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Comparison of permanent deformation and fatigue resistance of hot mix asphalts prepared with the same performance grade binders

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ABSTRACT

In this study, the volumetric properties, Marshall stabilities, the indirect tensile stiffness moduli, and the fatigue and permanent deformation strengths of hot mix asphalts prepared with the same performance grade binders in accordance with Superpave method at optimum binder contents were comparatively investigated. In addition, the effect of bitumen modification using SBS on the mechanical characteristics of the mixtures was evaluated. Dynamic creep and indirect tensile fatigue tests were conducted at two distinct stress levels and three different loading periods. As the binder tests, it was determined that the modified bitumen obtained by adding of 3% SBS by weight into the $B_{160/220}$ binder yielded the same level of performance with the $B_{70/100}$ bitumen. It was also found that using 3% SBS by weight for the purpose of bitumen modification enhanced the desired properties of the mixture to a significant degree. It was observed that the best performance belonged to the mixtures containing $B_{70/100}$ bitumen, while the worst performance was found for the mixtures made from $B_{160/220}$ bitumen. Additionally, although the mixtures prepared by the same performance grade binders in accordance with the Superpave system were expected to behave similarly, it was found that they differed considerably with respect to their stiffness, tensile strength and strength against permanent deformation.

1. Introduction

Surface layers, which are the most costly component of highway' pavement and in direct contact with the tires of overrunning motor vehicles, can be prepared by different techniques such as cheap seal, road-mix, and hot mix asphalts. Among these alternatives, hot mix asphalts (HMAs) possess the highest strength and are composed of two main components as bitumen and aggregate. In HMAs, cohesion is provided by the bitumen binder while the aggregate maintains the internal friction resistance and stability of the mixture. Bitumen binders exhibit viscoelastic and thermoplastic behavior, where the former property enables the bituminous materials to display elastic behavior and high strength at fast loading conditions whereas exhibiting viscous behavior and low strength at slow loading rates. As a result of the thermoplastic characteristics, they display low strength at high temperatures and vice versa at lower temperature levels. Bitumen, which is a significant determinant of several highway parameters, foremost cracking and permanent deformation, induces the HMA to show its viscoelastic and thermoplastic behaviors [1].

Various admixtures are used to elongate the service life of pavements via prevention or retardation of pavement collapse without negatively affecting the diverse performance parameters of asphalts [2,3]. There are a number of different additives available, which can either be introduced directly into the asphalt cement (AC) as a binder modifier, or added into the mixture containing the aggregate [4]. Polymers are the most heavily used material in bitumen modification. Polymers can be classified into four broad categories; namely plastics, elastomers, fibers and additives/coatings. In order to achieve the improvement of bitumen properties, any selected polymer should be able to create a secondary network or establish a new balance system within the bitumen through molecular interactions or by reacting chemically with the binder. The styrene–butadiene–styrene (SBS) thermoplastic elastomer is a widely used block copolymer [5]. In the several studies conducted, it was determined that the strength of HMAs against permanent deformation [6–8], fatigue [9] and moisture induced damage [10,11] increase after utilization of SBS in bitumen modification.

The serviceability of pavement structure throughout its entire service life is attained by properly designing the pavement layer in the laboratory. Superior Performance Asphalt Pavement (Superpave) method was developed for the purpose of conducting the binder and mixture design by taking account of the climate and geographical conditions of the application area and thereby delaying the rehabilitation and restructuring requirements of the pavement [12]. In this methodology, binder performance tests are carried out instead of the conventional binder experiments and the performance grades (PGs) are determined in accordance with the results of Superpave binder tests. This classification is

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performed by taking various parameters such as permanent deformation, fatigue and low temperature cracking into consideration. Consequently, mixtures prepared by the same performance grade binders are expected to demonstrate similar levels of permanent deformation, fatigue and low temperature cracking. However, it is reported that the specification of Superpave binder is unsuitable especially for modified binders [12,13].

Although a number of studies were conducted on Superpave specification and the use of SBS as an admixture, only a handful of studies exist which comparatively analyze the performances HMAs prepared from the same performance grade binders. In this study, differing from the limited number of studies about the subject, the performances of HMAs prepared from the same performance grade binders were compared in respect of indirect tensile stiffness modulus test as well as dynamic creep and indirect tensile fatigue tests. Additionally, the dynamic creep and indirect tensile fatigue tests were performed at three different load repetition periods and hence the effect of loading period on fatigue and permanent deformation characteristics of HMAs was investigated.

2. Experimental studies

2.1. Binder design according to Superpave method

In this study, it was attempted to evaluate the mechanical properties of binders possessing the same performance grades as per Superpave binder design technique through the assistance of dynamic tests. For this purpose, first of all B 70/100 ($B_{70/100}$) and B 160/220 ($B_{160/220}$) bitumen were supplied from the TUPRAS refinery and their usability was determined as per EN 12591 standard. The results obtained from the conventional tests performed on the binders are given in Table 1.

In the study, Kraton D1101 SBS manufactured by Shell Chemical Co. was used. For the purpose of preparing the modified binders, the pure bitumen and SBS were mixed for 60 min at a temperature of 180 °C inside a mixer with a rotating rate of 1000 rpm. SBS was entrained into the $B_{160/220}$ bitumen at five different proportions between 2% and 6% separated with 1% intervals. The pure and SBS modified binders were aged with RTFOT and PAV. The binders were subjected to dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests to determine their performance grades. The DSR test results of the binders are given Table 2, while the BBR test results and the performance grades of the binders are presented in Table 3, in which it is shown that the $B_{70/100}$ containing mixture shared the same performance grade (PG 64-34) with the modified binders obtained by the adding of SBS by 2% and 3% ($MB_{2\%SBS}$ and $MB_{3\%SBS}$) into $B_{160/220}$ bitumen.

The rutting parameter ($G^*/\sin\delta$) values obtained from the DSR tests of $B_{70/100}$ and $B_{160/220}$ pure bitumens and unaged binders containing five different proportions of SBS at four different temperature levels (52, 58, 64 and 70 °C) were used to establish the ultimate SBS content to be used in the study. The evolution of $G^*/\sin\delta$ values with temperature is given in Fig. 1. The least squares method (Eq. (1)) was used to determine the closest blend to $B_{70/100}$ reference binder considering the results for all temperatures.

$$\sum_{i=52}^{70}[((G^*/\sin\delta_{B_{70/100}})_{T_i})^2 - ((G^*/\sin\delta_{x\%SBS})_{T_i})^2] \tag{1}$$

As a result, it was found that $MB_{3\%SBS}$ binder displayed the closest rutting parameter with the $B_{70/100}$ bitumen binder. Furthermore, the manufacturer advises adding a minimum of 3% SBS into bitumen to attain a continuous polymer phase. In this context, the SBS content used in the remaining course of the study was chosen as 3%.

In order to determine the mixing and compaction temperatures of HMAs, rotational viscosimeter tests were carried out at 135 °C and 165 °C on unaged $B_{70/100}$, $B_{160/220}$ and $MB_{3\%SBS}$ binders. The viscosity values were plotted on the obtained temperature–viscosity chart and connected with a line. The bitumen binder is desired to exhibit a viscosity of 170 ± 20 cP in mixing of HMAs, while the desired level is 280 ± 30 cP for compaction [14]. The corresponding temperatures to these viscosity values were then selected as the mixing and compaction temperatures. Besides, the viscosity value at 135 °C should not exceed 3 Pa s (3000 cP) in terms of workability [15]. The results obtained from viscosity tests are given in Table 4, which shows that the binder fulfilled the workability requirement. Additionally, viscosity of the binders was found to be increasing with higher SBS content, hence escalating the required mixing and compaction temperatures.

2.2. Hot mix asphalt design

In this study, a crushed limestone aggregate obtained from Karayazi Region of Elazig Province was utilized as the aggregate. The physical properties of this aggregate used in the mixtures are summarized in Table 5, while the gradation used is presented in Table 6. The optimum bitumen contents in HMAs prepared by $B_{70/100}$, $B_{160/220}$ and $MB_{3\%SBS}$ binders were measured in accordance to Marshall method. The values and specification criteria obtained from the specimens prepared at optimum bitumen contents are listed in Table 7.

According to the test results, the lowest optimum bitumen content belonged to the mixture prepared by $B_{160/220}$ bitumen; while the highest belonged to the mixtures containing 3% SBS modified bitumen by weight. The SBS modification increased the bitumen requirement. It was observed that the mixtures prepared at optimum bitumen contents possessed similar volumetric properties while collectively meeting the specification criteria. Comparison of stability values showed that the mixtures prepared by $B_{70/100}$ bitumen and $B_{160/220}$ bitumen displayed the highest and lowest stability values respectively. All mixtures possessed similar Marshall quotients which differed by less than 5% in all cases. Despite having the minimum yield values, the mixtures prepared by $B_{160/220}$ bitumen had a lower Marshall quotient than the rest of the mixtures due to their low stability value.

2.3. Mixture tests

2.3.1. Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus (ITSM) test is a non-destructive test that can be used to evaluate the relative quality of materials and study the effects of temperature and loading rate. The repeated-load indirect tensile stiffness modulus test defined by BS DD 213 is identified as a potential means of measuring this property. The ITSM S_m in MPa is defined as below;

$$S_m = F(R + 0.27)/LH \tag{2}$$

where F is the peak value of the applied vertical load (repeated load, N), H is the mean amplitude of the horizontal deformation (mm) obtained from five applications of the load pulse, L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed as 0.35). The test was done via a universal testing machine (UTM) in deformation-controlled mode. The magnitude of the applied force was adjusted by the system during the first five conditioning pulses such that the specified target peak transient diametral deformation was obtained. An appropriate value was chosen to ensure that sufficiently high signal amplitudes were obtained from the transducers such that would produce consistent and accurate results. Accordingly, this value was selected as 5 μm for this test. The rise time, which is measured from the origination of load pulse and denotes the duration of the applied load rising from zero to the maximum value, was set at 124 ms. The load pulse application was adjusted to 3.0 s. ITSM tests were conducted at two different temperatures (5 °C and 20 °C). The ITSM test results are presented in Fig. 2, where the values denote the means of three specimens.

As seen in Fig. 2, the highest ITSM value was observed in mixtures with $B_{70/100}$ bitumen, while those containing $B_{160/220}$ bitumen displayed the lowest ITSM. As a

Table 1
Conventional test results of neat binders.

Properties	Standard	$B_{70/100}$		$B_{160/220}$	
		Result	Specification limits	Result	Specification limits
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	97	70–100	190	160–220
Softening point (°C)	ASTM D36	49.6	43–51	40.9	35–43
Penetration index (PI)	–	0.481	–	0.12	–
After RTFOT					
Mass loss (%)	ASTM D2872	0.769	Max. 0.8	0.935	Max. 1.0
Penetration (0.1 mm), 100 g, 5 s	ASTM D5	52	–	97	–
Retained penetration, (%)	–	54	Min. 46	51	Min. 37
Softening point (°C)	ASTM D36	58.3	Min. 45	50.3	Min. 37
Increase in softening point (°C)	–	8.7	Max. 9	9.4	Max. 11
Penetration index (PI)	–	0.782	–	0.67	–

Table 2
DSR test results.

Temp. (°C)	$B_{70/100}$	$B_{160/220}$	$MB_{2\%SBS}$	$MB_{3\%SBS}$	$MB_{4\%SBS}$	$MB_{5\%SBS}$	$MB_{6\%SBS}$
G^*/sinδ (Pa) (specification limit min. 1 kPa)							
52	6861	2263	5168	7452	9551	15,001	22,133
58	3172	1182	2387	3690	4735	7551	11,803
64	1495	523	1194	1788	2444	3896	6352
70	739	265	615	902	1271	2104	3276
76	–	–	333	484	687	1202	1801
G^*/sin δ (Pa) RTFOT residue (specification limit min. 2.2 kPa)							
58		7277					
64	5778		10,960	11,938			
70					7602		
76						6340	8311
G^*.sin δ (Pa 10^6) PAV residue (specification limit max. 5000 kPa)							
16		2.205					
19	0.4581	1.6270	1.3463	1.224			
22			0.6998	1.1521	0.359		
25					0.4947	0.584	
28						0.350	0.631
31							0.501

Table 3
BBR test results and binders performance grades.

Temp. (°C)	$B_{70/100}$	$B_{160/220}$	$MB_{2\%SBS}$	$MB_{3\%SBS}$	$MB_{4\%SBS}$	$MB_{5\%SBS}$	$MB_{6\%SBS}$
m-Value (specification limit min. 0.300)							
−18	0.329	0.362	0.355	0.372	0.330	0.338	0.345
−24	0.305	0.338	0.328	0.313	0.313	0.303	0.274
−30	0.268	0.270	0.239	0.260	0.216	0.242	0.245
Creep stiffness (Mpa) (specification limit max. 300 MPa)							
−18	110.21	89.31	97.22	99.41	91.92	100.72	94.74
−24	225.68	112.45	144.25	149.85	138.97	142.67	158.84
−30	226.30	129.31	224.55	267.15	207.53	202.55	207.25
Performance grades (PG)							
	64–34	58–34	64–34	64–34	70–34	76–34	76–28

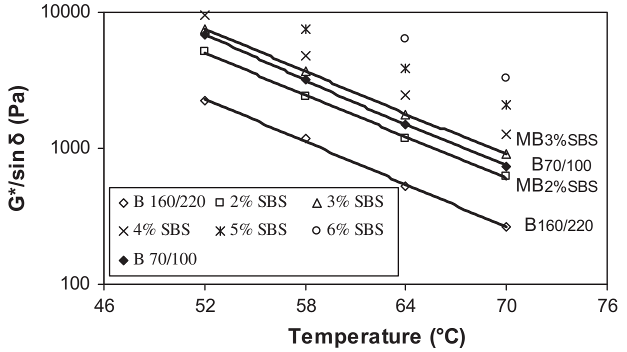

Fig. 1. Variation of G^*/sin δ values with temperature.

result of utilizing 3% SBS in bitumen modification, ITSM was enhanced by 20.2% at 5 °C and 34.5% at 20 °C in comparison to mixtures entrained with $B_{160/220}$ bitumen. The ITSM values of mixtures prepared by $B_{70/100}$ bitumen were measured to be higher than the mixtures containing $B_{160/220}$ bitumen by 41.5% at 5 °C and 59.3% at 20 °C. An evaluation of mixtures prepared by same performance grade binders displayed that stiffness of mixtures containing $B_{70/100}$ bitumen was higher compared to the mixtures prepared by $MB_{3\%SBS}$ bitumen by 17.7% at 5 °C and 18.4% at 20 °C. The results of ITSM tests demonstrated that the use of SBS in bitumen modification at a proportion of 3% led to an increase in the stiffness of HMAs, in addition a significant difference were found among the stiffness values of mixtures prepared with the same performance grade binders.

2.3.2. Dynamic creep test

One of the most commonly employed tests to determine the resistance of HMAs against permanent deformation is dynamic creep test. In this test conducted by the UTM, a constant load is dynamically applied at a certain periodic rate onto a cylindrical specimen. The plastic strains induced by the load cycles are determined by the assistance of LVDTs vertically attached onto the metal plate that is fixated onto the surface of the specimen. The creep moduli could be obtained from the formulas given below [16].

$$\varepsilon_c = (L3_n - L1)/G \tag{3}$$

$$\sigma = F/A \tag{4}$$

$$E_c = \sigma/\varepsilon_c \tag{5}$$

Table 4
Rotational viscosity test results.

Properties	Standard	$B_{70/100}$	$B_{160/220}$	$MB_{3\%SBS}$
Viscosity (cP, 135 °C)	ASTM D4402	500.0	237.5	587.5
Viscosity (cP, 165 °C)	ASTM D4402	162.5	87.5	175.0
Mixing temperature range (°C)	–	159–165	142–149	164–167
Compaction temperature range (°C)	–	145–151	127–133	155–160

Table 5
Physical properties of the aggregate.

Properties	Standard	Specification limits	Coarse	Fine	Filler
Abrasion loss (%) (Los Angeles)	ASTM D 131	Max 30	29	–	–
Frost action (%) (with Na_2SO_4)	ASTM C 88	Max 10	4.5	–	–
Flat and elongated particles (%)	ASTM D 4791	Max 10	4		
Water absorption (%)	ASTM C127	Max 2	1.37		
Specific gravity (g/cm^3)	ASTM C127		2.613	–	–
Specific gravity (g/cm^3)	ASTM C128		–	2.611	–
Specific gravity (g/cm^3)	ASTM D854		–	–	2.711

Table 6
Combined aggregate gradation.

Sieve size (mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing (%)	100	95	88	65	39	24	18	14	9.5	5

Table 7
Volumetric properties and stability test results of neat and SBS modified mixtures.

Mixture properties	Binder type			Specification limits
	$B_{70/100}$	$B_{160/220}$	$MB_{3\%SBS}$	
Optimum binder content (%)	4.96	4.83	5.09	%4–7
Volume of air voids (Va, %)	3.71	4.07	3.88	3–5
Voids filled with asphalt (VFA, %)	74.27	71.11	73.82	65–75
Voids in the mineral aggregate (VMA, %)	14.41	14.08	14.82	Min. 14
Stability (kN)	17.9	15.8	17.2	Min. 9
Flow (mm)	3.89	3.46	3.60	2–4
Dust proportion (DP)	1.06	1.09	1.03	Maks. 1.5
Marshall quotient (kN/mm)	4.60	4.56	4.76	–

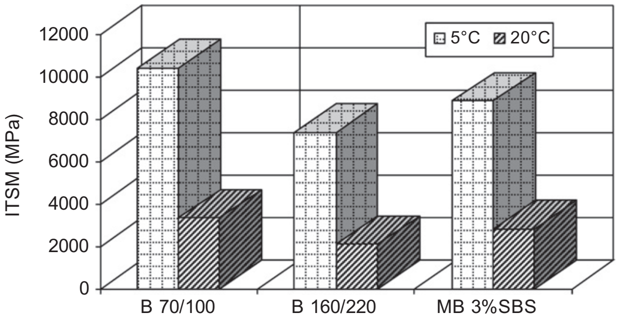

Fig. 2. ITSM values of mixtures at different temperature.

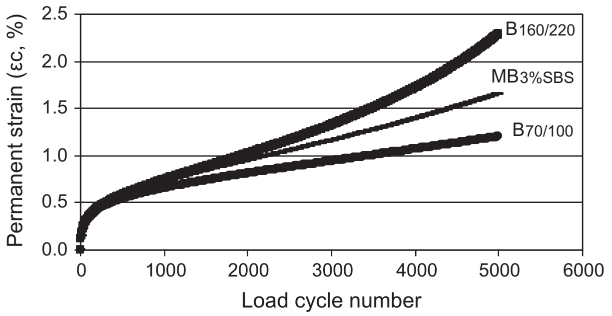

Fig. 3. Variation of load cycle number versus permanent strain at 300 kPa stress level and 1500 ms loading period.

In the equations above, ε_c is the total permanent (plastic) strain (%), E_c is the creep modulus (MPa), G is the initial height of the specimen (mm), $L1$ is the initial reference displacement of LVDT (mm), $L3_n$ is the level of displacement prior to the application of $(n+1)$th load pulse (mm) (plastic), σ is the maximum vertical stress (kPa), F is the maximum vertical load (N), and finally A denotes the cross-section area of the sample (cm^2). As seen in formula (5), the level of plastic strain is inversely proportional to the value of creep moduli. In this context, creep modulus is low when plastic strain is high. Thus, a high creep modulus demonstrates that the HMA specimen will exhibit a high resistance against permanent deformation.

The dynamic creep test temperature was chosen as 50 °C and the stress levels as 300 and 500 kPa. A static preloading was carried out on the specimens at 10 kPa stress during 90 s prior to the commencement of the test. The experiment was carried out at three different loading periods of 1500, 2000 and 2500 ms. The load rise time was kept constant at 500 ms in all tests and tests were carried on until reaching 5000 load cycles. In this study, the permanent strain and creep moduli of mixtures after the end of 5000 load cycles were compared at a stress of 300 kPa, while the load cycle number at 4% permanent strain were compared at a strain of 500 kPa. For instance, the change in permanent strain of the specimen with the number of load cycles at stress levels of 300 kPa and 500 kPa and a loading period of 1500 ms are given in Figs. 3 and 4, respectively; whereas the change in creep moduli of the specimens with the number of load cycles is displayed by Figs. 5 and 6. The measured values obtained from the tests are summarized in Table 8, where were all obtained from the means of three specimens.

As seen in Figs. 3 and 4, although early age collapsing occurred in the specimens at a stress level of 500 kPa, no such phenomenon was observed at a stress level of 300 kPa and after 5000 load cycles. At a stress of 300 kPa and, the highest and lowest permanent strain values were exhibited by the HMAs prepared by $B_{160/220}$ bitumen and $B_{70/100}$ bitumen, respectively. At 300 kPa stress and after 5000 loading cycles, the permanent strain in mixtures prepared by $MB_{3\%SBS}$ binder was found to be lower than those containing $B_{160/220}$ bitumen by 27.7%, 25.3% and 21.6% for loading periods of 1500, 2000 and 2500 ms, respectively. As for the mixtures containing $B_{70/100}$ bitumen, the permanent strain was lower by 27.5%, 38.3% and 38.0% than that of the mixtures prepared by $MB_{3\%SBS}$ modified bitumen for the same respective number of loading cycles.

The tests applied at 300 kPa stress level demonstrated that longer loading periods consistently resulted in higher levels of permanent strain for all mixtures. After increasing the loading period from 1500 ms to 2000 ms, the ε_c values of mixtures prepared by $B_{70/100}$, $B_{160/220}$ and the modified $MB_{3\%SBS}$ bitumens dropped by 24.2%, 13.8% and 10.9% after 5000 loading cycles, respectively. Similarly, the loading period rising from 1500 ms to 2500 ms reduced the ε_c values of the same mixtures by 38.6%, 33.8% and 28.2% under the same conditions, respectively. Accordingly, it is determined that a jump in loading period had the most effect on the mixture containing $B_{70/100}$ bitumen while the mixture prepared from $MB_{3\%SBS}$ binder was the least affected.

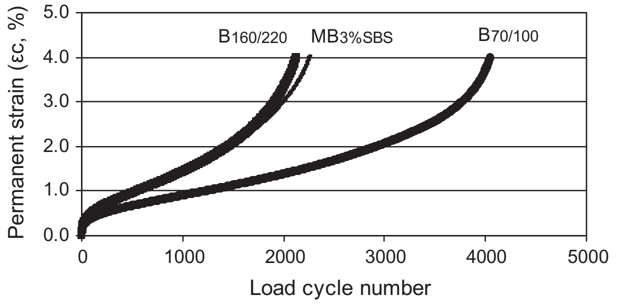

Fig. 4. Variation of load cycle number versus permanent strain at 500 kPa stress level and 1500 ms loading period.

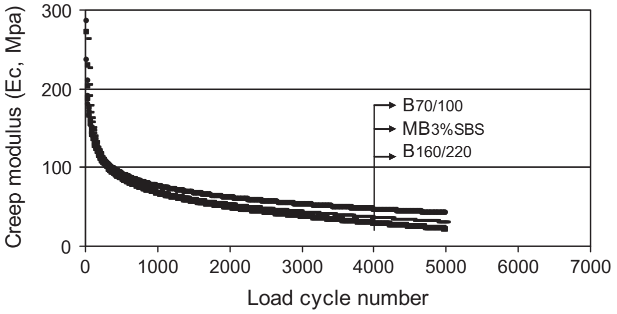

Fig. 5. Variation of load cycle number versus creep modulus at 300 kPa stress level and 1500 ms loading period.

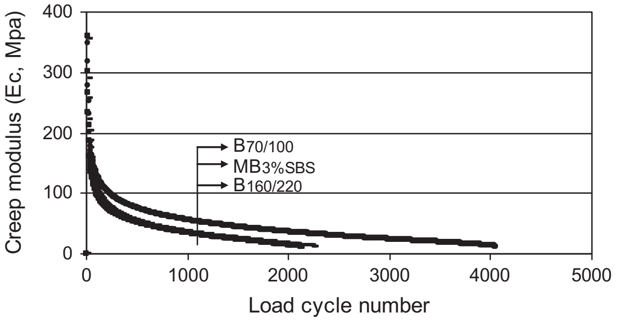

Fig. 6. Variation of load cycle number versus creep modulus at 500 kPa stress level and 1500 ms loading period.

At all loading periods, the lowest and highest creep moduli belonged to the HMAs prepared by $B_{160/220}$ bitumen and $B_{70/100}$ bitumen, respectively. The creep moduli of the mixtures rapidly fell up to 500 loading cycles, while dropping more slowly after this threshold. The initial plunge was induced by compression in the mixtures arising from consolidation effects. At 300 kPa stress and after 5000 loading cycles, the creep modulus of mixtures prepared by $B_{70/100}$ bitumen was found to be higher than those containing $MB_{3\%SBS}$ modified bitumen by 37.9%, 62.1% and 61.2% for loading periods of 1500, 2000 and 2500 ms, respectively.

In all cases, the creep modulus increased at longer loading periods, hence the strength of HMAs against permanent deformation decreased as the period of loading cycles became shorter. In line with the observations on permanent strain values, the creep modulus of mixtures containing $B_{70/100}$ bitumen was the most heavily influenced by changes in the loading period, while the mixtures prepared by $MB_{3\%SBS}$ modified bitumen were the least affected in the same regard.

A comparison of the number of loading cycles for 4% permanent strain values obtained from the dynamic creep tests conducted at a stress level of 500 kPa showed that the mixtures prepared by $B_{160/220}$ and $MB_{3\%SBS}$ binders possessed similar values especially at loading cycle periods of 1500 and 2000 ms. As seen in Table 8, the highest number of loading cycles were required in the mixtures prepared by $B_{70/100}$ bitumen to create a 4% permanent strain. In comparison, despite having the same performance grade, the number of loading cycles required to induce a 4% permanent strain in the mixtures prepared by $MB_{3\%SBS}$ modified bitumen was higher by 80.6%, 69.1% and 32.4% at loading periods of 1500, 2000 and 2500 ms, respectively.

2.3.3. Indirect tensile fatigue test

The indirect tensile fatigue test is one of the constant stress tests that can characterize the fatigue behavior of the mixture [17]. In this study, the fatigue tests were performed in controlled stress mode according to BS DD ABF standard. The universal testing machine (UTM) was used for this purpose. The machine has a servohydraulic test system. The loading frame was housed in an environmental chamber to control temperature during the test. The desired load level, load rate and load duration were controlled by a computer. The deformation of the specimen was monitored through linear variable-differential transducers (LVDTs). The LVDTs were clamped vertically onto the diametrical side of the specimen. A repeated dynamic compressive load was applied to specimens across the vertical cross-section along the depth of the specimen using two loading strips 12.5 mm in width. Finally, the resulting total deformation corresponding to the applied force was measured.

The indirect tensile fatigue test was conducted on HMAs prepared by $B_{70/100}$ and $B_{160/220}$ as well as the modified bitumen of $MB_{3\%SBS}$, each at their respective optimum bitumen contents and at 150 and 300 kPa stress levels. The indirect tensile fatigue test was carried out at a temperature of 25 °C. Prior to launching the test, the specimens were exposed to this testing temperature for 3 h. The test was conducted at three different loading periods (1500, 2000 and 2500 ms). Similar to the ITSM test, the first 124 ms of the loading period was calibrated as the load impact period. The tests were continued up to 20,000 loading cycles at 150 kPa stress level and until reaching the point of fracturing in the specimens at a stress level of 300 kPa. At 150 kPa stress, the mixture prepared by $B_{160/220}$ bitumen collapsed after 9000 loading cycles. For this reason, the vertical deformation values of the mixtures at 150 kPa stress and at the conclusion of 9000 loading cycles were compared. Furthermore, vertical deformation values of the mixtures prepared by $B_{70/100}$ and $MB_{3\%SBS}$ binders were compared at the end of 20,000 loading cycles. As for the stress level of 300 kPa, the numbers of loading cycles culminating in a deformation of 3 mm were evaluated. For illustration, the relationship of vertical deformation taking place in the specimens at stress levels of 150 and 300 kPa and a loading period of 1500 ms with the number of load cycles is presented in Figs. 7 and 8. The test results are also summarized in Table 9. All values were obtained from the means of three specimens.

Similar to Figs. 7 and 8, it was determined that the greatest vertical deformation for all loading periods was exhibited by the mixture containing $B_{160/220}$ bitumen, whereas the lowest vertical deformation belonged to the mixture prepared with $B_{70/100}$ bitumen. At 150 kPa stress level, the impact of SBS modification was explicitly observed. At this particular stress, it was found that all of the mixtures prepared from the $B_{70/100}$ and $MB_{3\%SBS}$ binders experienced similar changes in deformation with varying number of load cycles. At the conclusion of 9000 load cycles, the mix-

Table 8
Dynamic creep test results.

Properties	Stress level (kPa)	Loading period (ms)	Binder type		
			$B_{70/100}$	$B_{160/220}$	$MB_{3\%SBS}$
ε_c @ 5000 load cycles (%)	300	1500	1.20	2.29	1.66
		2000	0.91	1.98	1.48
		2500	0.74	1.52	1.19
E_c @ 5000 load cycles (MPa)	300	1500	41.63	21.83	30.18
		2000	54.95	25.31	33.89
		2500	67.81	32.98	42.06
Load cycles @ 4% ε_c	500	1500	4052	2132	2244
		2000	4776	2472	2824
		2500	5136	2660	3880

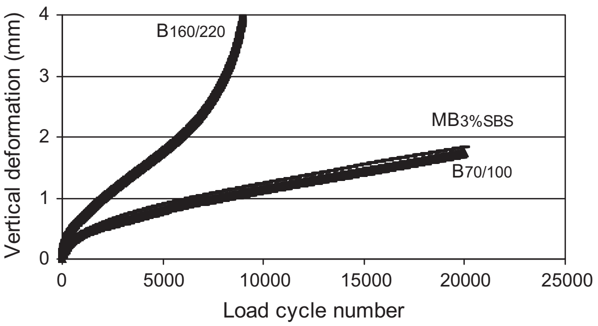

Fig. 7. Variation of load cycle number versus deformation at 150 kPa stress level and 1500 ms loading period.

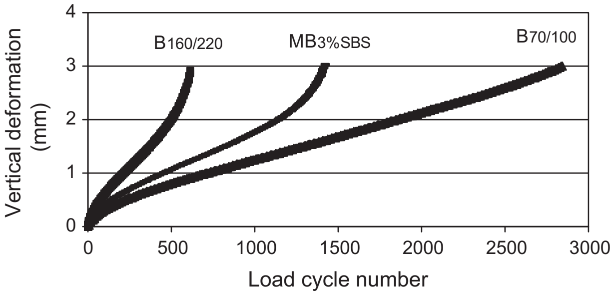

Fig. 8. Variation of load cycle number versus deformation at 300 kPa stress level and 1500 ms loading period.

Table 9
Indirect tensile fatigue test results.

Properties	Stress level (kPa)	Loading period (ms)	Binder type		
			$B_{70/100}$	$B_{160/220}$	$MB_{3\%SBS}$
Deformation @ 9000 load cycles (mm)	150	1500	1.077	3.900	1.178
		2000	1.008	3.352	1.099
		2500	0.871	2.765	0.929
Deformation @ 20,000 load cycles (mm)	150	1500	1.736	–	1.834
		2000	1.568	–	1.771
		2500	1.380	–	1.526
Load cycles @ 3 mm deformation	300	1500	2844	618	1422
		2000	2880	642	1419
		2500	2970	588	1536

tures containing $B_{160/220}$ bitumen suffered 3.6, 3.3 and 3.2 times higher vertical deformation compared to those prepared from $MB_{3\%SBS}$ modified bitumen at loading periods of 1500, 2000 and 2500 ms, respectively. On the other hand, the vertical deformation occurring in mixtures prepared by $B_{70/100}$ bitumen was lower by 8.6%, 8.3% and 6.2% than that of the mixtures containing $MB_{3\%SBS}$ modified bitumen at loading periods of 1500, 2000 and 2500 ms, respectively. Similarly, at the conclusion of 20,000 load cycles, the vertical deformation experienced by mixtures prepared with $B_{70/100}$ bitumen was lower by 5.3%, 11.5% and 9.6% compared to the mixtures containing $MB_{3\%SBS}$ modified bitumen at loading periods of 1500, 2000 and 2500 ms, respectively. It was determined from the deformation values measured after 20,000 load cycles that the mixtures containing $B_{70/100}$ bitumen were the most severely affected from the loading period.

At 300 kPa stress, the deformation versus number of load cycles plots for the mixtures were found to be significantly different. For instance, the number of load cycles needed to inflict a deformation of 3 mm was found to be 2.3, 2.2 and 2.6 times lower for the mixtures prepared from $MB_{3\%SBS}$ modified bitumen compared to the those containing $B_{160/220}$ bitumen for loading periods of 1500, 2000 and 2500 ms, respectively. As for the mixtures using $B_{70/100}$ bitumen, the same parameter was measured to be half as much compared to mixtures prepared from $MB_{3\%SBS}$ modified bitumen for all three loading periods.

3. Conclusions

In this study, the performances of HMAs prepared with the same performance grade binders in accordance with Superpave design technique were compared by numerous testing methodologies. Based on the results and analyses of this study, the relevant findings and conclusions can be summarized as follows:

According to the Superpave binder tests, the binder containing SBS by 3% was found to exhibit the closest results with the $B_{70/100}$ binder, therefore modified bitumen containing SBS at a proportion of 3% was used throughout the study in the mixtures.

A comparison of stability and ITSM values showed that the highest stability and stiffness values were displayed by the mixtures containing $B_{70/100}$, while the lowest values belonged to the mixtures prepared with $B_{160/220}$ bitumen. Thereby, it was determined that the use of SBS by 3% in bitumen modification improves the stability and stiffness of HMAs.

As a result of the dynamic creep tests, the creep behaviors of mixtures prepared with $B_{70/100}$ bitumen and $MB_{3\%SBS}$ modified bitumen were found to exhibit differences despite possessing the same performance grades. An evaluation of three mixtures showed that the strongest mixtures against permanent deformation contained $B_{70/100}$, while the mixtures with lowest strength contained the pure bitumen of $B_{160/220}$. In terms of the loading periods, the most affected mixtures contained $B_{70/100}$, while the mixtures prepared with $MB_{3\%SBS}$ modified bitumen were the least affected.

As a result of the indirect tensile fatigue tests, the fatigue behaviors of mixtures prepared with $B_{70/100}$ bitumen and MB3%SBS modified bitumen were found to exhibit differences. Similar to the other tests, the mixtures with the highest fatigue strength contained $B_{70/100}$, while the mixtures with lowest strength contained the pure bitumen of $B_{160/220}$. At 150 kPa stress level, although the mixtures prepared by the same performance grade binders displayed similar behaviors, they displayed different behaviors at 300 kPa stress. Additionally, the mixtures prepared with MB3%SBS binder were found to be the least affected from the loading period.

As a result of all these conducted tests, the adding of SBS was determined to exhibit a significantly positive impact on the performance of HMAs. The mixtures prepared by the same performance grade binders according to Superpave design method were found to demonstrate different performances. In light of these observations, it is believed that the Superpave binder design parameters should be reevaluated especially with respect to modified bitumens. Exhibited better resistance according to mixture tests, the pure binder which is in the same performance grade with the modified binders will ensure cost effective solution when use instead of modified binders in hot mixtures.

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