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RHEOLOGICAL PROPERTIES OF STYRENE BUTADIENE RUBBER MODIFIED BITUMEN BINDER

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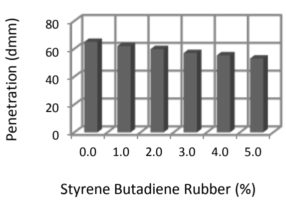
Graphical abstract



Abstract

The study investigates the rheological properties of bitumen of 60-70 penetration grade modified with Styrene Butadiene Rubber (SBR). SBR is an elastomer which is an important sort of synthetic rubber. It is a copolymer whose molecular structure primarily consists of organic compound styrene and butadiene chain. Bitumen is visco-elastic in nature. The rate of load application and temperature has a great influence on its performance. Various fundamental properties of bitumen were evaluated, namely complex shear modulus (G*), short-term ageing, long-term ageing, viscosity, penetration and softening point by using Dynamic Shear Rheometer (DSR), Rolling Thin Film Oven Test (RTFOT), Pressure Aging Vessel (PAV), Rotational Viscometer (RV), Penetrometer and Ring and Ball Test, respectively. The binders were mixed with varying percentage of SBR i.e. 0, 1, 2, 3, 4, and 5% by the weight of bitumen binder. The use of SBR has played an active role in improving the viscoelastic properties of bitumen. The use of SBR modifier changes the rheological behavior of bitumen by increasing its complex shear modulus (G*) and the resistance of mixture against permanent deformation (rutting). It was also found that increasing the content of SBR led to the increase in viscosity of modified bitumen, which helps in elevating the mixing and compaction temperature of asphalt mixtures.

Keywords: Viscosity, penetration, softening Point, SBR, complex shear modulus

1.0 INTRODUCTION

The use of polymer modified bitumen (PMBs) in road construction has been studied for a long time in order to achieve better performance [1]. A polymer is a large molecule built up from numerous small molecules. These large molecules may be linear, slightly branched, or highly interconnected [2]. Based on the rheological properties, polymers are divided into plastomer and elastomer. Elastomers are tough whereas plastomers are stiff in nature[3]. Elastomers and plastomers are typically used in bitumen modification, such as styrene butadiene rubber (SBR), styrene butadiene styrene tri-block copolymer (SBS) and polyethylene (PE) [4]. However, Styrene-butadiene-rubber (SBR) has been found as one of the most effective polymer additives [5]. SBR describes families of synthetic rubbers derived from styrene and butadiene [6]. The advantage of using SBR in binder modification is that it has excellent ageing stability. Also, it decreases the change of binder properties such as stiffness due to ageing [7].

Some of the important roles of SBR in asphalt binder include increasing the ductility of binder, improving its elastic recovery, decreasing viscosity and enhance its ageing by decreasing the rate of oxidation. The increase in ductility due to SBR polymer allows the pavement to be more flexible and crack resistant at low temperatures. Vasudevan *et al.* [8] reported that bitumen binders are modified in order to stiffen the binders and mixes at high temperatures to minimize rutting, improve fatigue resistance where higher strains are imposed on bituminous mixes and improve the aggregate bonding to reduce stripping. The performance of asphalt pavement is principally controlled by the quality of binder. Hence in case of a pavement when uncovered to high temperature, permanent deformation (rutting) occurs across the wheel road to the pavement. Read and Whiteoak [9] found that modifiers stiffen the bitumen which directly effects the pavement performance. However, bitumen at low temperature exhibits brittleness and pavement cracking [10].

The quality of road network of a country determines the level of development in that country. Most commonly, flexible pavements have to sustain increasingly large traffic loads. When these loads are combined with adverse environmental conditions, the issue of rutting and cracking of roads arises. The severity of former issue is more than latter and thereby under consideration. Due to the presence of cracks, some problems may emerge. For e.g., loss of waterproofing, loss of load spreading ability, pumping and loss of fines from the base course, loss of riding quality, etc. In case of a longitudinal deformation in a wheel path, rutting is irregularly occurring in the driving direction. Possible causes include settlement of the sub grade and base course and the plastic deformation of bituminous materials (flow) observed longitudinally. It is accelerated by the combined effect of traffic and high temperature and inadequate compaction of surfacing or base. Based on review, the use of SBR in bitumen modification is considered as a sustainable technology which transforms an unwanted residue into a new bituminous mixture resistant to rutting and fatigue.

2.0 MATERIAL AND EXPERIMENTAL PROCEDURE BINDER

In this study, bitumen 60-70 PEN was used. This grade of bitumen is widely used in Malaysia and other countries. The properties of base bitumen are illustrated in Table 1. Bitumen was obtained from UTM Highway lab; where SBR bitumen was obtained from ASA Infratech Sdn. Bhd.

2.1 Sample Preparation

Samples were prepared using blending techniques. Bitumen content of about 500gm was heated in oven till fluid condition and SBR was slowly added, while the speed of the mixer was maintained at 800-1000 rpm and temperature was kept between 130°C and 140°C. The concentrations of SBR used were 1, 2, 3, 4, and 5 % of the weight of the mixture. Mixing was continued for 1 hour to produce homogenous mixtures.

Table 1 Properties of the base bitumen

No.	Parameters	Capability Values
1	Penetration at 25°C (d-mm)	65.0
2	Softening point (°C)	52.0
3	Specific Gravity (g/cm^3)	1.03
4	Viscosity at 135°C (cP)	500
5	G*/sin δ at 64°C (kPa)	2.92

2.2 Test Methods

The tests to determine rheological properties such as penetration, softening point, viscosity, and direct shear test are performed in the following study. Binders are characterized by using a number of standard physical tests such as penetration test ASTM D5-97 (temperature, load and time at 25°C, 100g and 5sec, respectively), softening point test ASTM D36-95, viscosity test using Brookfield viscometer ASTM D 4402 (temperature ranging from 135 to 165°C, spindle No. 27, and a rotating speed of about 20rpm). The short-term aging test of the binder is conducted using RTFOT (ASTM D 2872) at 163°C for 85min; the long-term aging is performed using PAV (ASTM D6521-05) at 100 °C for 20hrs with 2.1Mpa. The aged samples are evaluated by measuring their rheological properties. Furthermore, the bitumen rheological properties are evaluated using dynamic shear rheometer (DSR) (tests conducted by using a temperature sweep starting from 22°C to 84°C and the frequency of 1.59Hz with 1mm gap [11].

2.3 Viscosity Test

Viscosity can be defined as resistance to the flow. It is a fundamental characteristic of bitumen binder as it determines how the material will behave at a given temperature or over a range of varying temperatures. It is used to determine the viscosity of bitumen binder in high temperature range of mixing and paving. The basic RV test measures the torque required to maintain a constant rotational speed (20RPM) of a cylindrical spindle when submerged in a bitumen binder at a constant temperature (135°C). This torque is converted into dynamic viscosity and displayed automatically by the RV. The viscosity characteristics of SBR modified bitumen were examined at two temperatures i.e. 135°C and 165°C.

2.4 Dynamic Shear Rheometer Test

The Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of the bitumen binder at high and intermediate service temperatures. It also facilitates to evaluate the rutting and fatigue cracking potential of the binder. The behaviors can be assessed by measuring the complex shear modulus (G*) and phase angle (δ) under a specific temperature and frequency of loading. The complex shear modulus (G*) is the total resistance of sample to deformation when repeatedly sheared, whereas phase angle (δ) is the lag between the applied shear stress and resulting shear strain. DSR tests are conducted on unaged binder, RTFO residue and PAV residue at each percentage. As shown in Table 2, high service temperature is a temperature at which the $G^*/\sin\delta$ is larger than 1kPa ($G^*/\sin\delta > 1$kPa) and 2.2kPa ($G^*/\sin\delta > 2.2$kPa) for unaged bitumen and RTFO aged bitumen, respectively. The intermediate service temperature is a temperature at which the $G^* \cdot \sin\delta$ is less than 5000kPa ($G^* \cdot \sin\delta \leq 5000$kpa) for PAV aged bitumen.

Table 2 Superpave binder specification

Bitumen Binder Condition	Parameter	Specification Value	Distress of Concern
Unaged Binder	G* / sin δ	≥ 1.0kpa	To concern rutting
RTFOT Aged Binder	G* / sin δ	≥ 2.2kpa	To control rutting
PAV Aged Binder	G* · sin δ	≤ 5000kpa	To control fatigue cracking

3.0 RESULTS AND DISCUSSION

3.1 Penetration

Figure 1 shows the effect of SBR concentration on penetration. The amount of penetration decreased as the amount of SBR increased, starting from 0% to 5%. This shows that SBR content has a significant effect on penetration value. It can be seen from the figure below that when SBR is increased from 1% to 5%, the penetration number gradually decreases from 62 to 53. It means that SBR has good effect on reducing the penetration value by increasing the stiffness of SBR bitumen binder and less susceptible. It also improves the resistance of binder against deformation like rutting. The only drawback is that it might affect the resistance to fatigue cracking.

3.2 Softening Point

It is quite evident from Figure 2 that with increase in the percentage of SBR, there is an increase in the softening point. In case of bitumen with 60-70 penetration, it can be observed that when SBR content is 1% by the weight of bitumen, the softening point is 55°C. And when SBR content is 5% by the weight of bitumen, the softening point temperature reaches to 75°C which is noticeably greater than when there is no SBR added into the mix i.e. 52°C. Based on the bar graph of softening point below it can be said that when the softening point is increasing, there is reduction of susceptibility at high temperature. This phenomenon indicates that the resistance of binder to the effect of heat is increased. Thus, it will exhibit a reduced tendency to soften in hot weather. Hence, with the addition of SBR, the modified binder will be less susceptible to temperature changes. Therefore it is expected that by using SBR in the bituminous mix, the rate of rutting will decrease due to the increase in softening point.

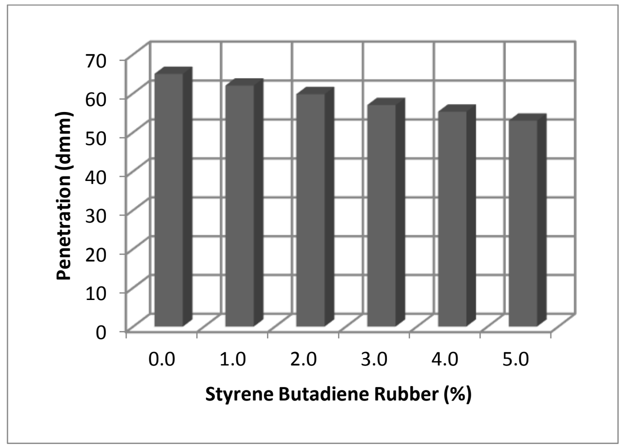


Figure 1 Penetration test results for SBR modified bitumen

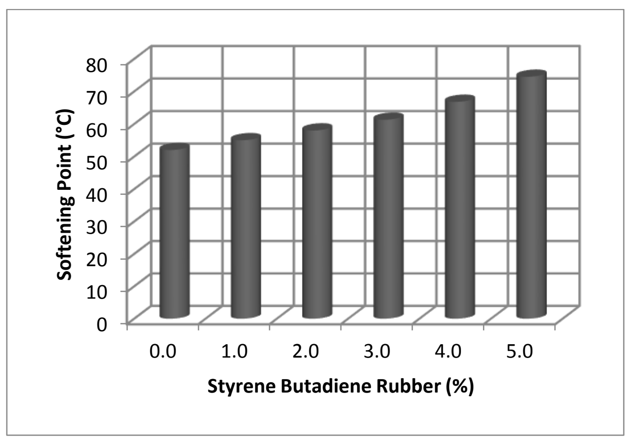


Figure 2 Softening point results for SBR modified bitumen

3.3 Penetration Index (PI)

PI value is defined as the measure of temperature susceptibility of bitumen. According to Hadavand [12], temperature susceptibility is defined as change in the consistency of bitumen as a function of temperature. Softening point (SP) together with Penetration (P) value is used to determine the Penetration Index. It can be determined using nomo-graph or the following equation:

$$PI = \frac{(1951.4 - 500logP - 20SP}{(50logP - SP - 120.14)} \quad (1)$$

Table 3 lists the PI values for mixtures prepared at different SBR contents of unaged bitumen. As shown in the table, the addition of SBR content in bitumen increased temperature susceptibility of the binder. Also, the PI value increased from -0.06 to 3.70 when the amount of SBR incorporated into the bitumen was increased. Higher PI values indicate higher resistance to low temperature cracking and permanent deformation.

Table 3 Penetration index of modified bitumen

Styrene-butadiene-rubber (%)	Penetration Index
0.0	-0.06
1.0	0.52
2.0	1.09
3.0	1.63
4.0	2.56
5.0	3.70

3.4 Viscosity

Figure 3 shows that the modified binder with SBR additive has greater viscosity than the base 60-70 penetration grade bitumen. With increase in the percentage of SBR the viscosity is increasing i.e. binder is getting more viscous. From the chart it can be seen that the viscosity of base bitumen 60-70 is 500cP at 135°C which is less viscous than when 5% of SBR is added in the mix giving us viscosity of 1200cP at the same temperature. The viscosity of bitumen with 5% SBR content is approximately 2.5 times the viscosity of base bitumen. At 165°C, the viscosity of base bitumen is 200cP which is increased to 900cP with the addition of 5% SBR in bitumen. High viscosity means there will be less chance of rutting at high temperatures. On the other side it also creates the chance of fatigue cracking at low temperatures. According to this chart, at high viscosity it resists the compactive effort and there are low stability values as well.

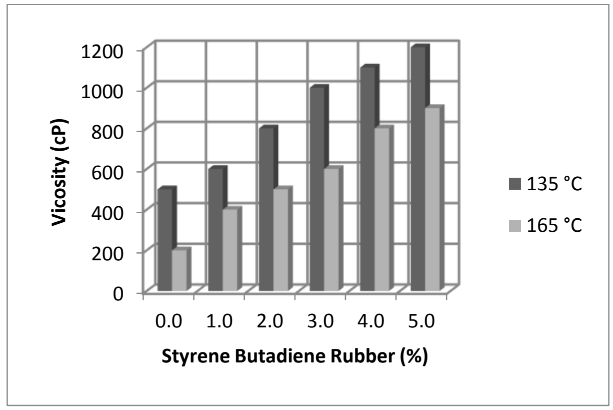


Figure 3 Viscosity test results for SBR modified bitumen

3.5 Penetration-Viscosity Number (PVN)

The PVN is based on penetration at 25°C and viscosity at 135°C. These are standard specifications for paving bitumen. According to Hainin *et al.* [13] the PVN can be expressed as follows:

$$PVN = \frac{L - X}{L - M}(-1.5) \quad (2)$$

where; X is logarithm of viscosity in centipoise measured at 135°C, L is logarithm of viscosity at 135°C for a PVN of 0.0, and M is logarithm of viscosity at 135°C for a PVN of 1.5. The values of L and M can be found by using the following equations:

$$L = \log(Vis.@135°C) = 4.258 - 0.7967 * \log(\text{Pen.} 25°C) \quad (3)$$

$$M = \log(Vis.@135°C) = 3.46289 - 0.61094 * \log(\text{Pen.} 25°C) \quad (4)$$

Table 4 shows the PVN values of bitumen containing different quantities of SBR. PVN value indicates the temperature susceptibility of bitumen within high temperature range. The result showed that PVN is directly proportional to SBR. In other words PVN value increases with increase in SBR content. The PVN value is increased from -0.38 to 0.59 with the increase of SBR content from 0% to 5%. Increase in PVN value means that the addition of SBR can significantly improve the temperature susceptibility of bitumen. The result also indicates that the addition of SBR into bitumen can improve the rutting resistance of bitumen at high temperatures.

Table 4 Penetration-Viscosity-Number

Styrene-butadiene-rubber (%)	PVN
0.0	-0.38
1.0	-0.17
2.0	0.19
3.0	0.45
4.0	0.54
5.0	0.59

3.6 Dynamic Shear Rheometer

According to this study, by increasing the SBR additive in base bitumen at a given temperature, the G* value is increased. A similar pattern is seen for modified bitumen after the RTFO aging process. In superpave binder specification, rutting is taken into account using a rutting factor (G*/ sin δ) which is solely dependent on the rheological properties of the bitumen binder. The higher the rut factor of the binder, the stiffer the asphalt concrete should be [14] and therefore more resistant to rutting.

3.7 Aging of Modified Bitumen

Figures 4 and 5 show the G*/ sinδ trend of base and modified bitumen, before and after the short termaging process in the temperature ranging from 46°C to 82°C and at the constant frequency of 1.59Hz. From the figures it is quite apparent that higher the SBR percentage, higher is the G* and accordingly higher is G*/sinδ (rutting factor) before and after short term aging process. The optimum percentage of SBR which gives the maximum value of G*/sinδ is 3%. This maximum value is decreased when the percentage of SBR content is further increased to 4% or 5%. Due to this reason, the optimum SBR percentage that can be used is 3% of SBR. Concluding it, the increase of G*/sinδ leads to the improved performance of modified bitumen againstpermanent deformation (rutting) at high temperature. The loss stiffness (G*sinδ) value of the aged binder is strongly associated with the fatigue life of the mixture and is a basic parameter for describing the fatigue characteristics of abitumen binder. The increase in loss stiffness is accompanied by a rather significant decrease in the fatigue resistance. Figure 6 shows the G*· sinδ (cracking factor) trend of base and modified bitumen after the PAV aging process within the temperature range of 22°C to 37°C. In Figure 6, there is an increase in the value of G*· sin δ with the increase of SBR content.The loss stiffness value at intermediate temperatures i.e. between 22°C and 37°C due to cracking. The graph indicates that the G*· sinδ values of the SBR modified binders are significantly more than 5000kPa when 4% and 5% of SBR content is added to the bitumen. Consequently above 3%, SBR cannot resist fatigue cracking. In other words, 3% SBR is the optimum percentage for the modification of bitumen. Because if we add more than 3% SBR to the bitumen, the G*· sin δ value is also increased which can be dangerous for the performance of pavement at intermediate temperatures. This may also be followed by the reduced strength of bitumen mixtures against fatigue cracking [15].

4.0 CONCLUSION

The study unveils the effects of SBR additive on the performance of 60-70 base bitumen. The following conclusions were made:

- The additive content has a noticeable effect on the temperature susceptibility. When SBR content increases, it decreases the penetration grade and thereby increases the softening point of bitumen.
- The addition of SBR significantly increases the viscosity of binder at high temperatures. High viscosity means that there will be less chance of rutting at high temperatures and will resist the compactive effort.
- Higher SBR percentage leads to higher G*/sinδ (rutting factor) before and after RTFO aging process. The increase in G*/sinδ means improvement of the performance of modified bitumen against rutting at high temperature. But SBR has diverse effect on cracking when the percentage of SBR added in bitumen is greater than 3%.

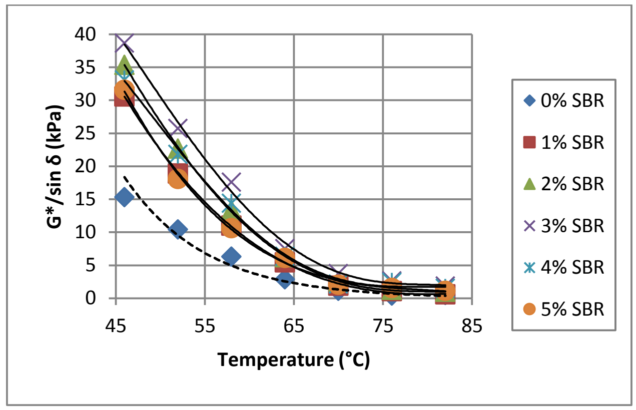


Figure 4 G* / sin δ of SBR modified bitumen in Original State

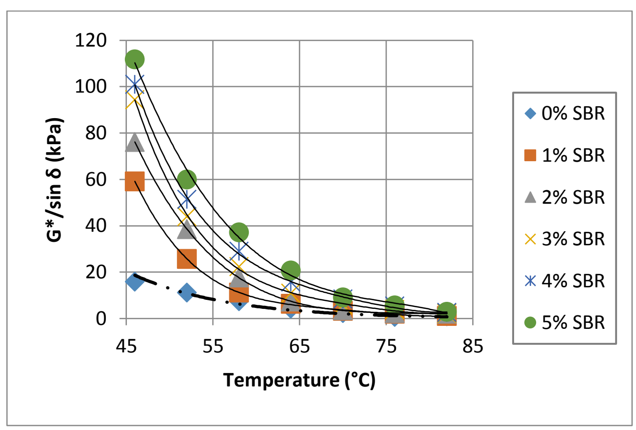


Figure 5 G* / sin δ of SBR modified bitumen in Short Term Aging State

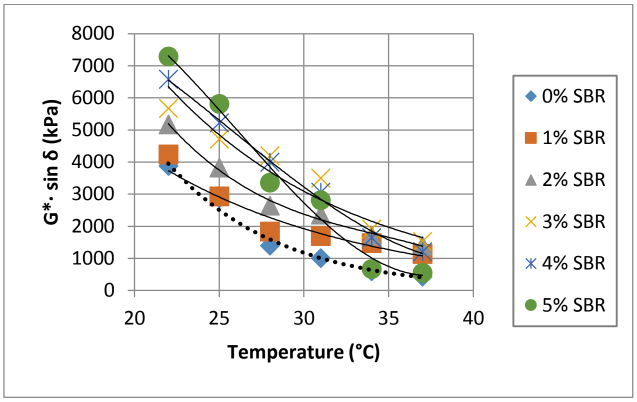


Figure 6 G*·sinδ of SBR Modified bitumen at Long Term Aging

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