Construction and Building Materials 44 (2013) 533–540

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of SBS and different natural asphalts on the properties of bituminous binders and mixtures

Mehmet Yilmaz *, Muhammed Ertuğrul Çeloğlu

Fırat University, Faculty of Engineering, Department of Civil Engineering, 23119 Elazığ, Turkey

HIGHLIGHTS

- Effects of different natural asphalts on the properties of HMAs were compared.
- SBS modified mixtures also compared with natural asphalt modified mixtures.
- Control and modified mixtures were subjected to HMA performance tests.
- All modifiers increased to resistance to permanent strain and fatigue cracks.

ARTICLE INFO

Article history:
Received 27 November 2012
Received in revised form 26 February 2013
Accepted 2 March 2013

Keywords:
Hot mix asphalt
Modification
Natural asphalt
Styrene–butadiene–styrene

ABSTRACT

In this study, three different natural asphalts (Trinidad Lake Asphalt, Iranian gilsonite and American gilsonite) and styrene–butadiene–styrene (SBS) were used as additive in bitumen modification. Results of binder tests showed that addition of 10.0% American gilsonite ($MB_{10\%AG}$), 9.5% Iranian gilsonite ($MB_{9.5\%IG}$), 60% Trinidad Lake Asphalt (TLA) ($MB_{60\%TLA}$) and 3.8% SBS ($MB_{3.8\%SBS}$) to pure bitumen (PG 58-34) achieved the desired performance level (PG 70-34). Experiments conducted on mixtures showed that mixtures prepared with $MB_{60\%TLA}$ had the highest stiffness, stability, tensile strength and resistance to fatigue and permanent deformation. On the other hand, mixtures prepared with $MB_{9.5\%IG}$ and $MB_{3.8\%SBS}$ were observed to have highest resistance to moisture induced damage.

1. Introduction

Hot mix asphalts found in flexible pavements basically consist of bituminous binders and aggregate. Due to their rheological properties, bituminous binders behave like elastic solids at high loading conditions and low temperatures, and behave like a viscous fluid at low loading conditions and high temperatures [1]. Bituminous binders exhibit similar behaviour in pavements, because these properties are preserved in their mixtures. Due to traffic and environmental conditions, hot mix asphalts are exposed to rutting, moisture induced damage, cracks due to low temperature and fatigue [2]. Additives are used to increase the lifespan of pavements by increasing the resistance of bitumen and bituminous mixtures to heat and traffic load [3]. The polymer, styrene–butadiene–styrene (SBS) is the most commonly used additive [4]. Various studies have shown that use of SBS in bitumen modification increases the resistance of bituminous mixtures to permanent deformation [5,6], moisture induced damage [7,8] and fatigue cracks [9].

Natural asphalts are another kind of additive used in hot mix asphalts. Trinidad Lake Asphalt (TLA) and gilsonite are the most widely used natural binder modifiers. Various studies have shown that use of TLA and gilsonite in hot mix asphalts enhances their properties [10–13]. TLA, the first binder used in hot bituminous mixtures in 1876 [14], comes from the world's largest commercial deposit of natural asphalt located in La Brea, Trinidad & Tobago. Typically, TLA consists of a mixture of bitumen and mineral matter. The bitumen component is made up of maltenes (63–66%) and asphaltenes (34–37%). Typically, refined TLA has a penetration at 25 °C of 2 dmm and a softening point between 93 and 99 °C [15]. Gilsonite, a naturally occurring solid hydrocarbon mineral, has the potential to improve the physical and chemical properties of bitumen [16]. Gilsonite is known for its easy use and good affinity with asphalt. Due to the fact that gilsonite is also a kind of asphalt binder in nature, it can be quickly dissolved into asphalt binder [17]. Important gilsonite resources are located in United States (Utah) and Iran.

Although there is a large body of literature on the use of natural asphalts for bitumen modification, there has been no study conducted to compare the effects of different natural asphalts collected from various places on earth. In this study, modified

* Corresponding author. Tel.: +90 424 2370000x5421.
E-mail addresses: mehmetyilmaz@firat.edu.tr (M. Yilmaz), meceloglu@firat.edu.tr (M.E. Çeloğlu).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.03.036

binders and mixtures were prepared using SBS, TLA, Iranian gilsonite and American gilsonite. Effects of natural asphalt modifiers and SBS modification on HMAs were compared using Marshall stability and flow, indirect tensile strength, indirect tensile stiffness modulus, indirect tensile fatigue and cyclic creep tests with the goal of identifying the most effective of the four additives.

2. Materials and sample preparation

In this study, binder and hot mix asphalt design were done according to Superpave method. Asphalt cement, PG 58-34, obtained from Turkish Petroleum Refineries was used as pure binder. The pure binder was modified with American gilsonite (AG), Iranian gilsonite (IG), TLA and SBS. The SBS polymer (Kraton D-1101), AG, IG and TLA (Epure Z 0/8) were obtained from Shell Chemicals Company, American gilsonite Company, Aydin Trade Company and Lake Asphalt of Trinidad and Tobago Limited, respectively.

For the purpose of preparing the modified binders, the pure bitumen and additives were mixed for 60 min at a temperature of 180 °C inside a mixer with a rotating rate of 1000 rpm. Natural asphalt and polymer additives were added to pure bitumen in different ratios and dynamic shear rheometer (DSR) experiments were conducted on unaged binders. The performance grade goal for the modified binders was a minimum PG 70-22 in compliance with traffic and climatic conditions of city of Elazığ, Turkey, which was selected as the application area. PG 70 was achieved when 10% and 12% AG by weight of pure binder was used (Table 1). Appropriate additive contents of IG, TLA and SBS were determined based on rutting parameter ($G^*/\sin\delta$) of 10% AG modified binder at 70 °C (Table 1). At the end of DSR experiments, it was decided that 10.0% AG ($MB_{10\%AG}$), 9.5% IG ($MB_{9.5\%IG}$), 60% TLA ($MB_{60\%TLA}$) and 3.8% SBS ($MB_{3.8\%SBS}$) should be used. DSR and bending beam rheometer (BBR) test results of pure and modified bitumens are presented on Table 2. As shown in Table 2, all modified bitumens performance levels were PG 70-34, which met the necessary level for the application area (PG 70-22).

The mixing and compaction temperatures were determined for binders by using 170 ± 20 and 280 ± 30 cP viscosity values, respectively. The viscosity values of binders are given in Table 3. Viscosity values increased due to use of additives, which in turn increased the mixing and compaction temperatures. Limestone aggregate was used for the asphalt mixtures. The properties of aggregate are given in Table 4. A crushed coarse and fine aggregate with maximum size of 19 mm was selected for a dense graded asphalt mixture. The gradation of the aggregate mixtures is given in Table 5.

The design bitumen contents (DBCs) of the mixtures were determined in accordance with Superpave mix design. A sample of TLA was subjected to extraction process and it was determined that the TLA was composed of 75% bitumen and 25% filler. Design bitumen contents of TLA-containing mixtures were determined by trial and error with the goal that all mixtures have same gradation. DBC of these mixtures was determined to be 5.80% (4.93% bitumen and 0.87% filler). Considering the amount of filler in TLA, the limestone filler ratio was decreased by 0.87% and 5.80% $MB_{60\%TLA}$ was used in mixtures prepared with TLA. The volumetric properties and specification limits of the control (prepared with pure bitumen) and modified mixtures prepared at the design binder contents are presented in Table 6. All mixtures ensured Superpave specification limits.

Table 2
DSR and BBR test results.

DSR test results					
Temp. (°C)	$G^*/\sin\delta$ (kPa) (specification limit min. 1 kPa)				
	PG 58-34	$MB_{10\%AG}$	$MB_{9.5\%IG}$	$MB_{60\%TLA}$	$MB_{3.8\%SBS}$
58	1.053	–	–	–	–
70	–	1.360	1.325	1.383	1.318
$G^*/\sin\delta$ (kPa) RTFOT residue (specification limit min. 2.2 kPa)					
58	2.430	–	–	–	–
70	–	5.776	6.005	5.658	6.245
$G^*/\sin\delta$ (kPa) PAV residue (specification limit max. 5000 kPa)					
16	1247		–	–	–
19	950	3704	3140	1735	2978
22	–	2847	2392	1360	2305
25	–	2158	1768	1043	1742
BBR test results					
Temp. (°C)	*m*-Value (specification limit min. 0.300)				
	PG 58-34	$MB_{10\%AG}$	$MB_{9.5\%IG}$	$MB_{60\%TLA}$	$MB_{3.8\%SBS}$
−18	0.363	0.339	0.338	0.329	0.345
−24	0.321	0.307	0.311	0.305	0.319
−30	0.292	0.283	0.288	0.258	0.285
Creep stiffness (specification limit max. 300 MPa)					
−18	106.8	124.5	122.1	152.5	111.4
−24	197.7	236.4	214.5	278.9	207.5
−30	390.2	448.7	432.9	521.6	418.6
Performance grades (PG)					
	58-34	70-34	70-34	70-34	70-34

3. Mixture tests

3.1. Marshall stability and flow test

Marshall stability and flow tests were applied according to EN 12697-34 standard test method [18]. The specimens were compacted at 4 ± 1% air voids with a Superpave gyratory compactor. The specimens were divided into two groups each of which consisted of 15 mixtures. The mean specific gravities of the specimens in each group were equal. The first group was unconditioned (immersed in water at 60 °C for 40 min) and the second group was conditioned (immersed in water at 60 °C for 24 h). The specimens were loaded to the point of failure by using curved steel loading plates along the diameter at a constant rate of compression of

Table 1
DSR test results of unaged binders.

Additive type	Additive content (%)	$G^*/\sin\delta$ (kPa) (specification limit min. 1 kPa) Temp. (°C)				
		52	58	64	70	76
AG	6	6.880	3.212	1.563	0.747	-
	8	8.591	4.062	1.914	0.943	-
	10	**12.754**	**5.882**	**2.712**	**1.360**	**0.689**
	12	16.788	7.927	3.722	1.795	0.919
IG	8	8.724	4.218	2.092	0.982	-
	9	10.625	5.016	2.524	1.260	0.673
	9.5	**12.540**	**6.002**	**2.612**	**1.325**	0.710
	10	13.662	6.183	3.042	1.532	0.782
TLA	40	8.035	3.662	1.715	0.850	-
	50	9.110	4.235	1.977	0.994	-
	60	**13.126**	**6.042**	**2.810**	**1.383**	**0.731**
	70	15.872	7.863	3.741	1.667	0.823
SBS	3	8.347	3.939	1.949	0.997	-
	3.5	10.471	4.933	2.477	1.236	0.594
	3.8	**11.280**	**5.207**	**2.552**	**1.318**	**0.700**
	4	13.895	6.273	3.007	1.541	0.820

Table 3
Rotational viscosity test results.

Properties	Standard	PG 58-34	$MB_{10\%AG}$	$MB_{9.5\%IG}$	$MB_{60\%TLA}$	$MB_{3.8\%SBS}$
Viscosity (cP, 105 °C)	ASTM D4402	1413	4663	5625	6038	6150
Viscosity (cP, 135 °C)		300	737.5	762.5	850	1188
Viscosity (cP, 165 °C)		100	200	187.5	225	350
Mixing temperature range (°C)	–	152–158	166–168	165–167	167–169	171–172
Compaction temperature range (°C)	–	134–143	159–162	159–162	161–164	166–169

Table 4
Physical properties of the aggregate.

Properties	Standard	Specification limits	Coarse	Fine	Filler
Abrasion loss (%) (Los Angeles)	ASTM D 131	Max 30	27.8	–	–
Abrasion loss (%) (Micro deval)	ASTM D 6928	Max 15	13.6	–	–
Frost action (%) (with Na_2SO_4)	ASTM C 88	Max 10	5.8	–	–
Flat and elongated particles (%)	ASTM D 4791	Max 10	3		
Specific gravity (g/cm^3)	ASTM C127		2.544	–	–
Specific gravity (g/cm^3)	ASTM C128		–	2.571	–
Specific gravity (g/cm^3)	ASTM D854		–	–	2.675

Table 5
Combined aggregate gradation.

Sieve size (mm)	Passing (%)	Control points		Restricted zone	
		Min.	Min.	Max.	Max.
19	100				
12.5	95	90	100		
9.5	88				
4.75	65				
2.36	35	28	58	39.1	39.1
1.18	23			25.6	31.6
0.6	14			19.1	23.1
0.3	10			15.5	15.5
0.15	8				
0.075	6	2	10		

50.8 mm/min. The stability and flow as well as the ratio of stability (kN) to flow (mm), defined as the Marshall quotient (MQ), which is an indication of stiffness of the mixtures was determined for each specimen. It is generally recognized that MQ is a measure of a materials resistance to shear stress, permanent deformation and hence rutting. High MQ values indicate a mix with high stiffness, greater ability to spread the applied load and resistance to creep deformation [19]. The Marshall stabilities and MQ values for both conditioned and unconditioned mixtures are given in Figs. 1 and 2 respectively.

The values are the average of three samples. Control mixtures had the lowest stability values while the mixtures prepared with $MB_{60\%TLA}$ had the highest stability values both before and after conditioning. It was observed that the mixtures prepared with $MB_{60\%TLA}$ had 45.6% higher stability before the conditioning, and 46.8% higher stability after the conditioning compared to control mixture. Mixtures prepared with $MB_{10\%AG}$ had higher stability values than mixtures prepared with $MB_{9.5\%IG}$, although stability values of these two mixtures were close to each other after conditioning. All three mixtures prepared with natural asphalt modified binders were found to have higher stability values than mixtures prepared with $MB_{3.8\%SBS}$. Examination of MQ values revealed that there was not a big change in flow values; changes similar to those that occurred in the stability values were observed. Unlike the changes in stability values, the mixture prepared with $MB_{3.8\%SBS}$ had the second highest MQ value after conditioning. Even though the mixture prepared with $MB_{60\%TLA}$ had the highest MQ value, it had the highest decrease (48.6%) due to conditioning. The mixture prepared with $MB_{3.8\%SBS}$ was least affected (5.2%) from conditioning, in terms of MQ values.

The retained Marshall stability (RMS) was calculated from the mean stability values of each group by the following formula:

$$RMS = 100 * (MS_{cond.}/MS_{uncond.}) \quad (1)$$

where RMS is the retained Marshall stability (%); $MS_{cond.}$ is the mean Marshall stability for conditioned specimens (kN); and $MS_{uncond.}$ is the mean Marshall stability for unconditioned specimens (kN).

Examination of retained Marshal stability values (Fig. 3) shows that all mixtures had higher RMS than control mixtures. Mixture prepared with $MB_{9.5\%IG}$ had 11.0% higher RMS than the control mixture and $MB_{3.8\%SBS}$ had 10.5% higher RMS than the control mixture. While the retained Marshall stability values of mixtures prepared with $MB_{9.5\%IG}$ and $MB_{3.8\%SBS}$ were higher than 90%, those values of mixtures prepared with $MB_{10\%AG}$ and $MB_{60\%TLA}$ were

Table 6
Volumetric properties of pure and modified mixtures.

Mixture properties	Specification limits	Binder type				
		PG 58-34	$MB_{10\%AG}$	$MB_{9.5\%IG}$	$MB_{60\%TLA}$	$MB_{3.8\%SBS}$
Optimum binder content (%)	–	4.72	4.85	4.91	4.93	4.97
Volume of air voids (Va, %)	4.0	3.97	4.06	3.98	4.08	4.04
Voids in the mineral aggregate (VMA, %)	Min. 14.0	14.36	14.34	14.45	14.26	15.10
Voids filled with asphalt (VFA, %)	65–75	72.37	71.66	72.43	71.38	73.23
Dust proportion (DP)	0.8–1.6	1.30	1.31	1.28	1.33	1.21
%Gmm@Nini. = 8 (%)	Max. 89	85.41	85.69	85.76	85.67	85.66
%Gmm@Ndes. = 100 (%)	96	96.03	95.94	96.02	95.92	95.96
%Gmm@Ndes. = 160 (%)	Max. 98	97.92	97.75	97.83	97.73	96.81

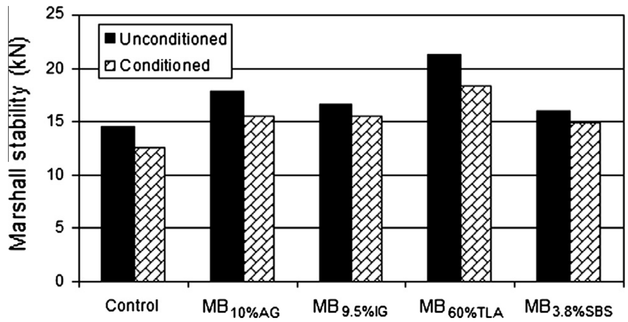

Fig. 1. Marshall stability values of mixtures.

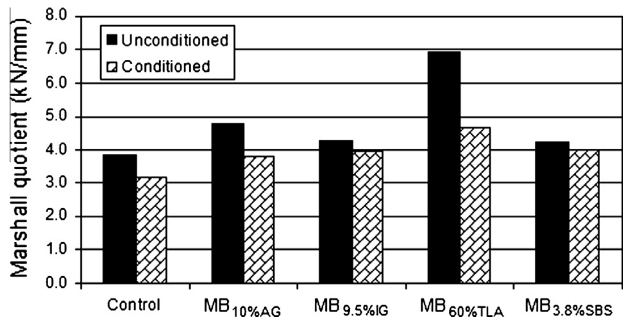

Fig. 2. MQ values of mixtures before and after conditioning.

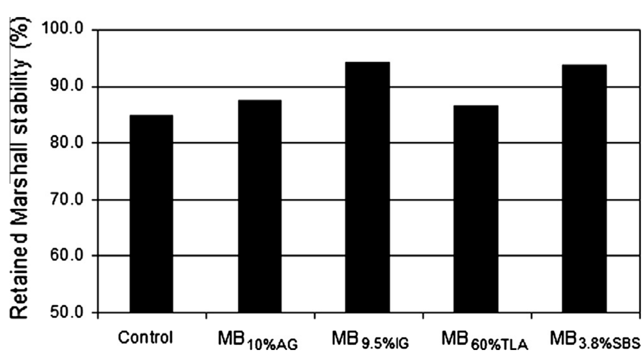

Fig. 3. RMS values of mixtures.

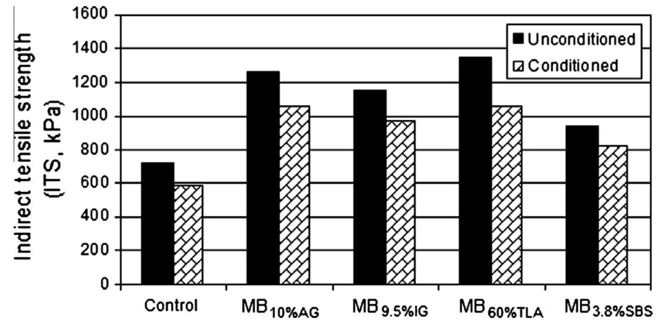

Fig. 4. ITS values of unconditioned and conditioned mixtures.

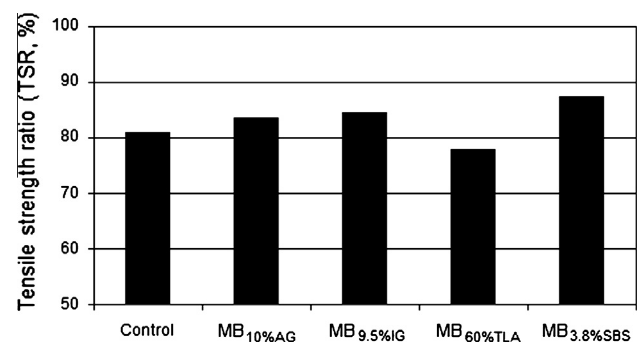

Fig. 5. TSR values of pure and modified binder included mixtures.

lower than 90%. Based on comparison of RMS values, it can be said that resistance of HMAs to moisture-induced damage can be improved especially using Iranian gilsonite and SBS.

3.2. Resistance to moisture-induced damage test

Resistances of the control and modified mixtures to moisture-induced damage were determined according to AASHTO T 283 standard test procedure [20]. The specimens were compacted at 7% ± 0.5% air void content with a Superpave gyratory compactor. The specimens were divided into two groups each of which consisted of 15 mixtures. The mean specific gravities of the specimens in each group were equal. The first group was unconditioned (immersed in water at 25 °C for 2 h), the second group was conditioned (in freezer at −18 °C for 16 h then immersed in water at 60 °C for 24 h and at 25 °C for 2 h). Before the conditioning procedure, the samples were vacuum-saturated so that 70–80% of the encompassed air voids were filled with water. Cylindrical specimens were subjected to compressive loads at a constant rate of 50.8 mm/min which acted parallel to the vertical diametral plane by using the Marshall loading equipment. Based on the maximum level of load at failure, the indirect tensile strength (ITS) in units of kPa is calculated by the following equation:

$$\text{ITS} = 2 * F/\pi * L * D \qquad (2)$$

where F is the peak value of the applied vertical load (kN); L is the mean thickness of the test specimen (m); and D is the specimen diameter (m). Indirect tensile strength (ITS) values of unconditioned and conditioned mixtures are shown in Fig. 4.

Additives increased ITS values in both conditioned and unconditioned samples. Control mixtures had the lowest ITS value among all the prepared mixtures. Mixtures prepared with $MB_{60\%TLA}$ had the highest ITS values before the conditioning (87.2% higher than control mixture), and mixtures prepared with $MB_{10\%AG}$ and $MB_{60\%TLA}$ (80.6% and 79.9% higher than control mixture) had the highest ITS values after the conditioning. All mixtures prepared with natural asphalts had higher ITS values before and after conditioning than the mixture prepared using $MB_{3.8\%SBS}$.

The indirect tensile strength ratio (TSR) was determined as per the equation below:

$$\text{TSR} = 100 * (\text{ITS}_{\text{cond.}}/\text{ITS}_{\text{uncond.}}) \qquad (3)$$

where $\text{ITS}_{\text{cond.}}$ is the indirect tensile strength of the conditioned specimens and $\text{ITS}_{\text{uncond.}}$ denotes the indirect tensile strength of the unconditioned specimens. A TSR value of 0.80 is considered to be the minimum threshold for hot mix asphalts as per the Superpave design procedure. TSR values of mixtures are given in Fig. 5.

As can be seen in Fig. 5, except the mixture prepared with $MB_{60\%TLA}$, all the mixtures met the 80% lower limit on TSR value of Superpave specifications. The highest TSR value, 7.8% higher than the control mixture, was achieved by mixtures prepared with $MB_{3.8\%SBS}$. TSR values of mixtures prepared with $MB_{10\%AG}$, $MB_{9.5\%IG}$ were lower than that of $MB_{3.8\%SBS}$. TSR value of $MB_{10\%AG}$ was 2.8% higher and TSR value of $MB_{9.5\%IG}$ was 4.0% higher than that of the control mixtures. Based on TSR values, it can be said that mixtures

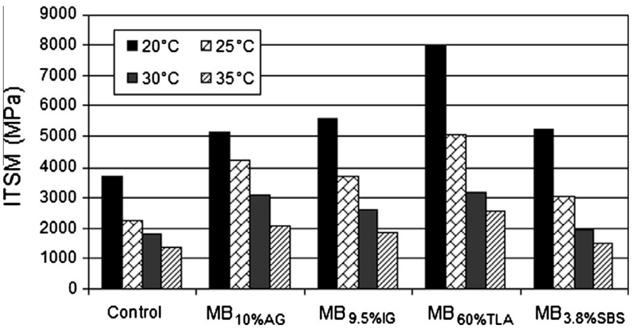

Fig. 6. Variation of ITSM values with temperature.

prepared with $MB_{3.8\%SBS}$ and $MB_{60\%TLA}$ had the highest and the least resistance to moisture induced damage respectively, and mixtures prepared with $MB_{10\%AG}$ and $MB_{9.5\%IG}$ had a similar resistance to moisture induced damage.

3.3. Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus (ITSM) test defined by BS DD 213, is a nondestructive test that can be used to study the effects of temperature and loading rate on relative quality of materials [21]. The ITSM, i.e. S_m, in MPa is defined as

$$S_m = F * (R + 0.27)/(L * H) \quad (4)$$

where, F is the peak value of the vertically applied repeated load (N), H is the mean amplitude of the horizontal deformation (mm) obtained from application of the load pulse from five applications, L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed to be 0.35). The test was performed using 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 consistent and accurate results would be produced. Accordingly, this value was selected as 5 μm in this test. The rise time, which denotes the duration between the origination of load pulse 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 with both control and modified mixtures at four different temperatures (20 °C, 25 °C, 30 °C and 35 °C). The relationships between ITSM values and temperature are shown in Fig. 6.

ITSM values decreased with increasing temperature. ITSM values increased at all temperatures in modified bitumen mixtures compared to control mixtures. At all temperatures, mixtures prepared with $MB_{60\%TLA}$ had the highest ITSM value while control mixtures had the lowest ITSM value. ITSM values of mixtures prepared with $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ were 1.4, 1.5, 2.2 and 1.4 times greater than that of the control mixtures at 20 °C. At 35 °C, mixtures prepared with $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ had respectively 1.5, 1.4, 1.9 and 1.1 times higher ITSM value compared to control mixture. It was determined that ratio of modified binders' ITSM values to control mixtures' ITSM values did not change significantly with the variation of temperature. ITSM values of mixtures prepared with pure binder, $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ decreased 2.8, 2.5, 3.0, 3.2 and 3.5 times respectively with raising the temperature from 20 °C to 35 °C. Results show that mixtures prepared with $MB_{3.8\%SBS}$ were affected most by temperature while mixtures prepared with $MB_{10\%AG}$ were least affected.

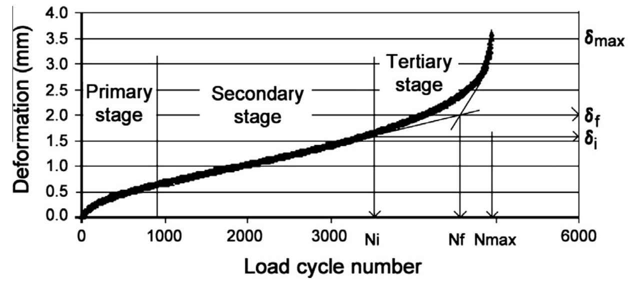

Fig. 7. A representative deformation–load cycle number relationship.

3.4. Indirect tensile fatigue test

The indirect tensile fatigue test is one of the constant stress tests that can characterize the fatigue behaviour of a mixture [22]. In this study, the fatigue tests were performed in controlled stress mode according to BS DD ABF standard [23]. As a result of the stress-controlled fatigue tests, the representative load repetition rate–deformation level graph can be plotted, see Fig. 7.

The response of the material against fatigue loading can be divided into three stages which can be followed by the graph given in Fig. 7. At the primary stage, excessive amount of deformation occurs due to void formation which is followed by a reduction in the axial deformation. At the secondary stage, a constant level of deformation is observed and an approximate linear change takes place. Finally, crack propagation initiates at the tertiary stage, in which the amount of deformation increases [24]. There are special terms defining the fatigue behaviour of a material. Fatigue life is described as the number of cycles at which the tangents drawn to the secondary and tertiary stages intersect with each other [25].

The indirect tensile fatigue test was performed on control and modified mixtures at 25 °C. Three different stress levels (300 kPa, 350 kPa and 400 kPa) were applied during the course of cyclic loading. In all experiments, the loading period and the load rise time were adjusted to be 1.5 s and 0.124 s, respectively. Fig. 8 shows the accumulated deformation versus load cycle at 300 kPa stress level. The corresponding values of N_f and δ_f as well as N_{max} and δ_{max} are given in Fig. 9.

Figs. 8 and 9 show that the load cycle number increased with use of modified binders. N_f values significantly decreased with increasing stress level. At all stress levels, it was observed that the highest N_f value was obtained from the $MB_{60\%TLA}$-containing mixture and the lowest N_f value was obtained from the control mixture. N_f values of mixtures prepared with $MB_{60\%TLA}$ were enhanced 17.8 times, 18.8 times and 12.8 times compared to the control mixture at a stress level of 300 kPa, 350 kPa and 400 kPa, respectively. For N_{max} values, the increase was 17.7 times, 18.4

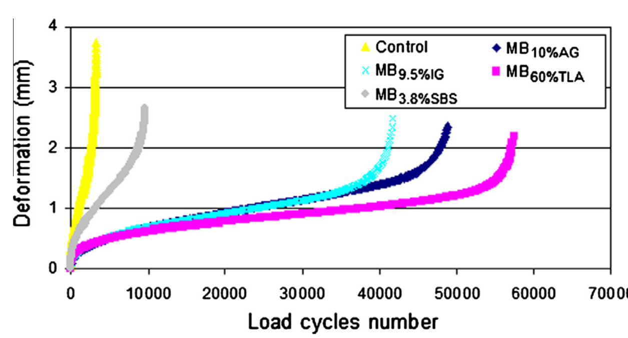

Fig. 8. The variation of deformation with load cycle number at the stress level of 300 kPa.

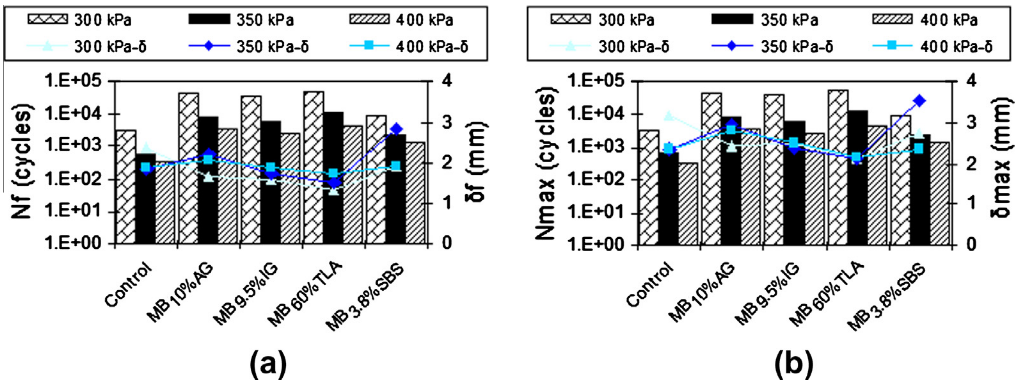

Fig. 9. The variation of N_f, δ_f (a) and N_{max}, δ_{max} (b) values of mixtures with the stress level and modifier type.

times and 12.7 times for the same respective stress levels. It should be noted that the variation in N_{max} value had a similar trend with that of N_f values. The δ_f and δ_{max} values obtained from deformation measurements indicate that the amount of deformation decreased for the $MB_{9.5\%IG}$ and $MB_{60\%TLA}$ including mixtures at all stress levels. This result indicates that the use of $MB_{9.5\%IG}$ and $MB_{60\%TLA}$ makes the mixtures more brittle.

Crack propagation rate (r_p) denotes the load repetition rate required to induce a deformation of 1 mm from initiation of the crack to the end of the fatigue life [26]. The crack propagation rate was determined as per the equation below;

$$r_p = N_p/(\delta_f - \delta_i) \tag{5}$$

where r_p is the crack propagation rate (cycle number/mm), N_p is the load cycle number for crack propagation, δ_f is the total deformation at failure (mm), and δ_i is the total deformation at crack initiation (mm). The crack propagation ratio is inversely proportional to crack propagation rate hence the higher the r_p, the lower the crack propagation ratio and vice versa.

It is known that the level of the tensile stress affects the fatigue life of a material [22]. Relationship between tensile stress and the number of cycles to failure can be determined by the Wohler fatigue prediction model. In logarithmic scale, a linear relationship between stress and number of cycles to failure is obtained and an equation for the prediction of fatigue life is readily developed. The equation developed by using the Wohler's fatigue prediction model is given in the following equation.

$$N_f = k_1 * (\sigma)^{-k_2} \tag{6}$$

Here N_f is the number of cycles to failure of the specimen, σ is the applied stress (kPa) and both k_1 and k_2 are the coefficients related to the properties of the sample examined [22]. In multicomponent systems, like additive-containing HMA, the coefficients k_1 and k_2 directly obtained from the fatigue equations can be used to assess the influence of the additives on fatigue characteristics of the mixtures. The coefficients of Wohler's fatigue prediction model and r_p values are presented in Table 7.

The r_p values showed that crack propagation rate increased with use of modified binder. Increasing stress level caused a decrease in r_p values. The highest bounce in the r_p values of the mixtures compared to the control specimen was observed in the $MB_{60\%TLA}$ containing mixture at 42.3 times. Collectively, crack propagation rates demonstrate that incorporation of $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ or $MB_{3.8\%SBS}$ enhanced the resistance against crack propagation.

Analyzing the data in Table 7 compiled from the fatigue life relationships, it can be seen that there is a high level of coherency in the values such that the coefficient of determination (R^2) was higher than 0.90 in all mixtures. A high value of the coefficient k_2 derived from the slope of the fatigue line indicates that the mixtures were brittle, whereas a low value implies a more resilient behaviour [27]. Amongst all of the mixtures, only the mixtures prepared with $MB_{3.8\%SBS}$ had lower k_2 values, and thus higher elasticity, compared to control mixture. All other mixtures had higher k_2 values and thus lower elasticity than the control mixture. The fatigue test results show that the fatigue life of the mixtures increases as a result of natural asphalt usage, albeit at the cost of exhibiting more brittle behaviour.

3.5. Cyclic creep test

The cyclic creep test is one of the most commonly employed tests for determination of the resistance of hot mix asphalts against permanent deformation. In this test, conducted by 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 help of LVDTs vertically attached onto a metal plate that is fixed onto the surface of the specimen. The creep moduli are obtained from the formulas given below [28];

$$\varepsilon_c = (L3_n - L1)/G \tag{7}$$

$$\sigma = F/A \tag{8}$$

$$E_c = \sigma/\varepsilon_c \tag{9}$$

In these equations, ε_c is the total 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 strain (kPa), F is the maximum vertical load (N), and A denotes the cross-section area of the sample (cm^2). As seen in Eq. (9), the level of plastic strain is inversely proportional to the values of the creep moduli. Thus, it can be stated that an HMA specimen with high creep modulus would exhibit a high resistance against permanent deformation.

Table 7
Indirect tensile fatigue test results.

Binder type	r_p (cycles/mm)			k_1	k_2	R^2
	300 kPa	350 kPa	400 kPa			
PG 58-34	1504	418	203	1.98E + 22	7.62	0.9257
$MB_{10\%AG}$	35438	4906	2133	5.53E + 26	8.93	0.9732
$MB_{9.5\%IG}$	32365	4731	1704	1.60E + 28	9.56	0.9556
$MB_{60\%TLA}$	63601	11071	3264	1.97E + 26	8.72	0.9908
$MB_{3.8\%SBS}$	5739	960	875	2.21E + 20	6.64	0.9243

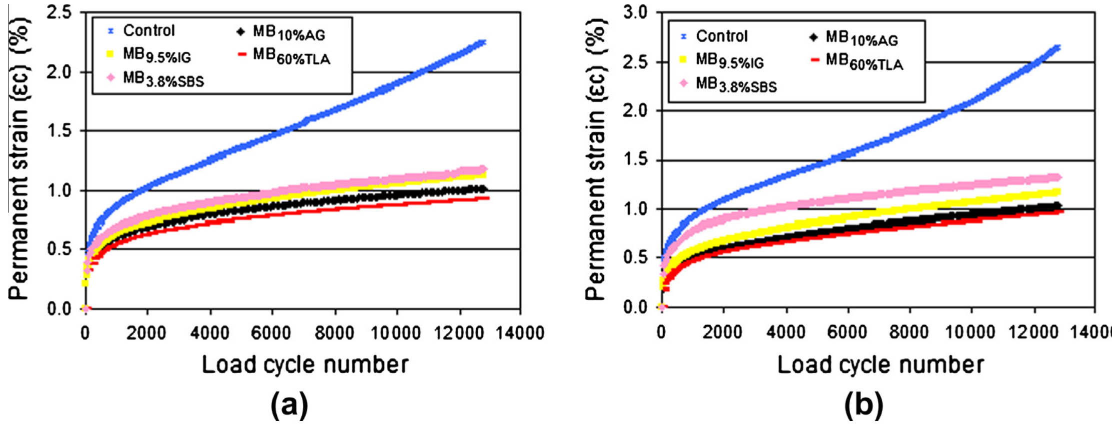

Fig. 10. The amount of permanent deformation of mixtures up to 12,800 cycles at 400 kPa (a) and 500 kPa (b) stress levels.

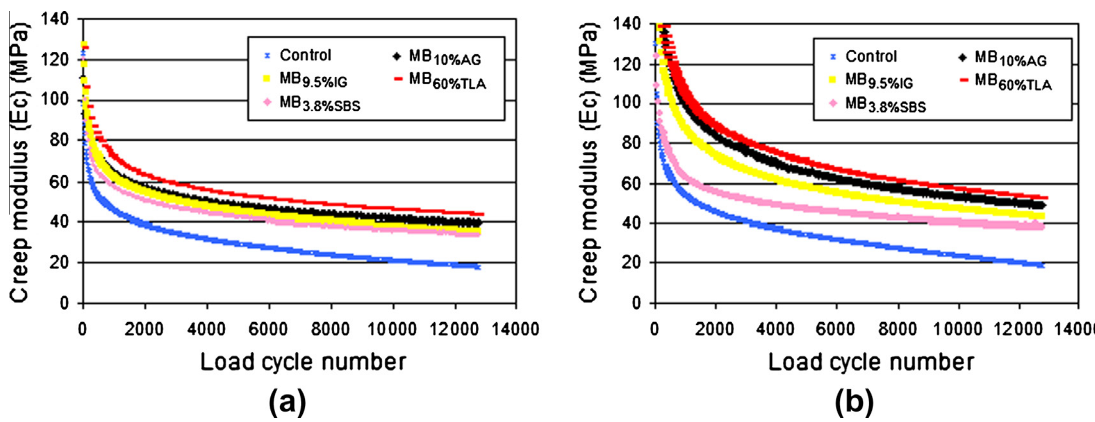

Fig. 11. Creep modulus values of mixtures up to 12,800 cycles at 400 kPa (a) and 500 kPa (b) stress levels.

Cyclic creep tests were performed at 50 °C to determine the resistance of hot mix asphalts against permanent deformation. The stress levels of 400 and 500 kPa were selected. The loading period and the load rise time were selected as 1.0 s and 500 ms, respectively. A static preloading was carried out on the specimens at a stress level of 10 kPa for 90 s prior to the commencement of the test. The earliest failure was seen on control mixtures at 500 kPa stress level (12,800 load cycles). Hence, permanent strain (ε_c) and creep modulus (E_c) values were investigated at 12,800 load cycle numbers for mixtures at 400 and 500 kPa stress levels. The variations of ε_c and E_c values at 400 and 500 kPa stress levels up to the 12,800th cycle are given in Figs. 10 and 11, respectively.

Detailed examination of Fig. 10a and b shows that ε_c values decreased with $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ usage. The highest and lowest values of ε_c at both stress levels belonged to the control mixture and mixture with $MB_{60\%TLA}$, respectively. ε_c values of $MB_{60\%TLA}$-containing mixture after 12,800 load cycles were 2.45 times lower at 400 kPa stress level and 2.78 times lower at 500 kPa stress level, compared to control mixture. It was observed that ε_c values of mixtures prepared with natural asphalts were lower than mixtures prepared with $MB_{3.8\%SBS}$. ε_c values of mixtures prepared with $MB_{3.8\%SBS}$ were 1.92 and 2.00 times less than control mixture at 400 and 500 kPa stress levels respectively.

When the creep modulus values after the first 12,800 load cycles being compared (Fig. 11a and b), a steady decline in E_c values due to the increase in the number of load pulses and the level of ε_c can be clearly observed. The experimental data show that creep modulus values increased with modified binder usage. At the end of 12,800 cycles, creep moduli of the mixtures containing $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ were 2.23, 2.00, 2.45 and 1.92 times higher, respectively, than the control mixture at 400 kPa. Mixtures that contained $MB_{10\%AG}$, $MB_{9.5\%IG}$, $MB_{60\%TLA}$ and $MB_{3.8\%SBS}$ had 2.60, 2.29, 2.78 and 2.00 times higher, respectively, E_c value compared to pure mixture at 500 kPa stress level.

In this context, the decrease in the permanent strain and the increase in the creep moduli of the mixtures following addition of modified binders show that the resistance of hot mix asphalts against permanent deformation is increased by the use of modified binders.

4. Conclusions

In this study, the effects of three different natural asphalts (American gilsonite, Iranian gilsonite and Trinidad Lake Asphalt) and styrene–butadiene polymer (SBS) on bituminous binders and performance of hot mix asphalts were examined. The following conclusions can be drawn from the results obtained from this study:

- $G^*/\sin\delta$ and viscosity values of binders increased with use of AG, IG, TLA and SBS. It was shown that modified binders prepared with pure binder and 10.0% AG, 9.5% IG, 60% TLA and 3.8% SBS had the same performance level (PG 70-34).
- Mixtures prepared with $MB_{60\%TLA}$ were found to have the highest ITS and Marshall stability values. It was seen that mixtures prepared with $MB_{9.5\%IG}$ and $MB_{3.8\%SBS}$ had the highest resistance to moisture induced damage, based on RMS values. Mixtures prepared with $MB_{3.8\%SBS}$ had the highest resistance to moisture induced damage, based on TSR values.

- ITSM and ITFT test results revealed that mixtures prepared with $MB_{60\%TLA}$ had the highest stiffness and longest fatigue life among all other mixtures. Cyclic creep test results showed that mixtures prepared with $MB_{60\%TLA}$ had the highest resistance to permanent deformation.
- Mixtures prepared with $MB_{10\%AG}$ overall showed better performance compared to mixtures prepared with $MB_{9.5\%IG}$. Even though mixtures prepared with $MB_{3.8\%SBS}$ significantly improved the performance of HMA compared to control mixture, they were not as effective as natural asphalts. On the other hand, when efficiency by additive content (1%) usage of additives was taken into account, SBS was found to be most efficient additive.

Acknowledgements

This study was supported by Fırat University Scientific Research Projects Unit (FUBAP) under Project Number MF.13.03. The financial contribution of FUBAP is gratefully acknowledged.

References

[1] Airey GD. Styrene butadiene styrene polymer modification of road bitumens. J Mater Sci 2004;39:951–9.
[2] Janoo VC, Korhonen C. Performance testing of hot-mix asphalt aggregates. US Army Corps of Engineering Project Number: 99-20; 1999.
[3] Roque R, Birgisson B, Drakos C, Sholar G. Guidelines for use of modified binders. Florida Department of Transportation Project Number: 4910-4504-964-12; 2005.
[4] Sengoz B, Isıkyakar G. Evaluation of the properties and microstructure of SBS and EVA polymer modified bitumen. Constr Build Mater 2008;22(9):1897–905.
[5] Kumar P, Chandra S, Bose S. Strength characteristics of polymer modified mixes. Int J Pavement Eng 2006;7(1):63–71.
[6] Tayfur S, Ozen H, Aksoy A. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. Constr Build Mater 2007;21:328–37.
[7] Kok BV, Yilmaz M. The effects of using lime and styrene–butadiene–styrene on moisture sensitivity resistance of hot mix asphalt. Constr Build Mater 2009;23:1999–2006.
[8] Gorkem C, Sengoz B. Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime. Constr Build Mater 2009;23:2227–36.
[9] Aglan H, Othman A, Figueroa L, Rollings R. Effect of styrene–butadiene–styrene block copolymer on fatigue crack propagation behavior of asphalt concrete mixtures. Transp Res Rec 1993;1417:178–86.
[10] Aflaki S, Tabatabaee N. Proposals for modification of Iranian bitumen to meet the climatic requirements of Iran. Constr Build Mater 2009;23:2141–50.
[11] Suo Z, Wong WG. Analysis of fatigue crack growth behavior in asphalt concrete material in wearing course. Constr Build Mater 2009;23:462–8.
[12] Ameri M, Mansourian A, Ashani SS, Yadollahi G. Technical study on the Iranian gilsonite as an additive for modification of asphalt binders used in pavement construction. Constr Build Mater 2011;25(3):1379–87.
[13] Sonmez I, Deniz MT, Tayfur S, Ozen H, Yildirim, SA, Eren BK. Effects of modifiers on the hot mix asphalt performance. In: sixth transportation congress, Istanbul; 2005. p. 334–48.
[14] Huang YH. Pavement analysis and design. 2nd ed. Pearson Prentice Hall; 2004.
[15] Widyatmoko I, Elliott R. Characteristics of elastomeric and plastomeric binders in contact with natural asphalts. Constr Build Mater 2008;22(3):239–49.
[16] Hamidi H. Stiffness modulus and permanent deformation characteristics of asphalt mix containing gilsonite. PhD thesis. Bandung: Bandung Technology Institute; 1998.
[17] Liu J, Li P. Experimental study on gilsonite-modified asphalt. In: Proceeding of the 2008 airfield and highway pavement specialty conference, Washington; 2008. p. 222–8.
[18] EN 12697-34. Bituminous mixtures – test methods for hot mix asphalt – Part 34: Marshall test. European Standard; 2007.
[19] Zoorob SE, Suparma LB. Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (plastiphalt). Cem Concr Compos 2000;22:233–42.
[20] AASHTO T283. Standard method of test for resistance of compacted hot mix asphalt (HMA) to moisture-induced damage, Washington: American Association of State Highway and Transportation Officials (AASHTO); 2003.
[21] BS DD 213. Method for determination of the indirect tensile stiffness modulus of bituminous mixtures. Draft for development, London: British Standards Institution; 1993.
[22] Nejad FM, Aflaki E, Mohammadi MA. Fatigue behavior of SMA and HMA mixtures. Constr Build Mater 2010;24(7):1158–65.
[23] BS DD ABF. Method for determination of the fatigue characteristics of bituminous mixtures using indirect tensile fatigue. Draft for development, London: British Standards Institution; 1997.
[24] Ghile DB. Effects of nanoclay modification on rheology of bitumen and on performance of asphalt mixtures. M.Sc. thesis. Delfth: Department of Road and Railway Engineering, Delfth University of Technology; 2006.
[25] Aragao FTS, Lee J, Kim YR, Karki P. Material specific effects of hydrated lime on the properties and performance behaviour of asphalt mixtures and asphaltic pavements. Constr Build Mater 2010;24(4):538–44.
[26] Subagio BS, Karsaman RH, Adwang J, Fahmi I. Fatigue performance of HRA (hot rolled asphalt) and Superpave® mixes using Indonesian rock asphalt (Asbuton) as fine aggregates and filler. J East Asia Soc Transp Stud 2005;6:1207–16.
[27] Molenaar AAA, Medani TO. Rational testing methods for performance based specifications. In: Proceedings of the first international conference world of asphalt pavements, Sydney; 2000. p. 484–500.
[28] ELE. Universal materials testing apparatus for asphalt and unbound specimens, reference and operating manual.