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Analysis of styrene-butadiene-styrene polymer modified bitumen using fluorescent microscopy and conventional test methods

Burak Sengoz*, Giray Isikyakar

Dokuz Eylul University, Faculty of Engineering, Department of Civil Engineering, 35160 Buca, Izmir, Turkey

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Abstract

This paper presents a laboratory study of modified bitumen containing styrene-butadiene-styrene (SBS) copolymer. Polymer modified bitumen (PMB) samples have been produced by mixing a 50/70 penetration grade unmodified (base) bitumen with SBS Kraton D1101 copolymer at five different polymer contents. The fundamental characteristics of the SBS PMB samples have been determined using conventional methods. The morphology of the samples as well as the percent area (%) distribution of SBS polymers throughout the base bitumen have been characterized and determined by means of fluorescence microscopy and Qwin Plus image analysis program, respectively. The mechanical properties of the hot-mix asphalt (HMA) containing SBS PMBs have also been analyzed and compared with HMA incorporating base bitumen. The effect of polymer addition on the short and long term aging characteristics of HMA have been evaluated by indirect tensile strength (ITS) test. The results indicated that polymer modification improved the conventional properties (penetration, softening point, etc.) and the mechanical properties (Marshall, ITS, etc.) of the base bitumen. It was also concluded that at low polymer contents, the samples revealed the existence of dispersed polymer particles in a continuous bitumen phase, whereas at high polymer contents a continuous polymer phase has been observed. Moreover, it was found out that the polymer addition minimizes the short and long term aging of HMA.

Keywords: Modified bitumen; Morphology; Fluorescence microscopy; Image analysis; Aging

1. Introduction

When the need for paved roads became a worldwide requirement, bitumen appeared very quickly as an ideal binder to build the pavement structure and the wearing course. At high temperatures, bitumen due to its viscous behavior can be mixed with aggregate to manufacture asphalt concrete, which remains sufficiently workable during placement and compaction. At ambient temperatures, bitumen behaves as a visco-elastic material providing essential properties for long lasting pavements such as stability and flexibility.

To accommodate ever increasing traffic loadings in varying climatic environments and resist to failures such as permanent deformation, cracking and water damage, major emphasis was placed on improving the level of performance and service life of roads. The level of service life of the roads, on the other hand, has a close relationship with the aging property of asphalt cement which is defined as the hardening of asphalt cement due to loss of volatile components oxidation. The effects of aging can be exacerbated in the case of permeable pavements or in regions with extreme climatic conditions [1,2]. This approach led to a fundamental variation in the design of long lasting asphalt pavements. For improving the bitumen characteristics and overcoming potential deficiencies revealed due to aging, specific performance enhancers were investigated. These include additive modification, polymer modification and chemical reaction modification [3,4].

Currently, the most commonly used polymer for bitumen modification is the SBS followed by other polymers such as styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA) and polyethylene [5].

SBS block copolymers are classified as elastomers that increase the elasticity of bitumen and they are probably the most appropriate polymers for bitumen modification. Becker et al. pointed out that polymers increased the low temperature

* Corresponding author. Tel.: +90 232 412 7072; fax: +90 232 412 7253.
E-mail addresses: burak.sengoz@deu.edu.tr (B. Sengoz), girayisikyakar@yahoo.com (G. Isikyakar).

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Table 1
Properties of the base bitumen

Test	Specification	Results	Specification limits
Penetration (25 °C; 0.1 mm)	ASTM D5 EN 1426	63	50–70
Softening point (°C)	ASTM D36 EN 1427	49	46–54
Viscosity at (135 °C)-Pa s	ASTM D4402	0.51	–
Thin film oven test (TFOT) (163 °C, 5 h)	ASTM D1754 EN 12607-1		
Change of mass (%)		0.07	0.5 (max.)
Retained penetration (%)	ASTM D5 EN 1426	51	50 (min.)
Softening point after TFOT (°C)	ASTM D36 EN 1427	51	48 (min.)
Ductility (25 °C) (cm)	ASTM D113	100	–
Specific gravity	ASTM D70	1.030	–
Flash point (°C)	ASTM D92 EN 22592	+260	230 (min.)

flexibility characteristics of the asphalt. They also stated that a decrease in strength and resistance to penetration was observed at higher temperatures [6].

Isacsson and Lu reported that SBS copolymers derived their strength and elasticity from physical and cross linking of the molecules into a three-dimensional network. They also found that the polystyrene end blocks imparted the strength to the polymer while the polybutadiene rubbery matrix blocks gave the material its exceptional viscosity [7].

Cavaliere et al. performed several experiments on SBS PMB. They stated that when SBS was blended with bitumen, the elastomeric phase of the SBS copolymer absorbed the oil fractions from the bitumen and swelled up to nine times as much as its initial volume. The results gained from the study showed that at suitable SBS concentration, a continuous polymer phase was formed throughout the PMB and significantly modified the base bitumen properties [8].

SBS polymers are usually provided in the form of pellets or powder which can be subsequently diluted to the required polymer content by blending with base bitumen by using low to high shear mixer. Blending pellets of with base bitumen results in a special polymer concentration suitable for different applications [9].

In spite of the significant research which has been carried out related to the SBS based PMBs in road applications, more studies have to be undertaken on the compatibility and in the interaction between the SBS polymer and the base bitumen. This paper aims to characterize the fundamental properties of the SBS based PMBs by using conventional test methods as well as to evaluate the morphology and distribution of polymer by assessing the state of dispersion of SBS polymer and bitumen phases. The mechanical and short term (aging of asphalt cement during mixing, transportation, laying and compaction) and long term aging (aging of asphalt cement during service life of the road) characteristics of asphalt mixtures prepared with the modified bitumen samples have also been investigated.

2. Experimental

2.1. Materials

The base bitumen with a 50/70 penetration grade has been procured from Aliaga/Izmir Oil Terminal of the Turkish Petroleum Refinery Corporation. In order to characterize the properties of the base bitumen, conventional test methods such as: penetration test, softening point test, ductility test, etc., were performed. These tests were conducted in conformity with the relevant test methods that are presented in Table 1.

The SBS polymer used was Kraton D-1101 supplied by the Shell Chemicals Company. Kraton D-1101 is a linear SBS polymer (in powder form) that consists of different combinations made from blocks polystyrene (31%) and polybutadiene of a very precise molecular weight [10]. These blocks are either sequentially polymerized from styrene and butadiene and/or coupled to produce a mixture of these chained blocks. The properties of the Kraton D-1101 polymer are presented in Table 2.

The asphalt mixtures were produced with limestone aggregate procured from Dere Beton/Izmir quarry. In order to find out the properties of the aggregate used in this study, sieve analysis, specific gravity, Los Angeles abrasion resistance test, sodium sulfate soundness test, fine aggregate angularity test and flat and elongated particles tests were conducted. Grading of aggregate has been chosen in conformity with the Type 2 wearing course of Turkish Specifications. Table 3 presents the properties of the aggregates.

2.2. Preparation of SBS modified bitumens

The SBS modified bitumen samples were prepared at continuous type polymer modified bitumen plant manufactured by the Massenza S.R.L. Company. The plant that involves two vertical

Table 2
The properties of Kraton D-1101 polymer

Composition	Specification	Kraton D 1101
Molecular structure	–	Linear
Physical properties		
Specific gravity	ASTM D792	0.94
Tensile strength at break (MPa)	ASTM D 412	31.8
Shore hardness (A)	ASTM D 2240	71
Physical form	–	Powder, pellet
Melt flow rate	ASTM D-1238	<1
Processing temperature (°C)	–	150–170
Elongation at break (%)	ASTM D 412	875

Table 3
The properties of the aggregate

Test	Specification	Grading passing (%)	Specification limit
Sieve no.	ASTM C 136		
3/4 in.		100	100
1/2 in.		86	83–100
3/8 in.		80	70–90
No. 4		48	40–55
No. 10		32	25–38
No. 40		15	10–20
No. 80		10	6–15
No. 200		6	4–10
Specific gravity (coarse agg.)	ASTM C 127		
Bulk		2.686	–
SSD		2.701	–
Apparent		2.727	–
Specific gravity (fine agg.)	ASTM C 128		–
Bulk		2.687	–
SSD		2.703	–
Apparent		2.732	–
Specific gravity (filler)		2.725	–
Los Angeles abrasion (%)	ASTM C 131	24.4	max. 45
Flat and elongated particles (%)	ASTM D 4791	7.5	max. 10
Sodium sulfate soundness (%)	ASTM C 88	1.47	max. 10–20
Fine aggregate angularity	ASTM C 1252	47.85	min. 40

shaft stirrers with blades (used for high shear mixing) is capable of producing up to 20 t PMB per hour.

The SBS Kraton D 1101 concentrations in the base bitumen were chosen as 2–6%. The utilization of this content is based on past research made by Isacsson and Lu. They concluded that, a significant improvement in the properties of base bitumen was observed when the SBS content was increased from 2% to 6% by weight [11].

2.3. Test methods

Following the determination of the properties of the materials used in this study and preparation of the PMB samples; conventional test methods, fluorescence microscopy, Qwin Plus image analysis were performed on each of the PMB samples. Mechanical properties and short and long term aging characteristics of the asphalt mixtures containing modified bitumens were also determined by the Marshall stability and ITS test.

2.3.1. Conventional bitumen tests

The base bitumen and SBS PMBs were subjected to the following conventional bitumen tests; penetration, softening point, thin film oven test (TFOT), penetration and softening point after TFOT and storage stability test (EN 13399).

The storage stability value has been determined by the difference of softening point temperatures of PMB samples taken from the top and bottom of cylindrical mould (32 mm diameter and 160 mm height) after they had been stored vertically at 163 °C in an oven for 48 h.

In addition, the temperature susceptibility of the modified bitumen samples has been calculated in terms of penetration index (PI) using the results obtained from penetration and softening point tests. Temperature susceptibility is defined as the change in the consistency parameter as a function of temperature. A classical approach related to PI calculation has been given in the Shell Bitumen Handbook [12] as shown with the following equation:

$$PI = \frac{1952 - 500\log(\text{Pen}_{25}) - 20 \times \text{SP}}{50\log(\text{Pen}_{25}) - \text{SP} - 120} \quad (1)$$

where Pen_{25} is the penetration at 25 °C and SP is the softening point temperature of PMB.

2.3.2. Fluorescence microscopy and Qwin image analysis

In describing the microstructure interacting between asphalt and polymer, the term “morphology” is often used [13]. A fluorescence microscopy has been used to investigate the morphology of the SBS PMBs by determining the state of dispersion of the polymer within the base bitumen as well as to characterize the nature of the continuous and discontinuous phase.

By far, fluorescent microscopy is the most valuable method for studying the phase morphology of polymer modified asphalt, as it allows the observation of the homogeneity and the structure in the raw state [14].

Fluorescent microscopy is based on the principle that polymers swell due to the absorption of some of the constituents of the base bitumen and due to the fluorescence effect in ultraviolet light [15]. The bitumen rich phase appears dark or black, whereas the polymer rich phase appears light.

Samples of each PMB were prepared (for imaging purposes) by using a standard sample preparation method that involves a heating and homogenizing procedure, a sample cooling regime as well as a surface preparation procedure over thin films of the samples [16].

PMB samples were examined at room temperature under a Leica DM EP microscope with fluorescent light (generated from a high pressure Xenon lamp) at magnification levels of 100×. Images were then taken by a 7.2 Mp Leica DFC 320 color camera (fitted in line with the optic axis of the microscope by means of an attachment to the trinocular observation head). The camera digitizes the image and stores the data as an image file in the permanent memory of workstation.

Digital image processing and analysis techniques were used in this study to quantify the polymer distribution area throughout the PMB samples. The polymer distribution area is expressed as the relative proportion of polymer phase to composite image based on each polymer content.

Along with the system mentioned in previous part, Qwin Plus image analysis program has been used to extract significant information from the captured images. The Qwin Plus image analyzer is a versatile software capable of providing full measurements of polymer distribution. Although digital image processing has increasingly been used in characterizing a number of civil engineering materials, its use in quantifying the distribution of polymers in the base bitumen on the area basis has not been evaluated.

After the images had been captured by means of color camera, they were transformed to grey scale. Using the algorithms within the Qwin Plus program, operations including shading corrections, contrast/brightness optimizing, white tophat and sharpen, enhancement were applied to transform the original image to binary image which has a bit depth of only two; i.e. it consists of areas/features of either black (0) or white phases (1). The main purpose of this step is to isolate polymers from composite images, therefore to prepare the images that are ready for quantified measurements.

2.3.3. Mechanical properties

The effect of SBS based PMB on the mechanical properties of HMA has been determined by the Marshall method (ASTM D1559) in terms of stability, flow, air void content and voids in mineral aggregate (VMA) as well as by the indirect tensile strength test (ITS). The ITS was performed by loading the specimens at a constant rate (50 mm/min vertical deformation at 25 °C) and the force required to break the specimen was measured.

The tests were conducted on asphalt concrete samples that contain PMB and samples prepared with the base bitumen (control specimens). Three samples were produced for each PMB content. Asphalt concrete specimens were prepared with a compaction effort of 75 blows simulating the heavy traffic loading conditions.

2.3.4. Aging procedures

In order to simulate the aging effect in laboratory, asphalt concrete samples were divided into two groups:

(a) Short term aged samples: the short term aging procedure subjected the loose mixture (involving SBS PMB) to 4 h curing period in a forced draft oven at 135 °C prior to compaction [17]. During the curing period, the loose mixture was spread in a pan. After short term aging, the samples were brought to the compaction temperature and compacted. Short term aging represents the aging of asphalt cement during mixing, transportation, laying and compaction.

(b) Long term aged samples: long term oven aging was used to simulate field aging. The procedure was carried out on compacted specimens after they were subjected to short term aging. The specimens were placed in a forced draft oven at 85 °C for 5 days [17]. After curing period, the oven was turned off to cool to room temperature. Long term aging represents the aging of asphalt cement during the service life of the road.

The effect of polymer content on the short and long term aging characteristics of polymer modified mixtures has been determined by means of ITS test.

The ITS is one of the most popular tests used for HMA characterization in evaluation of pavement structures. This test is recommended by several researchers for evaluating the extent of aging of HMA [18–20]. The flow chart of the experimental study is presented in Fig. 1.

3. Result and discussions

3.1. Conventional bitumen test

The effect of SBS polymer modification on the properties of the base bitumen can be seen in Table 4 as a decrease in penetration values and an increase in softening points with the increasing polymer contents. As seen in Table 4, there is a significant large decrease in the penetration values and a considerable increase in the softening point temperatures of SBS based PMB samples at polymer content of 3% and 5%, respectively. The increase in softening point is favorable since bitumen with higher softening point may be less susceptible to permanent deformation (rutting).

Polymer modification reduces temperature susceptibility (as determined by the penetration index-PI) of the bitumen. Lower values of PI indicate higher temperature susceptibility. As

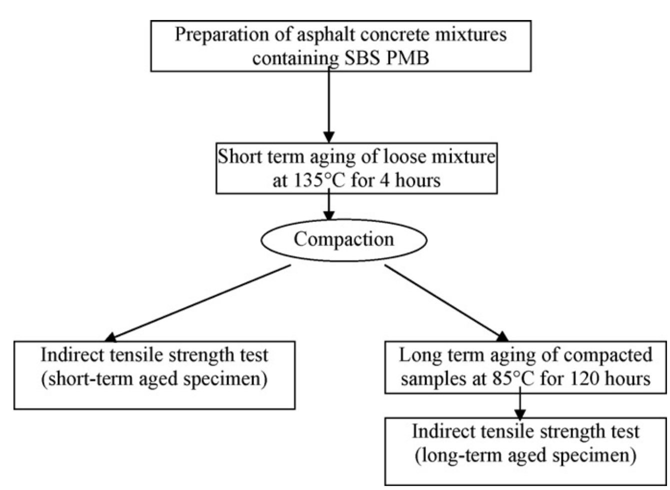

Fig. 1. Flow chart of the study related to aging.

Table 4
Conventional properties of polymer modified bitumen

Property	SBS content (%)						
	0	2	3	4	5	6	Specification limits
Penetration (1/10 mm)	63	61	51	49	48	48	20 (min.)
Softening point (°C)	49	50	54	57	67	69	65–75
Penetration index (PI)	−0.92	−0.73	−0.16	0.35	2.18	2.46	–
Change of mass (%)	0.07	0.06	0.06	0.07	0.07	0.07	1 (max.)
Retained penetration after TFOT (%)	51	41	31	24	21	21	40 (max.)
Softening point difference after TFOT (°C)	2	4	4	2	3	2	7 (max.)
Storage stability (°C)	–	3	3	2	3	2	4 (max.)
Brookfield viscosity 135 °C (η) (Pa s)	0.51	0.55	0.62	0.76	1.20	1.50	
Modification indice (η_{PMB}/η_{base})	1	1.08	1.22	1.49	2.35	2.94	

reported in the Journal of Testing and Evaluation, asphalt mixtures containing bitumen with higher PI were more resistant to low temperature cracking as well as permanent deformation [21]. As seen in Table 4 SBS modified bitumen samples exhibit less temperature susceptibility compared to base bitumen with increasing polymer content.

The age hardening of the bitumen during bulk storage is evaluated by the mass loss, retained penetration and softening point temperature difference in the TFOT. The mass losses corresponding to each SBS PMB samples are almost identical and within specification limits as seen in Table 4. This result indicates that, the SBS PMB samples are not affected by aging in the TFOT which simulates the aging (hardening) of bitumen during the bulk storage period.

Softening point test results on SBS taken from the top and bottom of the tube in the storage stability test indicate that, the SBS based PMB is not likely to be affected by storage.

The rotational viscosity values PMB samples together with the modification indices are also presented in Table 4. The results show a consistent increase in viscosity by polymer modification. As with the penetration and softening point results, the viscosities give an indication of the stiffening effect of SBS modification. The increase in viscosity is not favorable because the bitumen with high viscosity levels require higher mixing, laying and compaction temperatures which results in too much energy consumption.

3.2. Morphology and image analysis

Fig. 2 presents the examples of the PMB samples captured using digital camera.

A distinction can be made between the PMB samples whose continuous phase is a bitumen matrix with dispersed polymer particles and samples whose continuous phase is a polymer matrix with dispersed bitumen globules. In the images, the swollen polymer phase appears (light) while the bitumen phase appears dark.

As depicted in Fig. 2, the images show a clear change in morphology of the SBS based PMBs as polymer content increases. At low polymer content (below 5%), the small polymer globules that are swollen by the base bitumen compatible fractions are spread homogenously in a continuous bitumen phase.

At higher polymer content (above 5%), a continuous polymer phase with dispersed bitumen phase is observed. In this situation, the properties of the mixture are mainly determined by the polymer phase, therefore by the type of the polymer. The PMB samples with this phase morphology have the properties of high softening point and viscosity which make them difficult to be mixed with aggregate resulting in consuming too much energy.

At polymer content about 5%, two twisted continuous phases are observed. The two interlocked phases form a network structure which could enhance the properties of the bitumen. Brule et al. found that the phase morphology of two interlocked continuous phases was an ideal microstructure for polymer modified road asphalt, and the optimum polymer content was determined based on the formation of the critical network between asphalt and polymer [14].

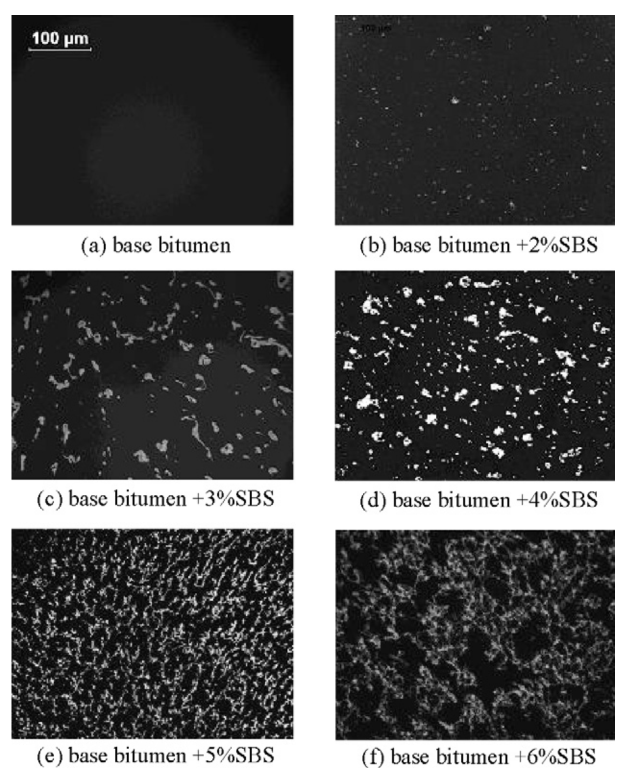

Fig. 2. Fluorescent images of SBS PMB samples with 100× magnification.

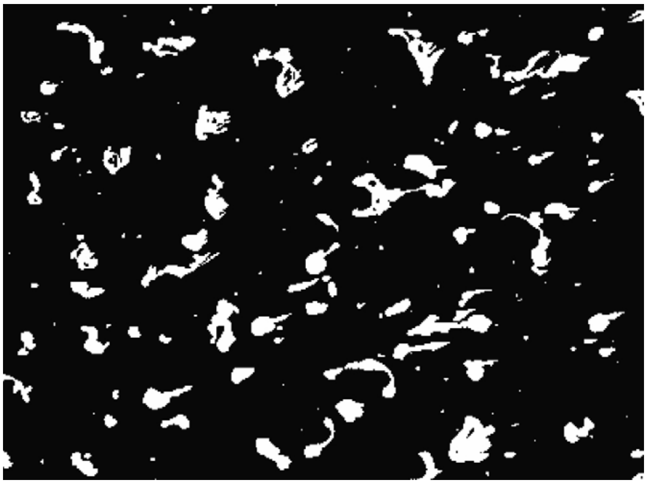

Fig. 3. An example of an image transformed to binary image of black and white phases.

The binary representation of the distribution of the polymers within the composite image is determined using the functions in Qwin Plus image analysis software. An example of the binary conversion of the resulting image is presented in Fig. 3.

As shown in Fig. 3, the white represents the region of interest – the polymer phase – and the black constitutes the bitumen phase. The determination of the region of interest (ROI) is significant as it is recognized by the software based on color depth (either black or white).

Having identified the region of interest, the mathematical parameter related to the ROI, based on pre-defined criteria (which is the polymer distribution area in this study), is calculated for each polymer content.

Fig. 4 presents the relationship between the polymer content and polymer distribution area (%). It should be noted that the calculated polymer distribution areas are the average values taken from the measured ROI's per each polymer content.

Based on the evaluation of the results, it can be concluded that the model reveals the existence of a relationship between the polymer content and polymer distribution area related to SBS Kraton D1101. It should be noted that, the model illustrated in Fig. 4, is valid only between the SBS content of 2–6%.

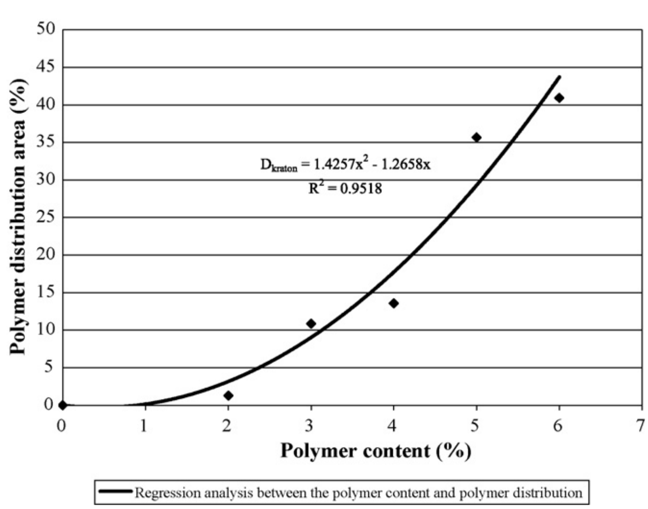

Fig. 4. Area of distribution of polymers in base bitumen.

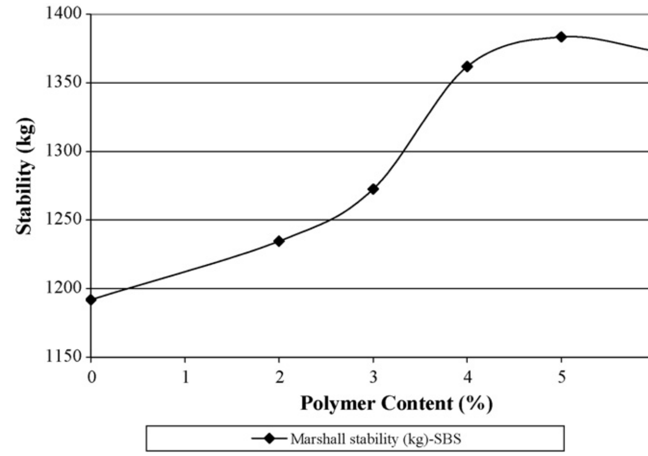

Fig. 5. Marshall stability values of polymer modified HMA.

3.3. Mechanical properties

In this study, the optimum bitumen content related to base (unmodified) and SBS based modified mixtures were determined (by the Marshall analysis) as 4.73% and 4.82% (by weight of aggregate), respectively. The mechanical properties of the HMA containing polymer modified bitumen and base bitumen such as stability, flow, voids and voids in mineral aggregate are presented in Figs. 5 and 6.

As illustrated in Fig. 5, all SBS modified asphalt mixtures provide adequate stability (min. 900 kg related to wearing course specification). Also the stability values increase with the increase in SBS content up to 5% and decreases there on. Therefore based on the data, 5% can be evaluated as optimum SBS content.

The Marshall flow values for SBS based HMA are within the specification limits (2–4 mm) and increase with the increasing polymer content. This indicates higher strain capacities to achieve failure as presented in Fig. 6. In general it is believed

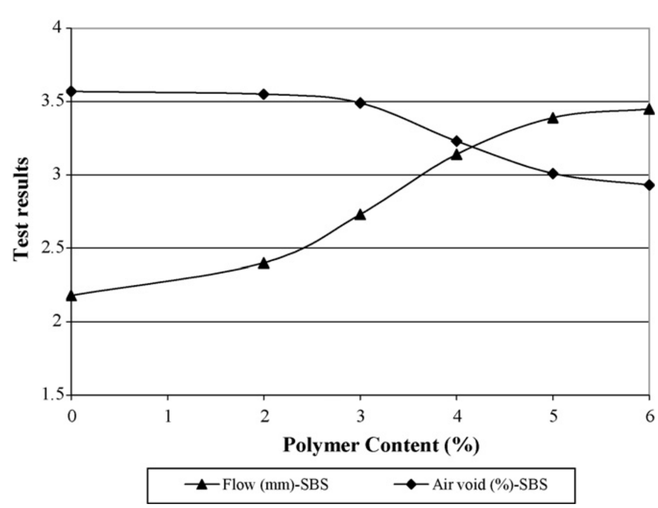

Fig. 6. Air void and flow values of polymer modified HMA.

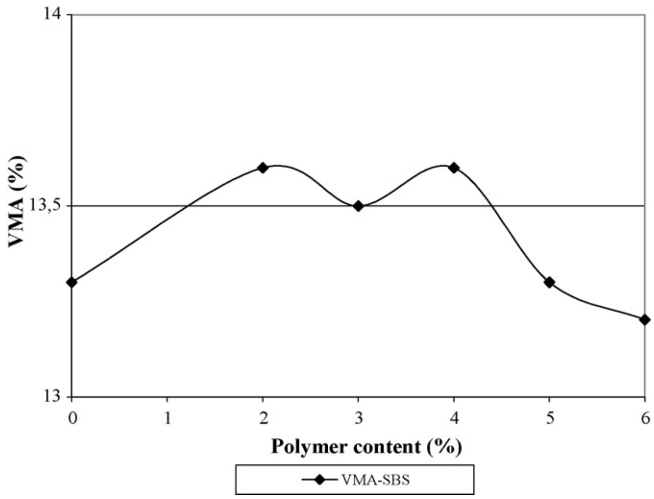

Fig. 7. VMA values of polymer modified HMA.

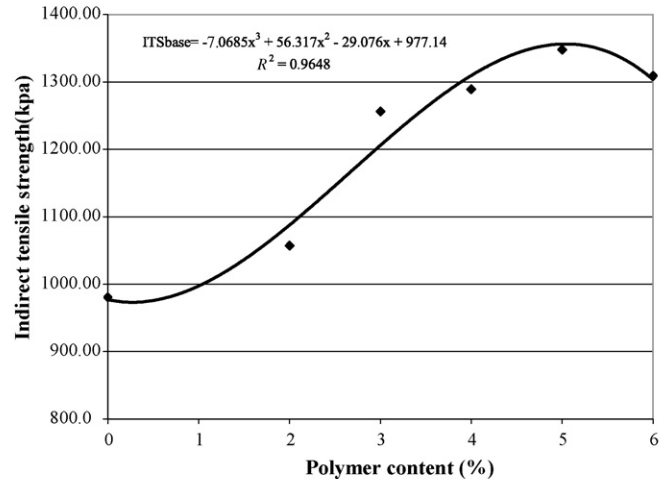

Fig. 8. ITS values of polymer modified HMA.

that asphalt mixtures containing higher asphalt contents provide higher plastic flow susceptibility.

The increased plastic susceptibility of the asphalt mixtures may lead to high permanent deformation (due to the increased asphalt cement content) that causes the loss of internal friction between the aggregate particles. This results in the load, being carried by the asphalt cement rather than aggregate structure. At the NAPA Education Lu and Isacsson found that although optimum asphalt content was higher for the modified mixtures than the unmodified mixtures, modified mixtures revealed more resistance to permanent deformation in LCPC wheel tracking test [22].

Also, the air void content of the SBS mixtures decreases as the polymer content in the base bitumen increases.

All the SBS modified samples provide adequate VMA content (min. 13%). The VMA values corresponding to SBS specimens are higher compared to control specimens as seen in Fig. 7.

The ITS results of samples are plotted for each polymer content in order to examine the relationship between the polymer content and the tensile strength properties of HMA containing SBS polymer which is presented in Fig. 8.

The concept of polynomial regression is employed as a tool to fit the test data to the curve, which quantify the relationship between the independent and dependent variables. The independent variable is the polymer content (%) whereas the dependent variable is the ITS results of the specimens. An acceptable model is established based on the polynomial regression presented in the same figure.

As seen in Fig. 8, the ITS of the modified mixtures is higher than the unmodified mixtures. The increase in indirect tensile strength of the mixtures can be attributed to the increased stiffness of the SBS modified bitumen. The greater the tensile strength of the modified mixtures as compared to unmodified mixture also indicates greater cohesive strength of the modified mixtures.

The ITS values increase with increasing polymer content up to 5% as depicted in Fig. 8, however above this content the values decrease implying that the increased viscosity of the PMB at 6% SBS content does not translate into an increase in the tensile strength of the mixture. Based on the investigated data, 5% can be accepted as an optimum SBS polymer addition.

3.4. Aging procedures

Fig. 9 presents the relationship between the polymer content and ITS results of the short and long term aged samples. Acceptable models are obtained based on the polymer regressions that are employed on the test data.

Based on the evaluation of the test data obtained from Figs. 8 and 9, for the specimen prepared with the base bitumen, as the aging time increases (from unaged to long term aged condition), the ITS values increase. The increase in the ITS is an indicator of the effect of aging on the asphalt paving mixtures. The aging is represented by a stiffening of the asphalt cement, a

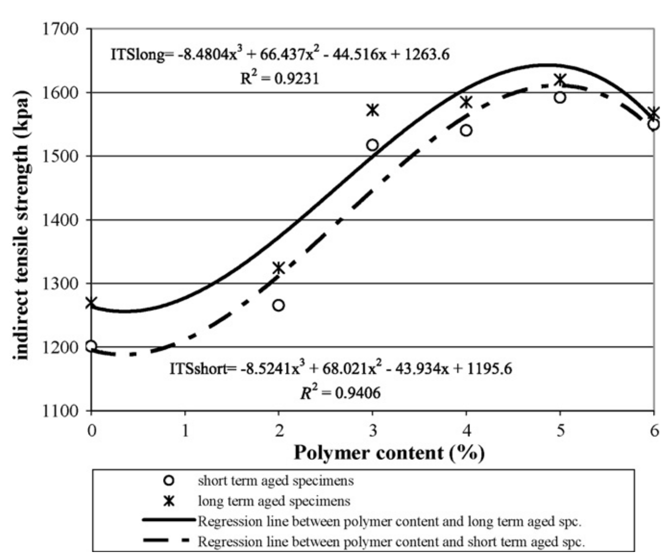

Fig. 9. Relationship between the polymer content and indirect tensile strength of short and long term aged specimens.

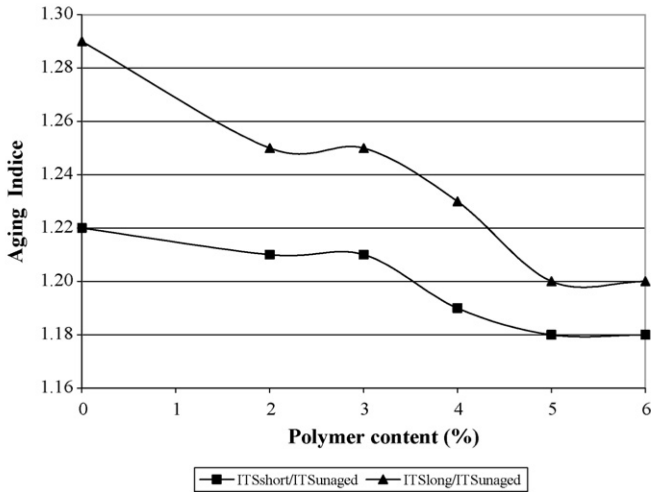

Fig. 10. Aging indices corresponding to polymer content.

higher viscosity and a more brittle condition. National Research Council found that the aged mixture was more susceptible to cracking and deterioration due to wear and moisture compared to unaged mixture [23].

As illustrated in Fig. 9, the rate of aging decreases with polymer addition. Same conclusion is achieved with the aging indices which were defined as the ratio of the ITS of the short and long term aged polymer modified mixture to the ITS of the unaged mixture. The results are presented in Fig. 10.

As illustrated in Fig. 10, the aging indices decrease with increasing polymer content; moreover no significant change is observed on the aging indices above 5% SBS polymer addition. This implies that, 5% can be accepted as an optimum SBS polymer content that minimizes the effect of aging, thus providing reasonable service life of the mixture.

According to the evaluation of the data presented in Figs. 8–10, it can be concluded that the polymer modification is a way of overcoming potential deformations revealed due to aging.

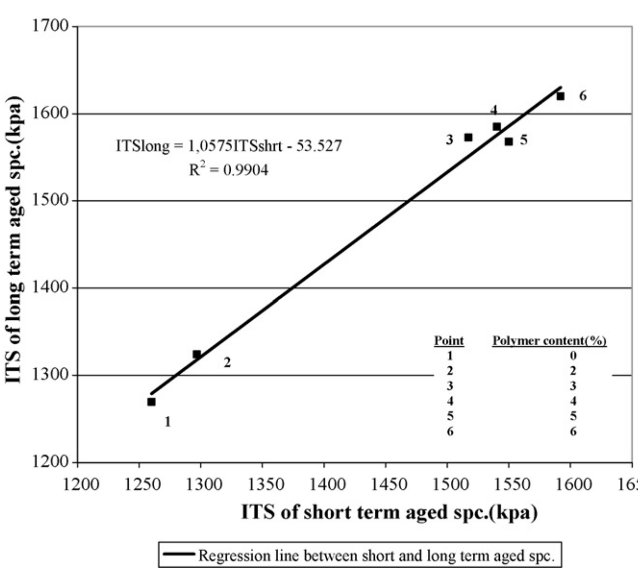

Fig. 11. Relationship between short and long term aging characteristics of polymer modified mixture.

Also, the change in ITS values with polymer content is investigated where the ITS values after short term aging is plotted against the corresponding value after long term aging. A linear relationship is obtained from the data and modeled in Fig. 11 where each point corresponds to one polymer content.

The high value of R^2 indicates that a linear model exactly represents the relationship between the long term and short term aged specimen. This indicates that the short and the long term aging of HMA is affected in the same manner by the SBS polymer modification.

4. Conclusion and recommendations

The properties of road bitumens are improved by means of SBS polymer modification. This result has been reached by the conventional test methods such as penetration, softening point, rotational viscosity, TFOT test results as well as by Marshall stability and indirect tensile strength tests.

SBS modification causes increases in softening point and reductions in penetration. Since, the decreased penetration, and increased softening point temperature indicate increased stiffness (hardness) of the PMBs, the results demonstrate that the asphalt mixtures prepared with the SBS PMBs may be less sensitive to permanent deformation. Along with the parameters related to penetration and softening point test; increased viscosity values and indices also indicate the stiffening effect of SBS modification. The increase in viscosity is not favorable since high viscosity makes mixing, laying, and compaction of the mixture more difficult.

SBS polymer modified bitumens display reduced temperature susceptibility than base bitumens. The reduced temperature susceptibility may be attributed to the resistance of SBS asphalt mixtures to cracking with the temperature change.

Marshall stability and indirect tensile strength values of SBS modified mixtures has been found higher than the control (unmodified mixtures). The greater the tensile strength of the modified mixtures as compared to unmodified mixture indicates greater cohesive strength of the modified mixtures.

In the light of the findings from aging investigations, it is possible to consider that SBS polymer addition minimizes the pavement deficiencies revealed due to aging, thus providing an increase in the service life of the road.

The phase morphology of the polymer modified bitumens is the result of the mutual effects of polymer and bitumen and is influenced by polymer content. Fluorescent microscopy can be used to group SBS type PMB samples either by displaying a continuous polymer rich phase with dispersed bitumen phase, displaying a continuous bitumen rich phase with dispersed polymer phase or displaying two interlocked phases. The formation of a continuous SBS polymer phase is dependent on SBS polymer content. For these particular materials, phase inversion from a continuous bitumen phase to continuous SBS polymer phase occurs when SBS content is around 5%. This content can be accepted as intertwisted phase which is an ideal microstructure for polymer modified road asphalt.

Image processing and analysis techniques are very useful in the study of investigating distribution of polymers through PMB samples. The model presented in this study is developed for the quality control purposes in the field—that means the area of distribution of polymers can be determined by the images of the recycled PMB taken from the field cores using image processing and analysis techniques. In this way, the appropriate utilization of polymer proportion can be assured.

The conclusion of this study covers the utilization of one type of polymer and penetration grade asphalt cement. More research should be carried out by using different kinds of polymers as well as the base bitumen obtained from different crudes.

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