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EFFECTS OF STYRENE-BUTADIENE-STYRENE ON STIFFNESS OF ASPHALT CONCRETE AT DIFFERENT TRAFFIC CONDITIONS

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Abstract

The previous studies have explored the effects of Styrene-Butadiene-Styrene (SBS) as the most prevalent modifier for asphalt mixtures. The current study intends to compare stiffness modulus of control and SBS modified asphalt mixtures under different traffic loadings. To this end, resilient modulus tests were performed on both conventional and SBS modified specimens. Tests were conducted at 5, 25 and 40°C with loading times of 50, 100, 300, 600 and 1000 milliseconds and 4, 9 and 30 as ratio of rest periods (between loading pulses) to loading times (R/L). Using these test parameters and haversine and square loading pulses that represent vertical stress distribution at different depths within an asphalt layer, a variety of traffic densities and vehicle speeds were simulated and their effects on stiffness of asphalt concrete were determined. Results indicated that SBS modification provide higher stiffness under haversine pulse with long loading time at 40°C, so that it was about 3 times of unmodified mixture stiffness. The effect of traffic density that represented by R/L was significant only in long loading time (1000 ms) especially under haversine pulse.

Keywords: Flexible pavements, Asphalt concrete, Stiffness, SBS, Traffic loading.

1. Introduction

The 1986 AASHTO Guide for Design of Pavement Structures has incorporated the resilient modulus of component materials into design process and it was pursued in the 1993 AASHTO Guide. In terms of current Mechanistic-Empirical pavement design procedures, multi-layer elastic analysis is the primary method for defining the pavement response to traffic loading and environmental changes. Within the framework of multi-layer elastic analysis, the well-known two material

Nomenclatures

C_2HCl_3	Trichloroethylene (Table 3)
D	Diameter of specimen, mm
G_{mb}	Maximum gravity of compacted asphalt mixture, kg/m^3
L_{eff}	Effective length, in
MR	Resilient Modulus, MPa
ms	Milliseconds
P	Maximum applied load or repeated load, N
S_t	Indirect tensile strength, KPa
t	Time of loading, sec (Eq. (2)); Height of specimen, mm (Eq.(6))
V_a	Air void, in percent
v_s	Velocity, mph
Z_{eff}	Effective depth, in

Greek Symbols

ΔH	Recoverable horizontal deformation, mm
ε_r	Recoverable strain
σ_d	Deviator stress, MPa
v	Poisson's ratio

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CR	Crumb Rubber
EVA	Ethylene Vinyl Acetate
HMA	Hot Mix Asphalt
ITS	Indirect Tensile Stress
LA	Los Angeles (Table 2)
LL	Liquid Limit (Table 2)
LT	Loading Time (Fig. 2)
M-E	Mechanistic-Empirical
PI	Plastic Index (Table 2)
PL	Plastic Limit (Table 2)
R/L	Rest period to Loading time ratio
rpm	Rotation per minute
SBS	Styrene Butadiene Styrene
SMA	Stone Mastic Asphalt
TFOT	Thin Film Oven Test (Table 3)
UTM	Universal Testing Machine
VFA	Voids filled with asphalt
VMA	Voids in mineral aggregates

properties required are elastic modulus and Poisson's ratio. Previous experience and the available literature have demonstrated that the elastic modulus has a much more significant impact on M-E analysis and predicted distresses [1].

The resilient modulus is elastic modulus that is used with elastic theory. If load is small compared to strength of the material and is repeated for a large number of times, all of deformation under each load repetition is approximately recoverable and can be considered elastic. At the initial stage of load applications, there is considerable permanent deformation, as considered plastic strain. As the number of repetitions increases, the plastic strain caused by each load repetition decreases [2]. After 100 to 200 repetitions, strain is practically all recoverable, as indicated by (ε_r). The elastic modulus based on recoverable strain under repeated loads is called resilient modulus (MR), defined as Eq. (1) [2]:

$$MR = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

where MR is resilient modulus (MPa), σ_d is deviator stress (MPa) and ε_r is recoverable strain (dimensionless).

Asphalt concrete is a viscoelastic material and its resilient modulus is both temperature and loading time dependent. Therefore, both temperature and loading time must be known in order to select a reasonably appropriate modulus for these materials. Additionally, there is another important aspect, rest period, and its effect on stiffness that is studied in this paper. As noted previously, asphalt concrete mechanical responses are time dependent; consequently, it is equally significantly influenced by the rest periods that occur between field traffic loads due to different traffic densities.

The resilient modulus that represents stiffness properties of asphalt concrete has a key role in design of flexible pavements and determination of performance related failures. With rapid increase in the number of vehicles and overloading trucks, premature distresses in asphalt pavements have increased. Then, researchers decided to improve stiffness characteristics of asphalt mixtures by incorporating additives such as polymers and rubbers. Unsaturated thermoplastic elastomers like styrene–butadiene–styrene (SBS) block copolymers are probably the most commonly used polymers. They enhance asphalt's elastic recovery capacities and, therefore, its resistance to permanent deformations [3]. The SBS modifier forms a lattice in binder, which provides the desired properties of elasticity, plasticity, and elongation. Therefore, SBS-modified asphalts tend to improve the adhesive property of mix, fatigue and rutting resistance, low temperature flexibility, and resistance to bleeding [4].

Many researches have studied the effects of SBS modification on asphalt binders and mixtures. These studies have evaluated the various properties of asphalt materials related to performance of flexible pavements in different conditions. Airey [5] studied polymer modification of road bitumen with SBS. The results of the investigation indicated that degree of SBS modification was a function of bitumen source, bitumen-polymer compatibility and polymer concentration. The aging resistance of SBS modified asphalt was superior to base asphalt because of effect of SBS modifier [6].

In a comparative study, the changes of rheological properties of 60/70 grades bitumen modified with different percentages of crumb rubber (CR), ethylene vinyl acetate (EVA), and SBS were evaluated. SBS-modified binder has lower viscosity temperature susceptibility than EVA- and CR-modified binders. It indicates that SBS-modified binder is more crack and rut resistant at low as well as high temperatures, respectively [7].

In a study by Chen et al. [8] SBS copolymer was blended with asphalt binders to investigate the effect of SBS modification on asphalt binder properties. Appearance of a continuous polymer structure was observed to begin at a SBS content of about 5%. A change of regime of the softening point and penetration profiles was seen at SBS weight concentration around 5%. The phase inversion appeared to occur when the SBS gradually became the continuous matrix phase. This suggests that a content that is slightly higher than the phase inversion content (5%) is the optimum content for SBS modification [8].

The effects of modification, mixture grading, and binder content on the linear viscoelastic limits and rheological characteristics of bituminous binders and asphalt mixtures were ascertained. In terms of modification, only the elastomeric SBS modified bitumen showed any significant differences in linearity limits and rheological properties compared to conventional materials, while the effect of mixture grading and binder content only lead to minor differences among the asphalt mixtures [9].

Kumar et al. [10] investigated strength characteristics of polymer-modified mixes. The SBS modified mixes had 1.2–1.9 times higher modulus values as compared to those of the unmodified mix. In another study, two different aggregate including limestone and basalt, and three SBS contents (3, 5, and 7%) were used for the asphalt mixtures. The specimens prepared with limestone exhibited higher stiffness than basalt specimens did. For both mixtures, the resilient modulus values were increased while SBS content increased [3].

Ping and Xiao [11] evaluated the SBS modified binder effect on resilient modulus properties of Florida asphalt mixtures. They found that the SBS polymer modifier made the HMA mixture softer at mid to low test temperatures and maintained stiffness level at high temperatures. An effective SBS polymer content appeared to exist between 3.0% and 6.0% depending on the actual conditions of mixture production.

Awanti et al. [12] showed that the static indirect strength values for SBS modified asphalt concrete were higher in order of 49-101% when compared to conventional asphalt mixtures in the temperature range of 15-40°C. The viability of using SBS as an additive in stone mastic asphalt (SMA) was investigated in another study. The mixture modified with 5% SBS showed higher stability and tensile strength, lower moisture susceptibility and about 40% increase in resilient modulus values at 25°C [13]. Singh et al. [14] recommended the 5% SBS content for better strength and moisture susceptibility. The use of SBS modified bitumen is recommended to be more beneficial with siliceous or aggregates exhibiting acidic character compared to calcareous aggregates.

The superior effects of SBS polymer on asphalt mixtures in terms of rutting and cracking resistance, stability, load spreading capacity, compactibility and ability of mix to absorb energy and deform without fracturing were investigated in the other literatures [15, 16, 17, 18, and 19].

The former studies examined the effects of SBS modification on stiffness modulus at different temperatures and by applying the typical test conditions (i.e. loading time=100 ms & R/L=9). Previous studies did not explore impacts of traffic loading parameters such as different R/Ls and waveforms on resilient modulus of modified asphalt mixtures. This study evaluates stiffness of control and SBS modified asphalt mixtures using indirect tensile resilient modulus test under different loading conditions. Application of two different loading pulse, five loading times, and three rest to load ratios (R/L) that demonstrate different traffic loading conditions differentiates this study from other ones.

2. Experimental Procedures

2.1. Materials

The asphalt samples were fabricated using granite aggregates. The aggregate gradation of asphalt mixtures was selected based on grading No.4 (0-19 mm), according to Iran Highway Asphalt Code [20]. This grading can be used for constructing surface and binder asphalt layers. The gradation specifications and physical properties of the aggregates are summarized in Tables 1 and 2, respectively.

Table 1. Gradation specifications of aggregates.

Sieve Size (mm)	Standard Limits (%)	Passing from Sieve (%)
19	100	100
12.5	90-100	95
4.75 (#4)	44-74	58
2.36 (#8)	28-58	43
0.3 (#50)	5-21	13
0.075 (#200)	2-10	6.4

Table 2. Physical properties of aggregates.

Aggregate property	Standard	Fraction		
		Coarse	Fine	Filler
LA abrasion loss (%)	ASTM-C131	18	-	-
Sodium sulphate soundness (%)	ASTM-C88	1.3	7.1	-
Sand equivalent (%)	ASTM-D2419	-	72	-
Flakiness (%)	ASTM-D4791	12	-	-
Crushed in one face (%)	ASTM-D5821	96	-	-
Plastic Index (PI)	ASTM-D4318	-	NP	8
Plastic Limit (PL)	ASTM-D4318	-	-	18
Liquid Limit (LL)	ASTM-D4318	-	-	26

Asphalt mixture samples were prepared by using two different types of binders. The base binder with the penetration grade of 60/70 from Tehran Refinery and SBS polymer modified bitumen was selected for this study. To prepare the SBS modified bitumen, the asphalt binder was heated upon reaching 180°C and then the powdered SBS polymer (5% by weight of base bitumen) was added gradually into the bitumen in a high shear mixer at the speed of 3500 rpm until reaching a homogeneous blend. The SBS polymer type was Calprene 501, which was produced by Dynasol® [21]. The specifications of the base bitumen and SBS polymer are given in Tables 3 and 4, respectively. The compacted asphalt mixture specimens are shown in Fig. 1.

Table 3. Properties of base bitumen.

Bitumen property	Value	Standard
Penetration (25°C, 0.1 mm)	69	ASTM-D5
Softening Point (°C)	50	ASTM-D36
Ductility at 25°C (cm)	>100	ASTM-D113
Solubility in C_2HCl_3 (%)	99.8	ASTM-D2042
Flash point (°C)	313	ASTM-D92
Viscosity at 135°C (cSt)	380	ASTM-D2170
Thin film oven test (TFOT) (163°C, 5 h)		ASTM-D1754
Change of mass (%)	0.01	
Retained penetration	86	
Ductility after TFOT at 25°C (cm)	>100	ASTM-D113

Table 4. SBS polymer properties [21].

Polymer properties	Value	Standard
Structure	Linear	-
Toluene solution viscosity 25% (Pa-s)	5	MA 04-3-064
Toluene solution viscosity 5.23% (cSt)	13	MA 04-3-003
Volatile matter (%)	0.4	ASTM-D5668
Hunterlab colour	2	ASTM-D1925-70
Total styrene (on polymer) (%)	31	ASTM-D5775
Hardness (°Shore A)	76	ASTM-D2240
Insoluble in Toluene (325 mesh) (%)	< 0.1	MA 04-3-018
Ashes (%)	< 0.35	ASTM-D5669

Fig. 1. Compacted asphalt mixture specimens.

2.2. Mix design

The mix design of HMA was carried out according to the Marshall method, a widely used compaction method in Iran, which is specified in AASHTO-T245 standard method [22]. The optimum bitumen content was selected as 5.5% by weight of mixture, which gave almost 4% air void. This bitumen content satisfied all the other requirements such as air void, special gravity, VMA, VFA and Marshall stability and flow [20]. The mix design results were shown in Table 5. For the SBS modified mixtures, the same optimum asphalt content, aggregate type and gradation was used in order to evaluate the influence of the SBS modification on the resilient modulus of asphalt mixes, specifically.

Table 5. Mix design results.

Bitumen content (%)	**G_{mb} (Kg/m^3)**	**V_a (%)**	**VMA (%)**	**VFA (%)**	**Stability (Kg)**	**Flow (0.25mm)**
4	2205	8.6	16.15	46.8	841	10.15
4.5	2226	7.1	15.7	55.2	889.5	10.7
5	2246	5.7	15.45	63.7	955.5	11.2
5.5	2269	4.1	15.1	72.95	1045	11.85
6	2277	2.85	15.2	81.1	959	12

2.3. Resilient modulus test

Since the magnitude of applied load in *MR* test should be selected as a portion of indirect tensile strength (ITS) of asphalt mix, the indirect tensile strength of both unmodified and SBS modified were measured [23 , 24]. The static indirect tensile strength of a given specimen was determined using the procedure outlined in ASTM-D6931 [25] at temperature of 25°C and loading rate of 50 mm/min. The load is applied and the failure load is noted from the dial gauge of the proving ring.

In this study, the resilient modulus of asphalt concrete samples was determined using the indirect tension method in accordance with AASHTO-TP31 standard [23] using UTM-14P device (Fig. 2). After 100 cycles of preconditioning, the final resilient modulus was computed according to the average of resilient modulus at five last loading cycles.

Resilient modulus test was conducted at three different temperature of 5, 25, and 40^{o}C for both unmodified and modified asphalt specimens. The minimum allowable loading time, which could be applied by UTM device, was 50 ms. According to common testing protocols [23 and 24] for determining the resilient modulus, the loading time and R/L have been proposed to be sequentially 100 ms and 9 under haversine loading pulses.

Some researchers showed that the shape and duration of loading in asphalt layer varies with respect to vehicle speed, asphalt thickness, depth and the ratio of asphalt layer modulus to base layer modulus [3]. They showed that the loading shape near the asphalt surface can be represented by square shape, and by increasing the depth the loading shape approaches to haversine or triangle shape.

For simulation of the loadings that exerted in different depths within pavement asphalt layer, loading waveforms in the resilient modulus test was assumed haversine and square. For demonstration of traffic flow with fast to slow speeds and with high to low densities, the tests were performed at five loading times of 50, 100, 300, 600, and 1000 ms and three R/L values of 4, 9, and 30, respectively. The diagram of experiments was summarized in Fig. 3.

Fig. 2. UTM 14P for resilient modulus test.

3. Theory

3.1. Determination of loading times

In M-E pavement design guide the following relationship relates the time of load to the vehicle speed (velocity) and the effective length of the pulse (Eq. (2)) [26].

$$t = \frac{L_{eff}}{17.6 v_s} \tag{2}$$

where t is time of load (sec), L_{eff} is effective length (inch) and v_s is velocity (mph). The effective length is the length that defines the extent of the stress pulse at a specified depth within pavement system. For any pavement layer the effective length of stress pulse is computed at a specific depth for computation of the modulus. This depth is transformed depth and is termed as effective depth (Z_{eff}). The effective depth is computed by the following relationship (Eq. (3)) [26]:

$$Z_{eff} = \sum_{i=1}^{n-1} \left(h_i \sqrt[3]{\frac{E_i}{E_{SG}}} \right) + h_n \sqrt[3]{\frac{E_n}{E_{SG}}} \tag{3}$$

where E_i is the modulus of ith layer (MPa), E_{SG} is the modulus of subgrade (MPa) h_n is the thickness of the layer of interest (layer n) at which the computation is being made.

In this study the effective depth is computed at the mid-depth of the first layer (n=1 for asphalt concrete layer). It is approximately correct that no overlap occurs between axles at mid-depth of first layer since the effective depth is smaller than the free distance between axles. Therefore, the effective length is defined by the Eq. (4) [26]:

$$L_{eff} = 2\left(a_c + Z_{eff}\right) \tag{4}$$

where a_c is the radius of contact area (in). Assumptions and computed effective depth and length for this study are shown in Table 6.

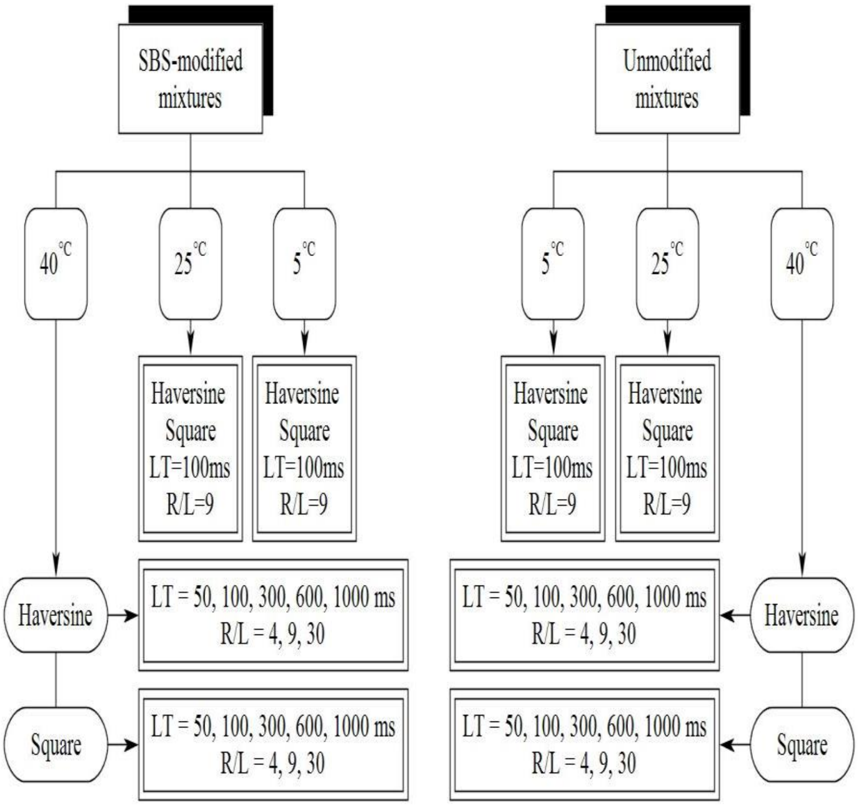

Fig. 3. Diagram of experiments.

Table 6. Assumptions and computed parameters.

a_c (in)	E_1 (MPa)	E_{SG} (MPa)	h_1 (in)	Z_{eff} (in)	L_{eff} (in)
3.5	3000	50	8	15.65	38.3

Using these parameters and Eq. (2), the selected loading times of 50, 100, 300, 600 and 1000 are the equivalent of vehicle speeds of 70, 35, 12, 6 and 3.5 km/hr. These values are the common velocities of urban traffic especially at rush zones of cities like downtowns.

3.2. Computation of ITS

In indirect tensile strength test, the ITS values can be determined by Eq. (5) [25]:

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \tag{5}$$

where S_t is the indirect tensile strength (kPa), P is the maximum applied load (N), t is the height of specimen (mm), and D is the diameter of specimen (mm). The ITS values of asphalt mix samples prepared by unmodified and SBS-modified bitumen were determined as 792.5 and 982.5 kPa, respectively.

3.3. Computation of MR

In Resilient modulus test based on AASHTO-TP31 standard, the maximum applied load at temperature of 5, 25, and 40°C assumed as 30, 15 and 5 percent of indirect tensile strength of asphalt mixture at temperature of 25°C [23]. Resilient modulus in indirect tensile method can be computed using Eq. (6) [24]:

$$MR = \frac{P \times (\nu + 0.27)}{t \times \Delta H} \tag{6}$$

where MR is the resilient modulus (MPa), P is the repeated load (N), ν is Poisson's ratio, t is the thickness of specimen (mm), and ΔH is the recoverable horizontal deformation (mm). The Poisson's ratio in Eq. (6) was selected according to the test temperature. The Poisson's ratio at three temperatures of 5, 25, and 40°C was determined based on M-E pavement design guide as 0.2, 0.35, and 0.4, respectively [26]. The difference between haversine and square pulses in terms of load and displacement curves at 40°C are presented in Figs. 4 and 5, consecutively.

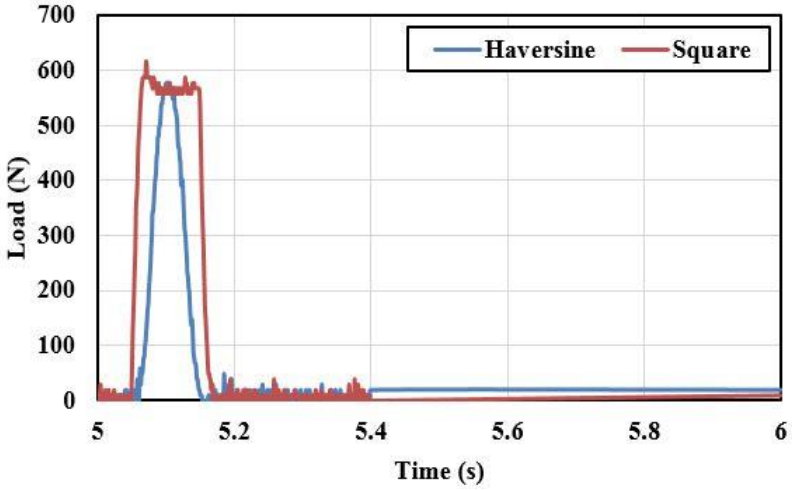

Fig. 4. Difference between haversine and square load pulses (100 ms, *R/L*=9).

4. Results and Discussion

The resilient modulus of asphalt mixtures for both unmodified and SBS modified samples were computed under different test conditions. To investigate the effects of SBS modification on resilient moduli of asphalt mixtures in different cases, the *MR* ratios are obtained by dividing the *MR* of modified mixture to *MR* of unmodified mixture at the same conditions.

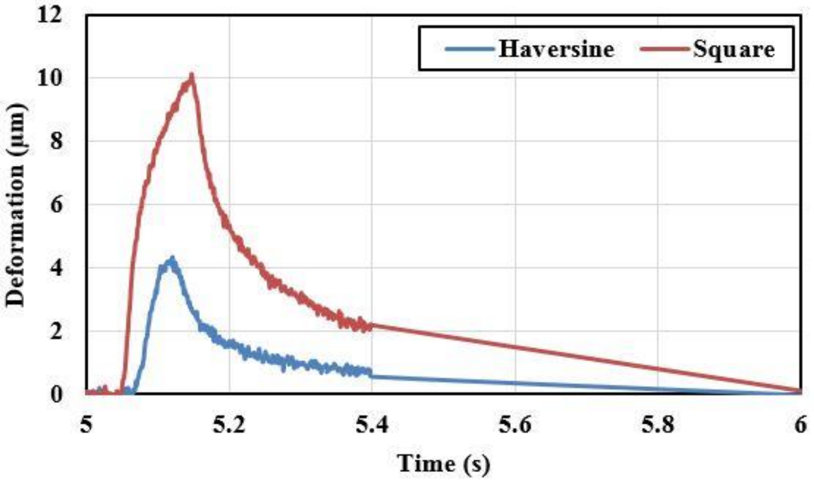

Fig. 5. Difference between deformations under haversine and square loadings (100 ms, *R/L*=9).

Figure 6 shows how the SBS modification alters the resilient modulus of mixtures at different temperatures under standard loading conditions (100ms, R/L=9).

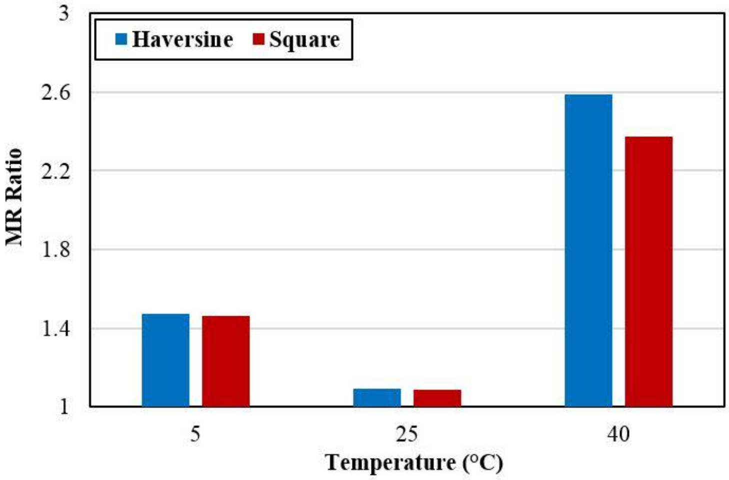

Fig. 6. MR ratios at different temperatures (loading time=100 ms, *R/L*=9).

It can be seen that modification effect on *MR* at mid temperature is negligible, but for low and high temperatures is significant. At 40°C, the *MR* of modified mixture is about 2.5 times of it for control mix, because of a continuous network that formed by polymer molecules in the bitumen. This network reduces viscous deformations occurred in the mixture and increases its modulus. This confirms the results of other studies [12, 16 and 18] related to superior performance of SBS modified mixtures in high temperature rutting resistance. A same mechanism occurs at 5°C, but in this case, the mixture behaviour is quasi-elastic and strengthening effect of polymer network is less apparent.

The low *MR* ratio at 5°C is beneficial to facilitate dissipation of induced loads and high *MR* ratio at 40°C is convenient to prevent from viscous behaviour of the mixture. In addition, the proper content of polymer (5%) and bitumen-polymer compatibility made a continuous elastic network in the mixture that increased the stiffness of the SBS modified sample. Since the differences in *MR* values are more obvious at 40°C, in the rest of study, the results are compared in different loading conditions and at temperature of 40°C.

Figure 7 illustrates the *MR* ratios in various traffic densities and axles' distances using three R/L values of 4, 9, and 30 and with standard loading time of 100 ms. The R/L had no considerable effect on *MR* ratios, especially in case of square loading. The results confirm the small effects of R/L on *MR* ratios that have been stated in another study [27].

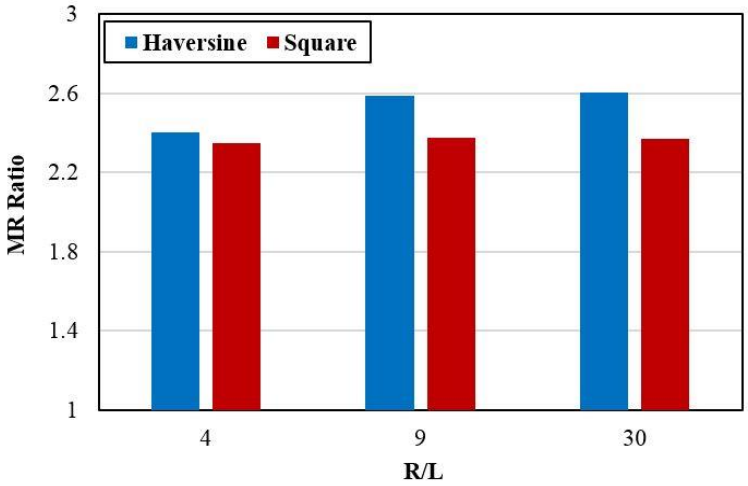

Fig. 7. MR ratios in different rest to load ratios *(R/L)* at 40°C (loading time=100 ms).

As shown in Fig. 8, the effects of SBS modification on stiffness of asphalt concrete become more obvious with increase in loading times so that *MR* ratio exceeds 3. This finding was more significant under haversine loading, because the haversine pulse simulates the stresses in higher depths of asphalt layer that experience the longer loading times than shallow depths. In other words, the polymer modifier had a great impact on the viscous or time dependent characteristics of asphalt concrete that agree with the findings of other researchers [15].

For better understanding of the effects of modification in different traffic conditions, the *MR* ratios under different loading times and R/L's were compared to each other, simultaneously.

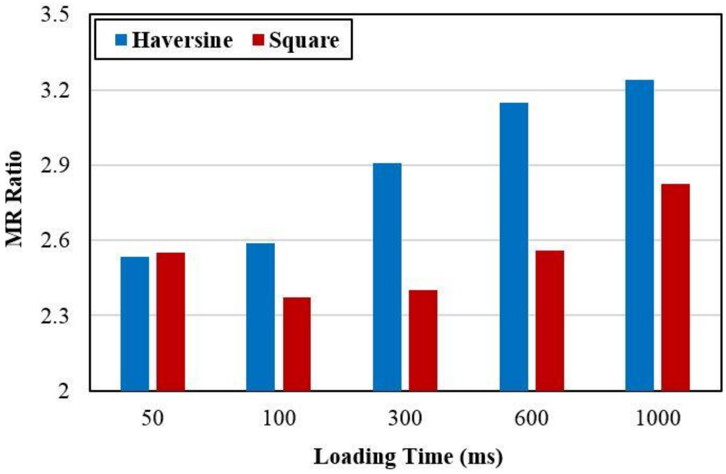

Fig. 8. MR ratios in different loading times at 40°C (*R/L* = 9).

Figures 9 and 10 depict the results related to haversine and square pulses, respectively. According to Fig. 9, the effects of SBS modifier was more considerable in long loading times and the differences between MR ratios in different R/L's for each of loading times were more significant when changed from 4 to 9. The increase in R/L resulted in greater recoverable strains and less MR values for unmodified mixtures. On the other hand, the modified mixes kept their stiffness and MR ratios increased. Changing the R/L from 9 to 30 exhibited no apparent difference among MR ratios that coincide with another study [28]. Because of more time for strains to recover, the differences between MR ratios with R/L equal to 4 and 9 were more evident in case of long loading times.

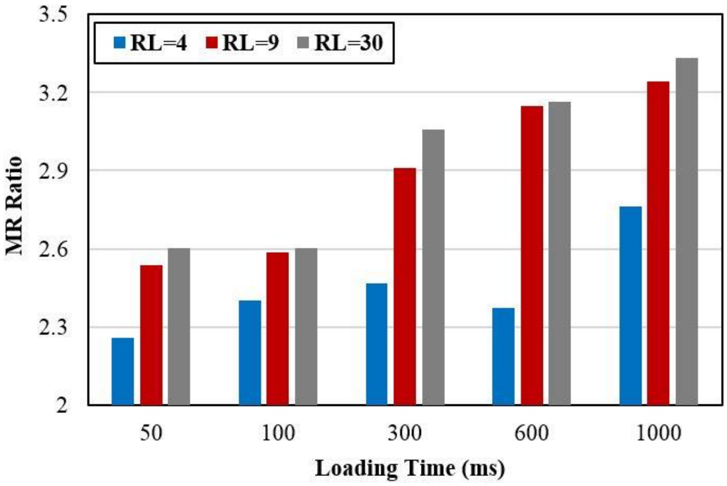

Fig. 9. Comparison of MR ratios under haversine pulse in different loading times and *R/L*s at 40°C.

Approximately same trends was observed under square loading, except the less changes in MR ratio values than haversine ones. The MR ratio for loading time of 50 ms is slightly more than 100 and 300 ms that can be due to different arrangement of aggregates in specimens during compaction. This phenomenon may change the level of strength provided by aggregate skeleton and lead to different modulus (Fig. 10).

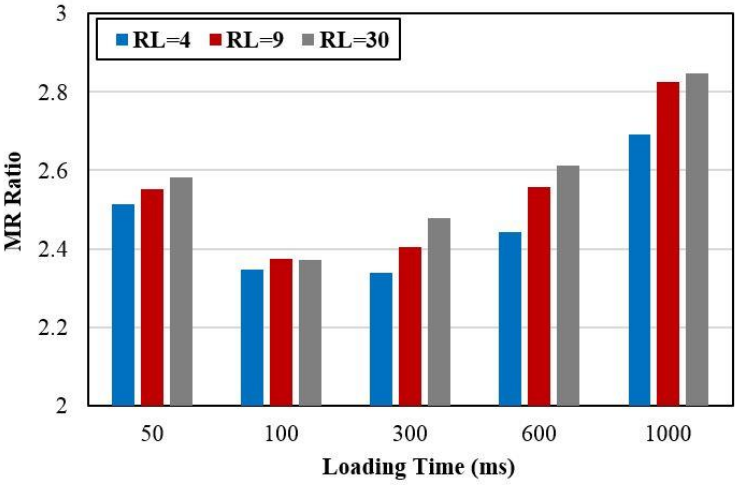

Fig. 10. Comparison of MR ratios under square pulse in different loading times and *R/L*s at 40°C

5. Conclusions

In this paper, the stiffness characteristics of SBS modified asphalt concrete under different traffic loadings including vehicle speed and traffic density was evaluated. The following are a summary of findings based on the results obtained in the present study:

- As it is expected, the *MR* of modified mixtures was considerably more than control ones, especially at high temperature (40°C) with *MR* ratios about 2.5. The different traffic densities as well as axle's distances were considered using three R/L values of 4, 9, and 30. The results showed the slight changes in MR ratios by altering the R/L values in common loading time of 100 ms.
- The effects of SBS modification on *MR* of asphalt concrete became more obvious with increase in loading times so that *MR* ratio exceeded 3 under 1000 ms haversine loading. The SBS modification can be more effective in slow vehicle speeds. The interaction impacts of loading times and R/L's for both haversine and square pulses indicated the differences between *MR* ratios in different R/L's for each of loading times were more significant when changed from 4 to 9. The difference between *MR* ratios in R/L values of 4 and 9 were greater in long loading times.
- Using the findings of this research, it is recommended that SBS modification be utilized for pavements undergoing slow and dense traffics such as that happened in rush urban streets and intersections, especially in high temperature climates. From practice point of view, SBS modifier can be more

beneficiary to incorporate in deeper asphalt layer (i.e. binder layer) mixture than near surface mat.

- In the scope of this study, we can conclude that the stiffness properties of SBS modified asphalt concrete should be evaluated more comprehensive at high temperatures and under haversine pulse with long loading times. The future studies may be conducted on SBS modified asphalt mixtures prepared using a variety of aggregates and binders.

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