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# Comparison of elvaloy and styrene-butadiene-styrene added polymer modified bitumen

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## Highlights

- Optimum SBS ratio is in the range of 1.6%-1.8% for B50/70 grade pure bitumen
- Optimum Elvaloy ratio is in the range of 4%-5% for B50/70 grade pure bitumen
- The non-homogeneous dispersion of SBS adversely affects storage stability

## Abstract

One of the methods used to produce road pavements resistant to increased traffic volume and harsh environmental conditions is to improve the properties of bituminous binders, such as high temperature resistance and aging resistance, by using various additives. Styrene-Butadiene-Styrene and Elvaloy are two different commercial additives that are frequently used in pavement construction. In this study, the performance of three different B50/70 grade pure bitumens was modified by using Elvaloy at 1.6%, 1.7%, and 1.8%, and five different B50/70 grade pure bitumens were modified using 4.0%, 4.5%, and 5.0% Styrene-Butadiene-Styrene. Penetration, softening point, elastic recovery, flash point, storage stability, dynamic shear rheometer, beam bending rheometer, rotational thin film oven, and pressure aging vessel tests were applied to the binders in accordance with the Polymer Modified Bitumen technical specifications. According to the test results, it was determined that the additive rates for both modifiers are the optimum values in accordance with the specification. The results of the storage stability tests also showed that the non-homogeneous dispersion of the Styrene-Butadiene-Styrene modified binders during mixing had a significant effect on the behaviour of the binder after storage.

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## 1. Introduction

Bituminous binders are frequently used in bituminous mixtures in the construction of highway pavements due to their good adhesion and viscoelastic behaviour [1]. However, increasing traffic density due to the increase in trade volume and the increase in the number of heavy-loaded vehicles in the traffic causes the road pavements to be exposed to more repetitive heavy axle loads. For this reason, it has become necessary to produce more durable road pavements. One of the most preferred methods for the fabrication of durable bituminous pavement layers is the modification of bitumen binders using various additives [2].

Bitumen modification is generally defined as changing the rheological properties of bitumen by mixing various [3]. With this process, which affects the consistency of the bitumen, the binder hardens, softens, or gains more elasticity. Some polymers compatible with bitumen used as additives reduce the sensitivity of the binder to temperature without harming the behaviour of bitumen at low temperatures [4]. The main contributions of the use of modified bitumen in mixtures on road pavement can be counted as increased resistance to fatigue cracks, increased resistance to rutting deformation, and decreased sensitivity to water [5].

Natural materials such as stone dust, lime, rubber tree sap, and lignin can be used as bitumen modifiers, as well as artificial materials such as polyethylene, acrylics, and

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polyvinyl chloride [6]. In some studies, researchers have categorized additives mixed with bitumen as fillers, elastomers, thermosets, fibers, thermoplastics, oxidants, antioxidants, hydrocarbons, anti-skinning agents, and reactive thermopolymers [6-7]. Artificial bitumen additives are generally commercial products. Among commercially produced additives, Styrene-Butadiene-Styrene (SBS) and Elvaloy are products that are frequently used by institutions constructing highways. These additives, which have a certain cost, are also used in academic studies for reasons such as providing economy in bitumen modification or increasing the performance of additive bitumen.

During the modification, some molecular structures in the SBS additive increase in volume and change the properties of pure bitumen [8]. The different molecular structures of the additive give the binder strength and elasticity [9]. Furthermore, SBS modification also affects the morphological structure of bitumen [10]. In modifications made with SBS, the amount of additive is generally limited to between 2% and 5% for economic reasons [11,12]. Elvaloy is an elastomeric thermopolymer added to the bituminous binder between 1.5% and 3% by weight. Due to its molecular structure, Elvaloy causes the binder to turn into a gel consistency when it is mixed into the bituminous binder in more than the necessary amount [13]. For this reason, lower amounts of Elvaloy are used as a modifier in studies compared to SBS. According to laboratory tests, bitumen modified with Elvaloy showed superior resistance to deformations and fatigue cracking [11].

Güngör et al. [14], stated that the properties of pure bitumen from different refineries are determinative on the performance of modified bitumen with SBS and Elvaloy additives. Geçgil and Seloğlu [15] prepared modified binders by adding Elvaloy at the rates of 0.5%, 0.75% and 1% to pure B 100/150 grade bitumen. According to the test results, the researchers found that the binders with soft consistency and high temperature sensitivity became harder with the addition of Elvaloy, the binder class changed and the temperature sensitivity decreased significantly. Kumandaş et al. [16] stated that the addition of Elvaloy has positive contributions to the high-temperature performance of bitumen, according to the results of DSR experiments. Yalçın [12] produced modified bitumen by adding 2%–3% and 4% SBS to B160/220 class pure bitumen, which he obtained from two different refineries, and applied penetration, softening point, viscosity, and DSR tests to modified bitumen. According to the results of the DSR tests, the researcher stated that although the different bitumen used were in the same penetration classes, the complex shear modulus and phase angle values were significantly different and exhibited different elastic behaviours from each other. Gedik [17] prepared concrete asphalt specimens according to the Marshall design method for the wearing course using B70/100 grade bitumen modified with different rates of SBS. The results showed that asphalt concrete mixtures modified with SBS can be used in cold climate regions.

Aydin et al. [5] investigated the rheological properties of Elvaloy and polyphosphoric acid (PPA)-modified bitumen binder by penetration, softening point, rotational viscosity, and dynamic shear rheometer (DSR) experiments. In the study, both additives were added to B50/70-grade pure bitumen at different rates. According to the results they obtained, the penetration values of the bitumen modified by mixing Elvaloy and PPA decreased and the temperature of the softening point increased. Although the viscosity value of the mixtures decreased, the viscosity value of 3 Pa.s, which is the limit condition for the workability of all binders at 135°C, was not exceeded. The results of the DSR experiments also showed that the addition of Elvaloy increased the $G^*/\sin\delta$ values.

In this study, tests were conducted to evaluate the performance of SBS and Elvaloy additives, which are frequently used in highway construction. The results of penetration, softening point, elastic recovery, flash point, storage stability, dynamic shear rheometer (DSR), beam bending rheometer (BBR), rotational thin film oven (RTFOT), and pressure aging vessel (PAV) tests applied to determine the usability of polymer-modified bitumen (PMB) prepared by adding SBS and Elvaloy at different rates were compared. According to the results obtained, it has been determined that PMBs that meet the required specification values can be produced by adding 1.6%, 1.7%, and 1.8% Elvaloy and 4%, 4.5%, and 5% SBS additives to B50/70 grade pure bitumen. Especially when the storage stability test results are examined, it has been determined that in cases where high amounts of SBS-added bitumen need to be stored due to the size of the road construction to be made, modification processes should be done carefully in order to provide homogeneous mixtures during the PMB preparation stage.

## 2 Material and Methods

The B 50/70 grade pure bitumen used in the modification in this study was produced in the Aliağa refinery. The bitumen performance tests specified in the "Polymer Modified Bitumen (PMB) Technical Specification" were applied to the samples obtained by mixing Elvaloy and SBS additives with bitumen. While preparing modified bitumen with SBS, pure bitumen was heated at 180 °C for 1 hour before adding the modifier material. Then, SBS was added in such a way that there was no agglomeration, and it was mixed mechanically at 1000 rpm rotation speed, 170 °C, and for 1 hour. Polymer-modified bitumen prepared with Elvaloy was preheated at 180 °C for 1 hour, and then Elvaloy additives were added and mixed mechanically for 8 hours at an 800 rpm rotation speed.

Table 1 shows the tests and specifications applied to modified bitumen.

Table 1. Tests and standards applied to modified bitumen [18-28]

| Test | Specification |
|---|---|
| **Penetration** | TS EN 1426 |
| **Softening Point** | TS EN 1427 |
| **Elastic Recovery** | TS EN 13398 |
| **Flash Point** | TS EN ISO 2592 |
| **Specific Gravity** | TS EN 15326+A1 |
| **Storage Stability** | TS EN 13399 |
| **Dynamic Shear Rheometer (DSR)** | TS EN 14770 |
| **Bending Beam Rhometer (BBR)** | TS EN 14771<br>ASTM D 6648 |
| **Rotional Thin Film Owen (RTFOT)** | TS EN 12607-1<br>AASHTO T 240 |
| **Pressure Aging Vessel (PAV)** | TS EN 14769 |

The tests given above were applied to 1.6%, 1.7% and 1.8% Elvaloy doped PMBs and 4%, 4.5% and 5% SBS doped PMBs. These ratios were determined by taking into account the recommendations of the additive producer companies.

## 3. Results and Discussions

In this study, the results of 3 different PMB modified with Elvaloy and 5 different PMB modified with SBS were examined.

### 3.1. Test results of Elvaloy modified binders

In Table 2, the results of traditional bitumen tests applied to three different bitumen binders of the B 50/70 grade modified with Elvaloy are summarized. According to the results of the penetration tests, as the Elvaloy content in all modified bitumen increases, the penetration depth decreases, and the binders acquire a harder consistency, although there is no significant difference. Similar results were observed in the softening point experiments: as the additive ratio increased, the softening point temperatures of the modified bitumens increased. As the Elvaloy ratio increased, the penetration index for B2 binder decreased, while the penetration index for B1 and B3 binders increased. According to the flash point test results, an increase of at least 5 °C was observed in the ignition temperatures of the binders as the Elvaloy ratio increased. While the specific gravity values, which are an important calculation parameter in the calculations of bituminous mixtures, did not show any change for the B2 binder as the Elvaloy content increased, it caused a decrease in the specific gravity of B1 and an increase in the specific gravity of B3. The specific gravity values calculated for the three binders are generally compatible with the bitumen specific gravity values, which are considered to be between 1.00 and 1.10. According to the results of the elastic recovery test of the modified bituminous binders, as the Elvaloy ratio increases for the B1 and B2 binders, the elastic recovery gain decreases, while it increases for the B3 binder.

The findings of the softening point and penetration tests applied to the top and bottom halves of the Elvaloy modified binders subjected to the storage stability test are summarized in Table 3. It was determined that the bitumen modified according to the differences between the penetration and softening point values of the top and bottom halves of three different samples, which were close to each other, formed a mixture close to homogeneous. According to the test results before and after storage, it was concluded that the softening point temperature and penetration values of the stored modified bitumen decreased, and according to these results, the binders aged to a certain extent during storage.

The results of the RTFOT tests and the penetration and softening point tests applied to the samples after RTFOT are summarized in Table 4. It was determined that the changes in the Elvaloy ratio in the mixtures made with each different bitumen sample did not affect the material loss after the RFTOT test. The softening point temperatures after RTFOT increased with the increase in the additive ratio for all three modified binders. Permanent penetration percentage after RTFOT increased as the Elvaloy content increased in B2 and B3 binders, while it decreased with the increase in Elvaloy content in the B1 binder. In the mixtures created by mixing 1.8% Elvaloy with B1 and B2 bitumens, the increase in softening point temperature after RTFOT exceeded the maximum 8 °C difference recommended in the "Polymer Modified Bitumen (PMB) Technical Specifications" [29]

Table 2. Results of conventional bitumen tests for Elvaloy modified binders

| Binder | Elvaloy Content (%) | Penetration (0.1 mm) | Softening Point (°C) | Penetration Indeks | Elastic Recovery (%) | Flash Point (°C) | Specific Gravity |
|---|---|---|---|---|---|---|---|
| **B1** | 1.7 | 47.6 | 65.25 | 1.89 | 48.0 | 307.5 | 1.046 |
| | 1.8 | 45.8 | 67.35 | 2.16 | 42.0 | 317.5 | 1.039 |
| **B2** | 1.7 | 40.8 | 68.20 | 2.02 | 76.5 | 292.5 | 1.024 |
| | 1.8 | 31.7 | 65.85 | 1.04 | 68.0 | 302.5 | 1.024 |
| **B3** | 1.6 | 45.5 | 62.30 | 1.24 | 63.5 | 225.0 | 1.02 |
| | 1.7 | 43.6 | 64.75 | 1.58 | 75.0 | 230.0 | 1.037 |

Table 3. Results of storage stability tests for Elvaloy modified binders

| Binder | Elvaloy Content (%) | Softening Point (°C) | | | | Penetration (0.1 mm) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $SP_{top}$ | $SP_{bottom}$ | ΔSP | Before storage | $P_{top}$ | $P_{bottom}$ | ΔP | Before storage |
| **B1** | 1.7 | 63.8 | 62.5 | 1.3 | 65.25 | 43.0 | 41.6 | 1.4 | 47.6 |
| | 1.8 | 63.7 | 63.0 | 0.7 | 67.35 | 43.8 | 42.5 | 1.3 | 45.8 |
| **B2** | 1.7 | 61.5 | 60.2 | 1.3 | 68.20 | 35.7 | 33.1 | 2.6 | 40.8 |
| | 1.8 | 65.7 | 64.3 | 1.4 | 65.85 | 31.4 | 32.3 | 0.9 | 31.7 |
| **B3** | 1.6 | 61.2 | 61.3 | 0.1 | 62.30 | 34.3 | 33.8 | 0.5 | 45.5 |
| | 1.7 | 61.8 | 61.1 | 0.7 | 64.75 | 36.7 | 35.6 | 1.1 | 43.6 |

(Storage Stability)

Table 4. Results of RTFOT experiments for Elvaloy modified binders

| Binder | Elvaloy Content (%) | Mass Loss | After RTFOT | | |
|---|---|---|---|---|---|
| | | | Softening Point (°C) | Softening Point Difference (°C) | Permanent Penetration (%) |
| **B1** | 1.7 | 0.3 | 72.25 | 7.0 | 62 |
| | 1.8 | 0.3 | 81.65 | 14.3 | 60 |
| **B2** | 1.7 | 0.3 | 73.95 | 5.8 | 61 |
| | 1.8 | 0.3 | 75.45 | 9.6 | 82.3 |
| **B3** | 1.6 | 0.03 | 66.35 | 4.1 | 83.7 |
| | 1.7 | 0.03 | 71.75 | 7.0 | 84.2 |

Table 5. Results of DSR and BBR tests for Elvaloy modified binders

| Binder | Elvaloy Content (%) | DSR Failure Temp.(°C) | After RTFOT | After RTFOT and PAV | |
|---|---|---|---|---|---|
| | | | DSR Failure Temp.(°C) | DSR Failure Temp.(°C) | BBR Failure Temp.(°C) |
| **B1** | 1.7 | 84.9 | 88.3 | 26.2 | -6 |
| | 1.8 | 86.2 | 93.0 | 26.8 | -6 |
| **B2** | 1.7 | 83.7 | 89.3 | 22.7 | -6 |
| | 1.8 | 83.0 | 81.0 | 22.7 | -6 |
| **B3** | 1.6 | 76.0 | 75.2 | 24.6 | -6 |
| | 1.7 | 80.4 | 77.0 | 23.3 | -6 |

Table 5 summarizes the results of DSR and BBR tests of Elvaloy-added binders. The results of DSR tests before aging, after RTFOT aging, and after PAV aging for all binder samples are given as the failure temperature under loading specified in the test standard. According to the results obtained, as the Elvaloy content increased, the failure temperatures of all samples before and after RTFOT aging increased. After pressure aging, as the Elvaloy content increased, a small increase was observed in the failure temperature for the B1 binder, while no change was observed for the B2 binder. In B3 binder, the increase in Elvaloy content decreased the failure temperature. According to the results of BBR tests, creep hardness values less than 300 MPa and m values greater than 0.300 were reached in all samples at -6 °C.

In the table of "Polymer Modified Bitumen (PMB) Technical Specifications" shown in the book "Bitumen Class Selection Maps for HMA Paved Roads" published by the General Directorate of Highways, there are 3 different types of modified bitumen, PMB 70-16, PMB 76-16, and PMB 82-16, for which BBR values at -6 °C are available. Accordingly, the penetration values of six different samples modified with Elvaloy are suitable for the PMB 70-16, PMB 76-16, and PMB 82-16 grades.

For the softening point values, all samples provided the values of the PMB 70-16 grade, while the B1 sample with 1.8% Elvaloy content and the B2 sample with 1.7% Elvaloy content also provided the limit values for PMB 76-16.

According to the results of the elastic recovery test, B1 binders with 1.7% and 1.8% Elvaloy content could not meet the limit values. The remaining binders meet all recommended values for PMB 70-16, PMB 76-16, and PMB 82-16.

Flash point, specific gravity, and softening point after storage for all samples, as well as the results of penetration tests, provide recommended limit values for PMB 70-16, PMB 76-16, and PMB 82-16.

Measurements of mass loss, softening point, and penetration after short-term aging (RTFOT) provide recommended limit values for PMB 70-16, PMB 76-16, and PMB 82-16. However, when the softening point differences were examined, it was determined that 1.8% Elvaloy added B1 and B2 binders did not provide any PMB limits.

According to the results of DSR tests performed before aging, after RTFOT aging, and after PAV aging of B1 and B2 binders added to 1.7% and 1.8%, Elvaloy provides the recommended breakpoints for PMB 70-16, PMB 76-16, and PMB 82-16. The B3 binder, on the other hand, provides the limit values determined for PMB 70-16 in both Elvaloy contents for DSR tests.

When the results of all tests for PMBs prepared with Elvaloy are examined together, it has been determined that all samples generally provide at least PMB 70-16 grade modified bitumen values.

### 3.2. Test results of binders modified with SBS

Table 6 shows the results of penetration, softening point, elastic recovery, flash point, and specific gravity tests applied to five different bitumen binders of the B 50/70 grade modified with SBS. As the SBS content in the modified bitumens increased, the penetration depth decreased for the B4, B7, and B8 binders, while limited increases occurred for the B6 and B7 bitumens. On the other hand, the softening point temperatures increased with the increasing amount of SBS in the other 4 binders, except for the B5 binder. Penetration index values generally increased with the increment of SBS ratio. According to the flash point test results, as the SBS ratio changed, close results were obtained in the ignition temperatures of the binders. Although the specific gravity values of SBS-modified bitumen are close to each other, they are compatible with the bitumen specific gravity values between 1.00 and 1.10. According to the results of the elastic recovery test, for B4, B7, and B8 binders, the elastic recovery gains showed limited changes with the amount of SBS, while the elastic recovery value decreased by 18% in the B5 binder and increased by 12.5% in the B6 binder with the increase of the SBS amount from 4% to 4.5%.

The findings of the storage stability test results are summarized in Table 7. It is seen that the difference values of the top and bottom halves of five different samples, which were subjected to both softening point and penetration tests after storage, are well above the limit values allowed in the PMB technical specification. This is due to the fact that the SBS additive brands and pure bitumen used are different from each other. As specified in the PMB technical specification, the results of storage stability tests become important if modified bitumen has to be stored during road construction.

The results of the RTFOT tests applied to the bituminous binders modified with SBS are summarized in Table 8. Accordingly, it was determined that adding SBS to different pure bitumen at the rates specified in the study changed the material loss after the RFTOT test to a limited extent. According to the results of the softening point tests performed after short-term aging, the softening point difference temperatures of the modified bitumen prepared with B5 and B8 binders higher than the limit values given in the PMB technical specifications. In modified binders prepared with B4, B6, and B7 binders, a difference within the limit values recommended in the specification was obtained. Permanent penetration percentages decreased when the SBS ratio was subtracted from 4.5% for B7 and B8 binders and increased with increasing SBS ratios in other binders. Permanent penetration percentages for all binders provide the limit values specified in the specification [29].

Table 6. Results of conventional bitumen tests for SBS modified binders

| Binder | SBS Content (%) | Penetration (0.1 mm) | Softening Point (°C) | Penetration Indeks | Elastic Recovery (%) | Flash Point (°C) | Specific Gravity |
|---|---|---|---|---|---|---|---|
| B4 | 4.0 | 35.8 | 71.20 | 2.19 | 80.0 | 310.0 | 1.037 |
| | 4.5 | 32.9 | 73.20 | 2.31 | 79.0 | 315.0 | 1.020 |
| | 5.0 | 32.5 | 75.00 | 2.55 | 82.0 | 310.0 | 1.026 |
| B5 | 4.0 | 29.0 | 88.60 | 4.07 | 94.5 | 310.0 | 1.030 |
| | 4.5 | 29.4 | 67.15 | 1.10 | 76.5 | 305.0 | 1.039 |
| B6 | 4.0 | 36.3 | 75.45 | 2.87 | 80.0 | 312.5 | 1.038 |
| | 4.5 | 36.6 | 82.50 | 3.86 | 92.5 | 307.5 | 1.037 |
| B7 | 4.5 | 45.9 | 98.50 | 6.27 | 97.5 | 312.5 | 1.031 |
| | 5.0 | 44.9 | 99.40 | 6.30 | 96.5 | 312.5 | 1.039 |
| B8 | 4.5 | 41.0 | 85.55 | 4.53 | 73.8 | 302.5 | 1.039 |
| | 5.0 | 38.0 | 89.55 | 4.82 | 74.0 | 307.5 | 1.040 |

Table 7. Results of storage stability tests for SBS modified binders

| Binder | SBS Content (%) | Storage Stability | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Softening Point (°C) | | | | Penetration (0.1 mm) | | | |
| | | SPtop | SPbottom | ΔSP | Before storage | Ptop | Pbottom | ΔP | Before storage |
| B4 | 4.0 | 30.6 | 63.0 | 32.4 | 71.20 | 89.2 | 22.9 | 66.3 | 35.8 |
| | 4.5 | 29.9 | 62.1 | 32.2 | 73.20 | 88.5 | 19.0 | 69.5 | 32.9 |
| | 5.0 | 31.0 | 60.2 | 29.2 | 75.00 | 90.1 | 18.4 | 71.7 | 32.5 |
| B5 | 4.0 | 30.6 | 63.0 | 32.4 | 88.60 | 48.5 | 27.4 | 21.1 | 29.0 |
| | 4.5 | 29.9 | 62.1 | 32.2 | 67.15 | 33.3 | 30.6 | 2.7 | 29.4 |
| B6 | 4.0 | 30.9 | 60.1 | 29.2 | 75.45 | 39.3 | 30.3 | 9.0 | 36.3 |
| | 4.5 | 80.1 | 99.5 | 19.4 | 82.50 | 38.4 | 26.0 | 12.4 | 36.6 |
| B7 | 4.5 | 77.6 | 65.4 | 12.3 | 98.50 | 66.2 | 22.5 | 43.7 | 45.9 |
| | 5.0 | 76.8 | 68.3 | 8.5 | 99.40 | 62.6 | 23.4 | 39.2 | 44.9 |
| B8 | 4.5 | 85.2 | 64.9 | 20.3 | 85.55 | 61.7 | 28.5 | 33.2 | 41.0 |
| | 5.0 | 86.8 | 64.6 | 22.2 | 89.55 | 57.1 | 25.4 | 31.7 | 38.0 |

Table 8. Results of RTFOT experiments for SBS modified binders

| Binder | SBS Content (%) | Mass Loss | After RTFOT | | |
|---|---|---|---|---|---|
| | | | Softening Point (°C) | Softening Point Difference (°C) | Permanent Penetration (%) |
| B4 | 4.0 | 0.28 | 73.65 | 2.5 | 88.8 |
| | 4.5 | 0.00 | 74.50 | 1.3 | 91.5 |
| | 5.0 | 0.28 | 77.45 | 2.5 | 91.6 |
| B5 | 4.0 | 0.30 | 81.50 | -7.0 | 82.4 |
| | 4.5 | 0.30 | 81.50 | 14.4 | 87.1 |
| B6 | 4.0 | 0.30 | 76.30 | 0.8 | 84.2 |
| | 4.5 | 0.00 | 84.05 | -1.6 | 85.2 |
| B7 | 4.5 | 0.30 | 99.60 | 1.7 | 85.8 |
| | 5.0 | 0.28 | 96.85 | 2.7 | 78.4 |
| B8 | 4.5 | 0.30 | 79.90 | -5.6 | 81.0 |
| | 5.0 | 0.40 | 78.65 | -10.9 | 71.6 |

Table 9. Results of DSR and BBR tests for SBS modified binders

| Binder | SBS Content (%) | DSR Failure Temp.(°C) | After RTFOT | After RTFOT and PAV | |
|---|---|---|---|---|---|
| | | | DSR Failure Temp.(°C) | DSR Failure Temp.(°C) | BBR Failure Temp.(°C) |
| B4 | 4.0 | 92.8 | 90.5 | 16.9 | -6 |
| | 4.5 | 95.3 | 93.1 | 18.1 | -6 |
| | 5.0 | 99.5 | 92.7 | 19.8 | -6 |
| B5 | 4.0 | 89.0 | 79.7 | 16.5 | -6 |
| | 4.5 | 84.7 | 78.9 | 7.0 | -6 |
| B6 | 4.0 | 85.7 | 78.9 | 11.9 | -12 |
| | 4.5 | 84.7 | 80.2 | 18.6 | -12 |
| B7 | 4.5 | 106.5 | 82.4 | 9.8 | -6 |
| | 5.0 | 105.5 | 82.6 | 8.9 | -6 |
| B8 | 4.5 | 88.0 | 81.1 | 19.2 | -6 |
| | 5.0 | 94.0 | 88.0 | 22.8 | -6 |

Table 9 summarizes the results of the DSR and BBR tests of SBS-added binders. The increase in SBS content increased the failure temperatures of B4 and B8 among the unaged binders, while it decreased the failure temperatures of B5, B6, and B7 binders. However, according to the results, the changes in the failure temperatures were limited. After short-term aging, the failure temperatures were found to decrease for all the contents of the SBS modification for all binders. After long-term aging, as the SBS content increased, the failure temperatures of B4, B6, and B8 binders increased, while the failure temperatures for B5 and B7 binders decreased. All results from DSR tests provide the limit values for failure temperatures specified in the PMB technical specification. According to the results of BBR tests, creep hardness values less than 300 MPa and m values greater than 0.300 were reached at -12 °C for the B6 sample and at -6 °C for other binders.

The B4 binder did not achieve the minimum 72 °C softening point limit value suggested for the PMB 82-16 class at 4% SBS content with a very tiny difference when the results of the storage stability tests are not taken into consideration. However, all remaining test results for the B4 binder provide recommended limit values for the PMB 82-16 grade. For mixtures prepared by adding 4.5% and 5% SBS to B4 binder, the recommended limit values for PMB 70-16, PMB 76-16, and PMB 82-16 grades were provided in all test results.

B5 binder could not provide the recommended softening point temperature limit value for PMB 82-16 grade at 4.5% SBS content. In addition, B5 binder could not provide the softening point increase and decrease limit values after RTFOT recommended for PMB 70-16, PMB 76-16, and PMB 82-16 grade binders at 4% and 4.5% SBS content, respectively. However, in all other tests for B5 binder, the recommended limit values were provided for PMB 70-16, PMB 76-16, and PMB 82-16 grade binders at 4% and 4.5% SBS content, respectively.

B7 binder provides the recommended limit values for PMB 70-16, PMB 76-16, and PMB 82-16 grade binders in all test results at both 4.5% and 5% SBS content.

B8 binder provided the recommended limit values in all the remaining tests, except for the after-RTFOT softening point increase/decrease temperature limit values recommended for PMB 70-16, PMB 76-16, and PMB 82-16 class binders at 4% and 4.5% SBS content, respectively.

B6 Binder, on the other hand, provided the required limit values for the BBR test at -12 °C. According to all test results obtained, B6 binder provides all recommended limit values for modified bitumen of PMB 70-22 and PMB 76-22 grades at 4% and 4.5% SBS content, respectively.

## 4. Conclusions

According to the results of this study, which was conducted to examine the rheological properties of Elvaloy and SBS-added PMBs, which are frequently used in highway construction, it has been determined that PMBs prepared by adding Elvaloy additives at the rates of 1.6%, 1.7%, and 1.8% to B50/70 grade pure bitumen meet the desired specification limit values in all tests. It was determined that PMBs prepared with pure bitumen of B50/70 class by adding 4%, 4.5%, or 5% SBS additives meet the other specification limit values when the storage stability test results are not taken into account. Due to the granular structure of the SBS additive, the fact that the material is not dispersed homogeneously when mixed with pure bitumen is the main reason why the limit values cannot be met in the storage stability experiments. However, as stated in the specification, if the prepared PMB at any polymer additive ratio is to be used in highway construction without being stored, storage stability limit values do not need to be met.

### Declaration of Interest Statement

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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