the complex shear modulus \( G^* \) for the asphalt binder. The fatigue parameter \((G^*\sin \delta)\) should be maximum of 5000 KPa at the intermediate temperature using the PAV aging condition. The intermediate temperature of the binder is calculated from the high temperature performance grade and the low temperature performance grade as follow (AASHTO M 320-16):

\[ \text{Intermediate temperature (°C)} = \frac{\text{highPG} + \text{LowPG}}{2} + 4 \]  
(3)

The Intermediate temperature is typically ranged from 19 to 40 °C. The Results presented in Figure 7 show that the fatigue parameter was decreasing with the increase of the temperature. It can be observed that at temperature of (28, 31 and 34 °C) the 6.1% showed better performance (2156.3 KPa) comparing with other binders. This implies that the SBS increases the elastic properties of asphalt binder, which decreases its complex shear modulus and the fatigue parameter \((G^*\sin \delta)\).
5.2. Stiffness (60s) and m (60s) value Analysis

SBS-modified binders were tested under different low temperatures (0, -6, -12 and -18 °C) and compared to the control asphalt binder. Table 1 shows the average m-value at (60s). The results are within the allowed bias for single-operator according to the AASHTO-T 313 [30].

| Binder   | 0 ºC m-value at 60 seconds | -6 ºC | -12 ºC | -18 ºC |
|----------|-----------------------------|-------|--------|--------|
| Control  | 0.421                       | 0.283 | --     | --     |
| 2.5%SBS  | 0.451                       | 0.3615| 0.342  | 0.2635 |
| 4.2%SBS  | 0.437                       | 0.377 | 0.3475 | 0.2705 |
| 4.8%SBS  | 0.4515                      | 0.379 | 0.326  | 0.2765 |
| 6.1%SBS  | 0.4565                      | 0.397 | 0.3365 | 0.2765 |

The m-value results presented in Figure 8 showed that the SBS-modified asphalt binders exhibited higher m-values compared to the control asphalt binder and therefore expected to have better low temperature performance.

For the m-value criterion, it can be noticed that all asphalt binders have passed the AASHTO limit with m-value of more than 0.3 at a test temperature of 0 ºC, which corresponding to a minimum pavement temperature of -10 ºC. however, the 6.1 and 4.8% achieved highest m-value of 0.4565 and 0.4515 and showed improvements of 8.43% and 7.24%, respectively compared to the control binder. The control asphalt binder was found to be failed at temperature of -6 ºC with m-value of 0.283, whereas all the SBS-polymer modified asphalt binders have passed a minimum temperature of up to -12 ºC, however all failed at -18 ºC according to the AASHTO criterion of minimum m-value.

For the creep stiffness values shown in Table 2, it was observed that at temperature higher than -12 ºC, all the tested SBS-modified asphalt binders succeeded to achieve the maximum creep stiffness criterion (300 MPa). At -18 ºC, all SBS-modified asphalt binders have failed, note Figure 9.
Table 2. Results of Creep Stiffness of Tested Asphalt Binders at Different Temperatures

| Binder Type | Sample | 0 ºC | -6 ºC | -12 ºC | -18 ºC |
|-------------|--------|------|-------|--------|--------|
| SBS Content (%) | Stiffness (MPa) – 1hr Conditioning | | | | |
| Control | S1 | 58.9 | 164.9 | -- | -- |
| | S2 | 60.1 | 158.8 | -- | -- |
| 2.5% SBS | S1 | 52.1 | 120.5 | 231.8 | 397.2 |
| | S2 | 46.7 | 116.0 | 225.167 | 395.4 |
| 4.2% SBS | S1 | 43.0 | 100.5 | 189.6 | 397.1 |
| | S2 | 38.6 | 101.2 | 194.7 | 418.2 |
| 4.8% SBS | S1 | 42.8 | 98.6 | 169.5 | 364.3 |
| | S2 | 34.3 | 106.0 | 171.9 | 399.2 |
| 6.1% SBS | S1 | 40.6 | 79.4 | 196.5 | 371.4 |
| | S2 | 36.806 | 79.4 | 198.1 | 333.9 |

Figure 8. BBR m-values of the Asphalt Binders at Low Temperatures vs. AASHTO O Limit (0.3)

Figure 9. Average Creep Stiffness (MPa) vs. SBS Percentages (%)
The improvements in the performance SBS binders was observed, where the SBS binders resist the 4 minutes applied load for temperatures of more than -12 as shown in Figure 10.

![Graph showing creep stiffness vs. temperature for different asphalt binders.](image)

**Figure 10.** Results of Creep Stiffness (MPa) at Different Temperatures of Tested Asphalt Binders

5.3. **Minimum Temperature Performance Grade**

According to the test results, the calculated PG low temperature is -10 °C for the control binder and -22 °C for all the SBS-modified asphalt binders. All SBS-modified asphalt binders could resist thermal cracking at low temperatures of more than or equal to -12 °C and less than -18 °C. Regression analysis has been applied to predict the actual low temperature at which the asphalt binder will fail as presented Table 3.

| Binder Type | Equation          | $R^2$ | Actual PG(X), m= 0.3 | Minimum PG design = $T_{\text{passed}}$ - 10 °C |
|-------------|-------------------|-------|----------------------|------------------------------------------|
| Control     | $y = 0.0080x + 0.3742$ | 1.000 | -5.3                | -10                                    |
| 2.5% SBS    | $y = 0.0097x + 0.4418$ | 0.952 | -14.6               | -22                                    |
| 4.2% SBS    | $y = 0.0088x + 0.4374$ | 0.974 | -15.6               | -22                                    |
| 4.8% SBS    | $y = 0.0096x + 0.4450$ | 0.991 | -15.1               | -22                                    |
| 6.1% SBS    | $y = 0.0100x + 0.4567$ | 1.000 | -15.7               | -22                                    |

The regression analysis obtained indicated that all asphalt binders failed at actual temperature beyond which the creep stiffness value becomes more than 300 MPa and less than 0.3 for the m-value according to the AASHTO-T 313 [31]. As having safety factor is important in selecting the design PG minimum temperature, therefore the minimum actual pavement temperatures were rounded down to nearest standard minimum pavement temperature according to the PG AASHTO PP 42 as reported in Table 3.
5.4. Analysis of BBR Deflection Results

As a basic procedure of the BBR, the test is starting by applying the load on the two-point supported beam for 240 seconds and measuring the beam deflection over time. There is an inverse relationship between the creep stiffness value and the deflection. The greater the deflection, the lower of the stiffness is which can be concluded from Eq. (2). This means as deflection increases remarkably under applied load at low temperature, the asphalt binder ability to resist the thermal cracking becomes higher.

At 0 °C, the SBS-modified asphalt binders exhibited higher deflection values compared to the control asphalt binder (1.10 mm). It was also noted that the 4.8% and 6.1% SBS-modified asphalt binders recorded the highest deflection value (2.09 mm) and (2.05 mm), respectively at time of 60s, note (Figure 11-a). At temperature of -6 °C (Figure 11-b), the SBS-modified asphalt binders showed high values of the deflection. The 6.1% SBS-modified asphalt binder showed the highest deflection value (1.003 mm) compared to other SBS-modified asphalt binders at time of 60s.

At temperature of -12, the SBS-modified asphalt binders showed high increasing in the deflection. It can be observed (Figure 11-c) that 4.8% SBS-modified asphalt binders have shown the highest deflection value (0.47 mm) at time of 60s.
In order to verify the validity of the experimental data of the fatigue parameter ($G*\sin \delta$) and the creep stiffness values (MPa) of different asphalt binders, the correlations between these two parameters have been established and fitted using logarithmic fitting as shown in Figure 12. The coefficient of logarithmic fitting ($R^2$) ranged 0.9214 to 1, which indicates a strong relationship between the fatigue parameter and the creep stiffness values. Similarly, strong correlations were found between m-value and $G*\sin \delta$ as shown in Figure 13. These strong correlations between the fatigue cracking parameter and the thermal cracking parameters confirm the consistency of the enhanced performance of SBS-modified asphalt binders against both cracking types as captured in this study. It also indicates that the performance of SBS-modified asphalt binders against certain crack type can be postulated if the performance against the second crack type are available.
6. Conclusion
The laboratory testing results in this research work showed that the use of SBS polymer improves the binder’s performance in terms of fatigue and thermal cracking resistance the detailed findings are summarized in the following points:

- Fatigue cracking test results showed that the SBS increased the fatigue resistance at intermediate temperature range. 6.1% SBS-modified binder showed the best performance compared to other asphalt binders modified with lower SBS contents.
- The SBS-modified asphalt binders showed better resistance against thermal cracking. The 6.1% and 4.8% SBS-modified asphalt binders achieved high m-value of 0.4565 and 0.4515 with improvements up to 8.43% and 7.24%, respectively compared to the control binder at time of 60 s at temperature of 0 ºC.
- At temperature of -12 ºC, the results showed that all SBS-modified binders passed the AASHTO minimum limit, with close values.
- From the deflection analysis, it’s noted that at temperature 0 ºC, the 6.1% showed a slightly higher value of the deflection at time of 60s comparing with 4.8% while at -6 ºC 6.1% achieved a high value comparing with other SBS-modified binders and that is happened due to the high percentage of the SBS which gives the asphalt binder more elastic behavior to resist cracking.
- 6.1% SBS-modified asphalt binder has better performance comparing with the other SBS-modified asphalt binders and the control one. The 6.1% SBS-modified asphalt binder could resist the thermal cracking at up to -15.7 ºC, where the actual performance temperature for the control asphalt binder is -5.3 ºC.
- In general, the SBS-modified asphalt binders have a good performance in terms of flexibility at low temperatures and it gives the asphalt binder high rubber –properties.
- Correlations between BBR and DSR parameters is recommended for future research. This correlation will be very useful in developing low temperature specifications considering local asphalt binders and climate conditions in the UAE.
7. References

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