Experimental Investigation of the Rutting Potential of Polymer-modified Asphalt Binders using the Multiple Stress Creep Recovery Test

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ABSTRACT

Polymer-modified binders have become increasingly important in enhancing the durability and strength of asphalt flexible pavements, allowing them to withstand higher traffic volumes, heavier loads, and extreme weather conditions. Although the Dynamic Shear Rheometer (DSR) test is widely used, it is inadequate to accurately capture the viscoelastic properties of polymer-modified asphalt binders. As a result, the Multiple Stress Creep Recovery (MSCR) test, a recently developed method for assessing the high-temperature performance of asphalt binders, is expected to replace the DSR for short-term aged binders. In this study, binders comprising 40/60 pen unmodified bitumen, a hard polymer-modified binder, and a softer polymer-modified binder, were evaluated using MSCR testing under various stress and temperature conditions. The MSCR results showed that incorporating Styrene–Butadiene–Styrene (SBS) modifiers into the bitumen significantly enhanced the permanent deformation resistance of the modified binders by reducing the non-recoverable compliance and increasing the recovery percentage. Moreover, a comparison of the MSCR results at the 3.2 kPa stress level with the AASHTO standard confirmed that the examined asphalt binders were modified with an elastomeric polymer of acceptable quality.

Keywords-multiple stress creep recovery; polymer-modified asphalt; percent recovery; non-recovery creep compliance

I. INTRODUCTION

It is recognized that the mechanical behavior of materials, such as bitumen, that exhibit viscoelastic properties, is influenced by loading duration and temperature, while the performance of bitumen significantly affects the behavior of asphalt mixtures and the longevity of flexible pavements [1, 2]. In addition, asphalt modification has a longstanding history aimed to enhance performance in road engineering. Among these modifications, Styrene–Butadiene–Styrene (SBS) modified asphalt stands out as a prominent example and is extensively utilized worldwide for its superior properties [3-6]. The resistance of an asphalt mixture to permanent deformation (rutting) is significantly dependent on the properties of its binder. Some previous empirical tests (i.e. penetration and softening point) have been used to evaluate the resistance of the binder to rutting. However, this evaluation has recently shifted to more fundamental rheological tests using DSR devices to attain detailed characterization and specific permanent deformation results [7-11]. The rheological Superpave permanent deformation evaluation parameter (G*/sinδ) has also been proposed as an indicator of the rutting potential of a material at high temperatures, and it has worked well for binders without modifiers [12]. However, the G*/sinδ parameter was found to be unable to distinguish between successful modifiers and others. The problems associated with the G*/sinδ parameter were summarized in a detailed review in [13]. Therefore, repeated creep protocols such as the MSCR test have been designed and it was suggested that they could replace the oscillatory shear test and the G*/sinδ parameter. The nonrecoverable compliance J_{nr} achieved from the MSCR test replaced the G*/sinδ parameter in the revised versions of Superpave [14]. It is also widely accepted as a more accurate indicator to rank binders (pure or modified bitumen) in terms of permanent deformation (rutting), it is simple and easy to perform while being well correlated to the rutting performance of asphalt mixtures [15-20].

In the area of pavement engineering, asphalt binders used for flexible pavements are considered as materials susceptible to the effects of service temperatures. Authors in [21] evaluated the real benefits of using Polymer-Modified Binder (PMB) at different temperatures. Based on the data observed, the addition of SBS polymer to asphalt binders increases their elasticity and consistency at high temperatures, leading to the prevention of the appearance of plastic deformation in flexible pavement at service temperatures. In addition, the results from MSCR tests indicated that temperature has a strong effect on the rheological response of the binder. As the temperature increases, the strain imposed on the binder also increases. Moreover, an increase in the testing temperature probably causes a decrease in the recovery capacity of the binder. However, interestingly, it has been revealed that the influence of the polymers becomes more marked as the temperature increases. At high temperatures, if the polymer content is high enough, the binders can generate a considerable degree of recovery. In [22], the temperature was around 50 °C.

The current study examines three types of binders: 40/60 pen unmodified bitumen (commonly used in UK pavement design), a hard SBS PMB, and a softer SBS PMB. This selection offers a diverse range of bituminous materials to investigate the mechanical properties of binders in asphalt pavements. The experimental program will assess these binders through penetration, softening point, and MSCR tests, evaluating them under various conditions. The MSCR test results will serve as the basis for analysis, assessment, and discussion.

II. MATERIALS AND METHODS

A. Materials

In order to prepare the experimental binder samples, test binders were poured into vials or molds used for MSCR, penetration, and softening point tests. Three types of binder were considered: 40/60 unmodified bitumen, hard SBS polymer modified (PMB1) and soft SBS modified binder (PMB2).

B. Experimental Program

1) Penetration and Softening Point

Penetration and softening point tests were carried out according to [22, 23]. The penetration value is determined by applying a 100 g load to a needle, which vertically penetrates the bitumen for 5 s at 25 °C. The depth of the needle's penetration is recorded as the penetration value, expressed in tenths of a mm. A greater needle penetration indicates a higher bitumen grade. The Softening Point – Ring and Ball method was used to assess the behavior of bitumen at higher service temperatures. The test determines the temperature at which a bitumen sample, contained in a brass ring, undergoes specific deformation under the weight of a steel ball as the temperature increases.

2) MSCR Test

The MSCR test is a creep and recovery test performed on creep binder samples using the DSR apparatus in accordance with [24]. In this study, a Bohlin Gemini DSR machine from the University of Nottingham was utilized to conduct the MSCR test, as shown in Figure 1. The thickness of an asphalt binder sample is 1 mm and its diameter is 25 mm. The test is carried out at a range of high temperatures. Generally, two stress levels, 0.1 kPa and 3.2 kPa, are applied and a total of 10 cycles are conducted at each stress level. Each cycle has 1 s loading period followed by a recovery period of 9 s [25]. As shown in the figure, the MSCR test characterizes the elastic and viscous properties of an asphalt binder under a shear load, defined as percent recovery and non-recovery creep compliance (J_{nr}). The percentage recovery and J_{nr} are expressed in (1) and (2):

$$Recovery\ (\%) = \frac{Peak\ Strain - Unrecovered\ Strain}{Peak\ Strain} \quad (1)$$

$$J_{nr} = \frac{Unrecovered\ Shear\ Strain}{Applied\ Shear\ Stress} \quad (2)$$

Fig. 1. Bohlin Gemini DSR Equipment

The percent recovery averages over 10 cycles at 0.1 kPa and 3.2 kPa are calculated and represented as R_{100} and R_{3200}, respectively. Likewise, the average non-recoverable creep compliance at 0.1 kPa and 3.2 kPa is denoted as $J_{nr}0.1$ and $J_{nr}3.2$. Furthermore, stress sensitivity parameters, R_{diff} and $J_{nr-diff}$, are by [26]:

$$R_{diff} = \frac{R_{100} - R_{3200}}{R_{100}} \times 100 \quad (3)$$

$$J_{nr-diff} = \frac{J_{nr}3.2 - J_{nr}0.1}{J_{nr}0.1} \times 100 \quad (4)$$

This test was conducted on the three selected binder types at 45 °C, 60 °C, and 70 °C, in accordance with several previous studies [21, 26, 27].

III. RESULTS AND DISCUSSION

A. Penetration and Softening Point Test

The penetration and softening point test results are presented in Table I.

TABLE I. PENETRATION AND SOFTENING POINT TEST RESULTS

Test	Unmodified	PMB1	PMB2
Penetration (0.1mm)	41	21	65
Softening point (°C)	51.4	93.1	78.8

Penetration test is widely used to measure bitumen hardness. In some cases, the test is also used to investigate the consistency of bitumen. The reported penetration value was taken as the average of three readings. As the results show in Table I, the penetration values of unmodified bitumen, PMB1, and PMB2 were 41, 21, and 65 (0.1 mm), respectively.

The softening point test, another empirical test, is commonly used to indicate the consistency of a binder by measuring the equiviscous temperature at which the consistency of the binder is between solid and liquid behavior. In the context of asphalt binder materials, equiviscous temperature often denotes the temperature at which a material reaches a specified viscosity, ensuring comparable flow or deformation characteristics. In addition, the result of the softening point test can be linked to the permanent deformation behavior of asphalt mixtures. The ring and ball softening point values of unmodified, PMB1, and PMB2 were 51.4, 93.1, and 78.8 ^{o}C, respectively as presented in Table I.

B. MSCR Test

MSCR tests using the DSR machine were carried out on the three different types of binders at temperatures of 45, 60, and 70 ^{o}C with 10 cycles of creep and recovery at two standard stress levels of 0.1 and 3.2 kPa.

Figure 2 presents the recovery percentages of all binders at various temperatures for the two standard stress levels. The figure reveals that the recovery percentages of polymer-modified binders are significantly higher than those of the unmodified binder across all standard stress levels. Additionally, it is confirmed that samples tested at the 0.1 kPa stress level exhibit higher recovery percentages than those at 3.2 kPa for each binder.

Figure 3 presents the non-recoverable compliance results. As shown in the Figure, PMBs exhibit lower non-recoverable compliance compared to the unmodified binder, particularly at higher temperatures. While there is a slight difference in non-recoverable compliance between the 0.1 kPa and 3.2 kPa stress levels, it is not significant except for the polymer-modified binders at 60 °C and 70 °C.

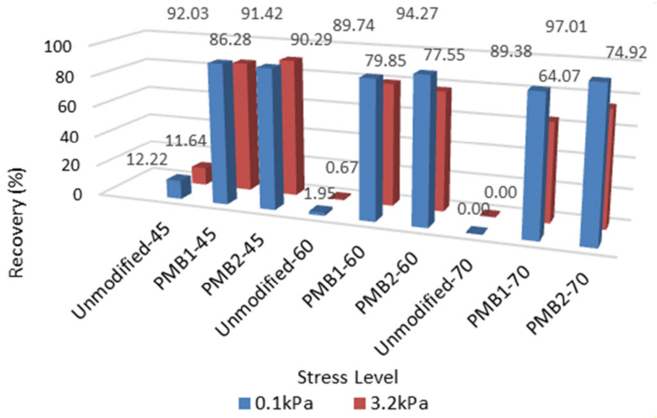

Fig. 2. Recovery percentages of all binders at various temperatures at 0.1 and 3.2 kPa.

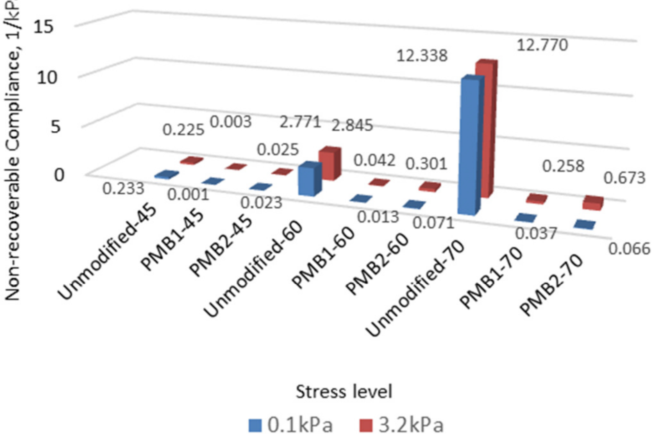

Fig. 3. Non-recoverable compliances of all binders at various temperatures at 0.1 and 3.2 kPa.

In order to evaluate the effect of testing temperatures on recovery percentages and non-recoverable compliance using the MSCR test, Figures 2 and 3 illustrate the results for each stress level separately. Figure 2 shows that, as the testing temperature increases, the recovery percentage generally decreases, except for PMB2 at 0.1 kPa. Similarly, Figure 3 indicates that non-recoverable compliance increases with rising testing temperatures across all stress levels. These findings align with the results of previous studies [20, 21, 26, 27].

Table II displays the stress sensitivity parameters, R_{diff} and $J_{nr\text{-}diff}$ at two high-temperature levels. It can be obviously seen that for the two PMBs, the R_{diff} values increase from 11 to 28 and from 18 to 23 as the temperature rises from 60 °C to 70 °C. However, for the $J_{nr\text{-}diff}$ parameter, the increase rates are approximately threefold for PMB1 and PMB2. Moreover, compared to PMB1, the R_{diff} of PMB2 is lower at 70 °C but higher at 60 °C. In contrast, the $J_{nr\text{-}diff}$ for PMB2 is consistently higher than that of PMB1 at both 60 °C and 70 °C. This is unsurprising because PMB2 is softer than PMB1, as shown in Table I.

TABLE II. STRESS SENSITIVITY PARAMETERS AT 60^{O}C AND 70^{O}C

Stress sensitivity parameters	**Unmodified**		**PMB1**		**PMB2**	
	60^{o}C	70^{o}C	60^{o}C	70^{o}C	60^{o}C	70^{o}C
R_{diff}	66	23	11	28	18	23
$J_{nr\text{-}diff}$	3	4	213	589	322	913

Figure 4 illustrates the typical effect of PMBs on binder recovery behavior, showing strain versus time at a stress level of 3.2 kPa and a temperature of 60°C. The Figure displays the instantaneous and peak strain during a single creep and recovery cycle for all binders, with average strain values calculated from 10 testing cycles under the same conditions. Similar strain patterns were observed for all binders at the other testing temperatures and at both stress levels. The MSCR results reveal that PMB1 exhibited the lowest peak strain among the tested binders, followed by PMB2. As the temperature increases, the difference in peak strain between the PMBs and the unmodified binder becomes more pronounced.

This suggests that incorporating the SBS modifier enhances the stiffness and elastic recovery of bitumen, with the improvement being more evident at higher temperatures.

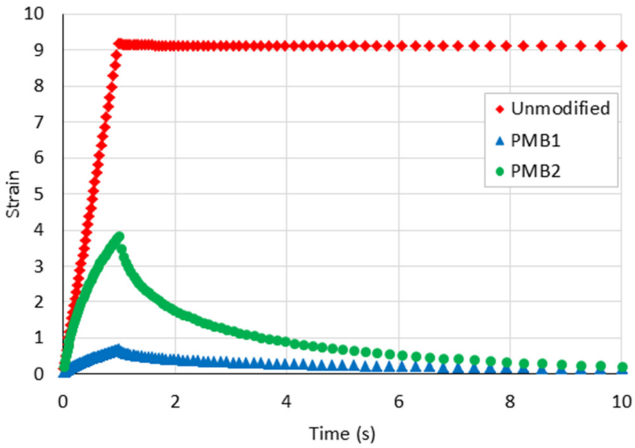

Fig. 4. Strain vs time at 3.2k Pa stress level and 60 °C.

To evaluate the behavior more precisely, the relationship between accumulated strain and accumulated time is illustrated in Figure 5. The Figure presents typical test data, including 10 cycles of creep and recovery at a stress level of 3.2 kPa and a temperature of 60 °C. The graph indicates that the unmodified binder exhibits the largest strain highlighting its poorer resistance to permanent deformation compared to the both PMB types. Conversely, PMB1 demonstrates the smallest accumulated strain, indicating superior resistance to permanent deformation. At the same stress level, the accumulated strain for each binder increases significantly as the testing temperature rises from 45 °C to 70 °C. Similarly, at a constant testing temperature, the accumulated strain increases as the creep stress level rises from 0.1 kPa to 3.2 kPa.

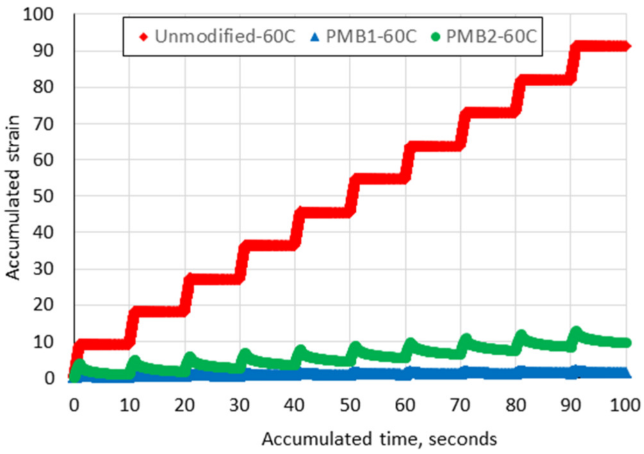

Fig. 5. Accumulated strain vs accumulated time at 3.2 kPa stress level at 60°C.

Because of the importance of elastic behavior, AASHTO TP 70 has presented a graph to evaluate the elastic response of binders. According to [24], the percent recovery is intended to provide a means for determining the presence of elastic response and stress dependence of polymer modified and unmodified binders. As can be seen from Figure 6, at 3.2 kPa stress level, PMB1 and PMB2 binders at all testing temperatures are located above the AASHTO elastic response line. This indicates that the asphalt binders used in the study are modified with an acceptable elastomeric polymer [24]. In contrast, the three points representing the 40/60 unmodified binder fall below the line on the graph, as expected.

The results of the evaluation of the elastic response of binders in this study are similar to those of several previous studies. Authors in [26] conducted MSCR tests on SBS polymer-modified binders with and without sulfur at 0.1 and 3.2 kPa, at 64 and 70 °C. The results showed that data points from SBS-modified binders with sulfur at 3.2 kPa stress were above the curve. Similarly, authors in [27] considered three types of binders (PG 64-22, PG 70-28, PG 76-28) which were tested at 3.2 kPa and temperatures of 64, 67, and 70°C with the MSCR method. The results indicated that all modified binders tested were above the curve.

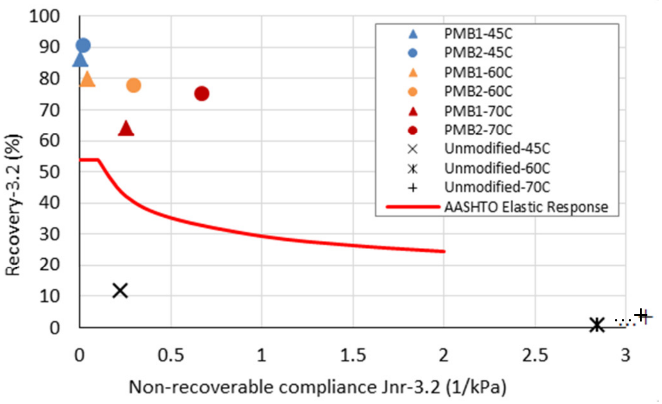

Fig. 6. Recovery versus non-recoverable using AASHTO elastic response at testing temperatures.

IV. CONCLUSIONS

This study used three types of binders: 40/60 pen unmodified bitumen, PMB1 (a hard SBS polymer-modified binder), and PMB2 (a softer SBS polymer-modified binder). The experimental program included penetration, softening point, and MSCR tests to evaluate the properties of the considered binders. Based on the MSCR results at 0.1 and 3.2 kPa at 45 °C, 60 °C, and 70 °C, the conclusions of this study are:

- The MSCR results demonstrated that the addition of SBS modifiers to bitumen significantly enhanced the resistance of the modified binders to permanent deformation. This was reflected by a reduction in non-recoverable compliance (J_{nr}) and an increase in recovery percentage values ($\%R$).
- The MSCR data further revealed that, in terms of strain and time, PMB1 exhibited the lowest peak strain among the three binders tested, with PMB2 following closely behind. As the temperature increased, the disparity in peak strain

between the modified binders and the unmodified binder became more pronounced.

- Regarding the relationship between accumulated strain and time, the unmodified binder consistently showed the highest strain across all testing temperatures and stress levels, indicating its lower resistance to permanent deformation compared to the two PMBs. In contrast, PMB1 exhibited the lowest accumulated strain, signifying superior resistance to permanent deformation.
- A comparison of the MSCRT results at a 3.2 kPa stress level across all testing temperatures with the AASHTO standard confirmed that the asphalt binders used in this study (PMB1 and PMB2) were modified with an acceptable elastomeric polymer (SBS).

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