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Investigating the resistance of asphaltite containing hot mix asphalts against fatigue and permanent deformation by cyclic tests

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Abstract: In this study, the aim was to determine the influence of asphaltite addition on the stiffness of the hot mix asphalts as well as on their resistance against fatigue and permanent deformation through cyclic tests. The asphaltite was included as filler into the hot mix asphalt specimens at five different proportions. The cyclic tests were performed on both the short-term aged and the long-term aged specimens. The study demonstrates that the optimal asphaltite content for utilization as filler with respect to volumetric design is 3% by weight. It was inferred from the results of indirect tensile stiffness modulus test that asphaltite increases the stiffness of hot mix asphalts. Similarly, the indirect tensile fatigue tests demonstrate that the use of asphaltite improves the fatigue life of the hot mix asphalts, albeit causing them to exhibit a more brittle behavior. The cyclic creep tests conducted on the specimens point out that the strength against permanent deformation increases by prolonged aging durations and the mixtures display less elastic behavior with the use of asphaltite.

Key words: hot mix asphalt, asphaltite, fatigue, permanent deformation, cyclic tests.

Résumé : Dans ces travaux on a essayé de préciser la rigidité des chauds mélanges bitumineux par les testes dynamiques, l'influence d'asphaltite sur l'endurance contre la déformation permanente. Asphaltite a été utilisé dans les mélanges bitumineux comme les substances de remplissage cinq proportions différentes en poids. Les testes ont été réalisés sur les échantillons âgés à court ou à long terme. Par conséquent, du point de vue de la conception volumétrique on a déterminé que le contenu d'asphaltite à employer en tant que la substance de remplissage la plus appropriée est 3 % en poids. Il résulte des conséquences de testes que le module de dureté de traction indirecte augmente la rigidité des chaudes mélanges bitumineux. Des testes de tractions de fatigue indirectes résulte que d'autant plus que le contenu d'asphaltite s'augmente plus la durée de fatigue des mélanges s'augmentait mais les mélanges montraient des comportements plus fragiles. A la suite des testes de fluage appliqués aux mélanges on a remarqué que la résistance des mélanges à la déformation permanente s'augmente en raison de l'asphaltite et de LTA, mais que le comportement élastique des mélanges diminue. [Traduit par la Rédaction]

Mots-clés : chaud mélange bitumineux, asphaltite, fatigue, déformation permanente, testes dynamiques.

Introduction

Hot mix asphalts used in highway pavements are produced from the compaction of mixtures comprising bitumen and aggregate at an appropriately high temperature. Asphalt pavements frequently work at severe environmental and loading conditions, e.g., humidity, cyclic variation of temperature, cycling loadings due to traffic. As a result of these, asphalt pavements exhibit many types of failure modes such as moisture damage, permanent deformation, low temperature failure, and fatigue cracking.

Of the many failure modes, fatigue failure is one of the most frequently observed. Fatigue failure is a phenomenon that takes place as a result of small irrecoverable strains building up in the outermost parts of a bituminous bound layer induced by the repetitive wheel loads (Khalid 2000). In the initial stages of fatigue failure, usually microcracks originate and gradually evolve into macrocracks. With further cyclic loading, these macrocracks propagate through the material as a result of the concentrated shear and (or) tensile stresses, which results with sudden failure due to the unstable crack growth (Abo-Qudais and Shatnawi 2007). The distress arising from the fatigue phenomenon begins with the cracking that emerges in the form of map or alligator patterns on the surface (Tapkin 2008).

Rutting is the other common failure mode observed in the asphalt pavements. It is defined as the progressive accumulation of permanent deformation in each layer of the pavement structure under repetitive traffic loading (Tayfur et al. 2007). In terms of the permanent deformation, the most important layer of the pavement is its surface layer being directly exposed to traffic loading (Khodaii and Mehrara 2009). There are basically two mechanisms for rutting, which can take place in different periods of the pavement's service life. The first mechanism, namely initial rutting, occurs in the first few years of the pavement's service life. It emerges from the densification of asphalt mixtures and especially observed in loosely compacted pavements. This initial rutting stage is frequently followed by the second mechanism called shear deformation, which describes the sinking of the material under the axial loading and lateral displacement along the shear plane. In general, shear deformation is the primary rutting mechanism in pavement structures whereas densification is the secondary mechanism (Alavi et al. 2011).

Over the years, different types of materials were proposed as additives into hot mix asphalt (HMA) so as to achieve better road performance (Isacsson and Lu 1995). There are a number of different additives available that can be introduced directly to the asphalt cement (AC) as binder modifier. Styrene-butadiene-styrene (SBS) (Kim et al. 2003; Al-Hadidy and Yi-qiu 2011), ethylene-

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Table 1. Fundamental properties of PG 64-34 binder.

Properties	Binder type	Results	Specification limits
Viscosity (cP, 135 °C)	Original	500	max. 3000
Viscosity (cP, 165 °C)	Original	162.5	—
$G^*/\sin\delta$ (kPa), 64 °C	Original	1.50	min. 1.0
Mixing temperature range (°C)	Original	159–165	—
Compaction temperature range (°C)	Original	145–151	—
Mass loss (%)	RTFOT Residue	0.769	max. 1.0
$G^*/\sin\delta$ (kPa), 64 °C	RTFOT Residue	5.78	min. 2.2
$G^*\sin\delta$ (kPa), 19 °C	PAV Residue	4.58	max. 5000
Creep stiffness (MPa), –24 °C	PAV Residue	225.6	max. 300
m-value, –24 °C	PAV Residue	0.3047	min. 0.300

vinyl-acetate (EVA) (Lu et al. 1999; Airey 2002), and rubber (Kok and Colak 2011) are the most widely used additives for binder modification. Additives can also be added into the mixture in combination with the aggregate (Roque et al. 2005). Hydrated lime (Kok and Yilmaz 2009), carbon black (Geckil 2008), and fly ash (Tapkin 2008) are frequently used for this purpose. Apart from these, natural hydrocarbons, e.g., Trinidad Lake asphalt, asphaltite (Yilmaz et al. 2011), and gilsonite (Liu and Li 2008), are applicable in modification of HMA.

In Turkey, pylon-type natural hydrocarbon deposits at economically feasible thicknesses are located in the provinces of Şirnak and Silopi in Southeastern Anatolia Region. Although the natural hydrocarbons mined from this region are classified between asphaltite and pyrobitumens with respect to their solubility in carbon disulfide, they are collectively named as asphaltite. The estimated asphaltite reserves of the Southeastern Anatolia Region of Turkey is around 82 million tonnes, of which 44.5 million are proved reserves (Kavak 2011).

Various types of mechanical tests could be performed to understand the long-term response of the HMA in severe environmental and loading conditions. It is apparent that to investigate the resistance of hot mix asphalts against traffic loads, constant rate loading tests remain largely inadequate in simulation of the field conditions in a laboratory environment. Hence, cyclic tests were increasingly adopted instead of static tests.

In this study, mixtures of asphaltite and HMA were prepared at five different proportions in which the asphaltite was added into the HMA as filler so as to improve its resistance against fatigue failure and permanent deformation. The mechanical performance of the mixtures as well as control specimens were examined by various laboratory tests such as indirect tensile stiffness modulus test (ITSM), indirect tensile fatigue test (ITFT), and cyclic creep test. The results of the tests were discussed in detail to identify to what extent the filler addition improves the mechanical response of HMA.

Materials and sample preparation

An asphalt cement, PG 64-34, purchased from Turkish Petroleum Refineries was used as binder for the mixture preparation. For binder, the mixing and compaction temperatures at viscosity values of 170 ± 20 and 280 ± 30 cP (1 cP = 0.001 Pa·s) respectively, were used. The rheological properties of bitumen and AASHTO M320 binder specification limits are given in Table 1.

Limestone aggregate was used for the asphalt mixtures. The properties of aggregate are given in Table 2. A crushed coarse and fine aggregate with a maximum grain size of 19 mm was chosen for a dense graded asphalt mixture. The gradation of the aggregate mixtures is given in Fig. 1. The asphaltite was supplied from an asphaltite mine in Silopi region of Turkey. Because of its low hardness value, i.e., approximately 2 on the Mohs scale, the asphaltite was ground up and the particles smaller than 0.075 mm were assorted to be used as filler in HMA.

In this study, six different types of mixtures, one control mixture and five tests mixtures with asphaltite, were investigated.

The only filler in the control mixture is limestone, whereas in the test mixtures, asphaltite was also entrained ranging from 1 to 5 wt.% by partially replacing limestone. The optimum bitumen contents of the mixtures were determined in accordance with Superpave mix design. The volumetric properties and specification limits of the pure and asphaltite containing mixtures prepared at the optimum levels of bitumen content are presented in Table 3. Accordingly, as the proportion of asphaltite is increased, the optimum bitumen content decreases. As seen in Table 3, the mixtures containing 4% and 5% asphaltite were also subjected to the tests despite failing to meet the Superpave specification criteria, for the sole purpose of investigating the influence of asphaltite at a wider scope. In addition, short-term aged mixtures compacted at the optimum levels of bitumen content were subjected to long-term ageing by exposure to heat in an air-circulation oven at 85 °C for 120 h (Bell et al. 1994).

Test methods

Indirect tensile stiffness modulus test

The indirect tensile stiffness modulus (ITSM) test is a nondestructive test that can be used to study the effects of temperature and loading rate on relative quality of materials. Defined by BS DD 213, the repeated-load indirect tensile stiffness modulus test is frequently used for this purpose (BS DD 213, 1993). The ITSM, i.e., S_m , in MPa is defined as

$$[1] \quad S_m = F(R + 0.27)/LH$$

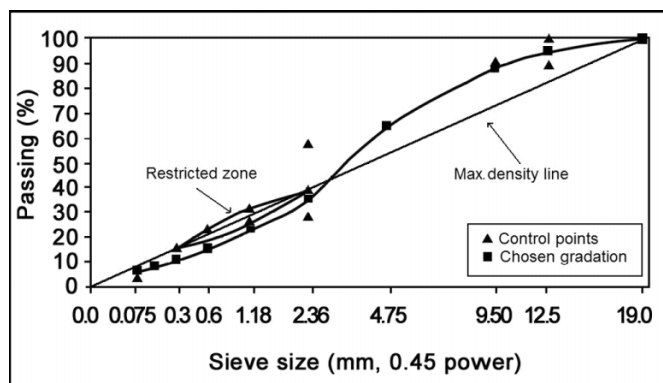
where F is the peak value of the vertically applied repeated load, H is the mean amplitude of the horizontal deformation (mm) obtained from application of the load pulse for five times, L is the mean thickness of the test specimen (mm), and R is the Poisson's ratio (assumed to be 0.35). The test was 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 that would produce consistent and accurate results. Accordingly, this value was selected as 5 μ m 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.

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 (Nejad et al. 2010). In this study, the fatigue tests were performed in controlled stress mode according to BS DD ABB standard (BS DD ABB, 1995). As a result of the stress-controlled fatigue tests, the representative load repetition rate – deformation level graph can be plotted, see Fig. 2.

Table 2. Physical properties of aggregate.

Properties	Standard	Aggregate			
		Coarse	Fine	Filler	Asphaltite
Abrasion loss (%) (Los Angeles)	ASTM DC131	29	—	—	—
Frost action (%) (with Na ₂ SO ₄)	ASTM C88	4.5	—	—	—
Coarse aggregate angularity (%)	ASTM D5821	98/96	—	—	—
Fine aggregate angularity (%)	AASHTO T304	—	49	—	—
Flat, elongated particles (%)	ASTM D4791	2	—	—	—
Specific gravity (g/cm ³)	ASTM C127	2.675	—	—	—
Specific gravity (g/cm ³)	ASTM C128	—	2.687	—	—
Specific gravity (g/cm ³)	ASTM D854	—	—	2.711	1.483

Fig. 1. Aggregate gradation.

The response of the material against fatigue loading can be divided into three stages, which can be followed by the graph given in the Fig. 2. At the primary stage, excessive amount of deformation occurs due to void formation that 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 (Ghile 2006).

There are special terms defining the fatigue behavior 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 (Aragao et al. 2010). 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 (Subagio et al. 2005). The formula yielding the crack propagation rate is given by the following below:

$$[2] \quad r_p = N_p / (\delta_f - \delta_i)$$

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 can have an influence on the fatigue life of a material. Relationship between tensile stress and the number of cycles to failure can be determined by Wohler fatigue prediction model. In logarithmic scale, a linear relationship between stress and number of cycles to failure is obtained and equation for the prediction of fatigue life is readily developed. The equation developed by using the Wohler's fatigue prediction model is given in Fig. 3.

$$[3] \quad N_f = k_1(\sigma)^{-k_2}$$

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 (Nejad et al. 2010). 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. A large value of the exponential coefficient k_2 indicates a less inclined slope for the fatigue line. For mixtures with equal values of k_1 , the one with the higher k_2 exhibits longer fatigue life. On the other hand, if mixtures with same k_2 values are compared to each other, it can be stated that the one with lower value of k_1 has shorter fatigue life (Simms 1998).

Cyclic creep test

To determine the resistance of hot mix asphalts against permanent deformation, one of the most commonly employed tests is the cyclic creep test. In this test, conducted by UTM, a constant load is dynamically applied at a certain periodic rate onto a cylindrical specimen. The plastic and elastic strains induced by the load cycles are determined by the help of LVDTs vertically attached onto the metal plate that is fixed onto the surface of the specimen. The creep and resilient moduli could be obtained from the following formulas (ELE 1994):

$$[4] \quad \varepsilon_c = (L3_n - L1)/G$$

$$[5] \quad \varepsilon_r = (L2_n - L3_n)/[G - (L3_n - L1)]$$

$$[6] \quad \sigma = F/A$$

$$[7] \quad E_c = \sigma/\varepsilon_c$$

$$[8] \quad E_r = \sigma/\varepsilon_r$$

In these equations, ε_c is the total plastic strain (%), ε_r is the total elastic strain (%), E_c is the creep modulus (MPa), E_r is the resilient modulus (MPa), G is the initial height of the specimen (mm), $L1$ is the initial reference displacement of LVDT (mm), $L2_n$ is the maximum amount of displacement at n number of pulses (mm) (elastic + plastic), $L3_n$ 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 (cm²). As seen in eqs. [7] and [8], the levels of plastic and elastic strain are inversely proportional to the values of the creep and resilient moduli. Thus, it can be stated that a HMA specimen with high creep modulus value would exhibit a high resistance against permanent deformation, while if it has high resilient modulus it would be expected to display limited elastic behavior.

Another parameter that shows the resistance of HMAs against permanent deformation is the flow number (FN). A deformation vs. change in the load cycle number curve similar to that generated by the fatigue test could be obtained from the cyclic creep test. The transition point from the secondary stage to tertiary

Table 3. Volumetric properties of neat and asphaltite modified mixtures.

Mixture properties	Specification limits	Asphaltite content (%)					
		0	1	2	3	4	5
Optimum binder content (%)	—	5.27	5.19	5.15	5.10	5.08	5.04
Volume of air voids (V_a , %)	4.0	4.00	4.01	4.05	3.98	3.98	4.03
Voids in the mineral aggregate (VMA, %)	min. 14.0	15.44	15.00	14.52	14.01	13.38	13.10
Voids filled with asphalt (VFA, %)	65–75	74.12	73.27	72.15	71.58	70.27	69.21
Dust proportion (DP)	0.8–1.6	0.98	1.02	1.07	1.11	1.18	1.22
$\%G_{mm}@N_{ini} = 8$ (%)	max. 89	85.56	85.59	84.97	85.28	85.64	85.56
$\%G_{mm}@N_{des} = 100$ (%)	96	96.00	95.99	95.95	96.02	96.02	95.97
$\%G_{mm}@N_{des} = 160$ (%)	max. 98	96.55	97.29	97.11	97.30	97.77	97.52

Fig. 2. A representative deformation–load cycle number relationship.

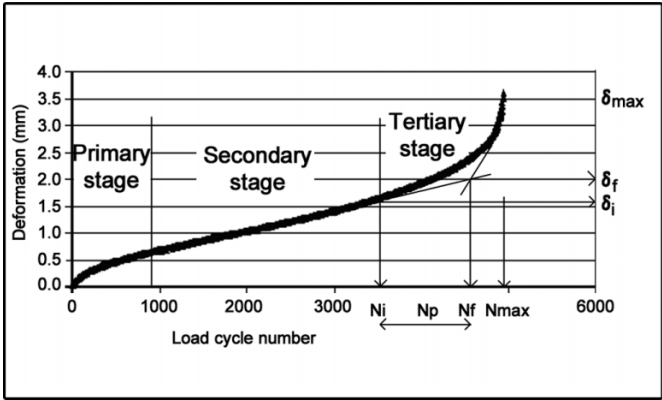
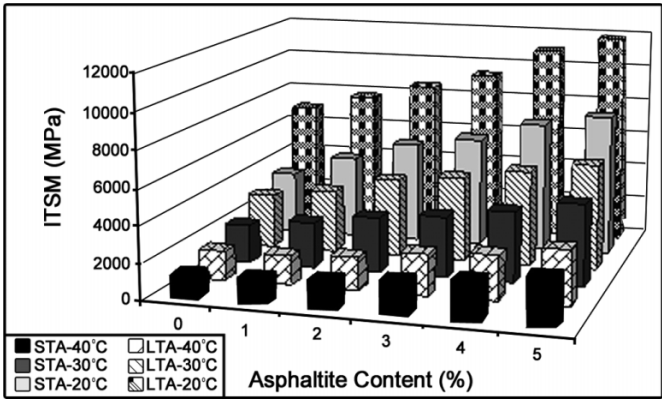


Fig. 3. The variation of ITSM with temperature and asphaltite content.



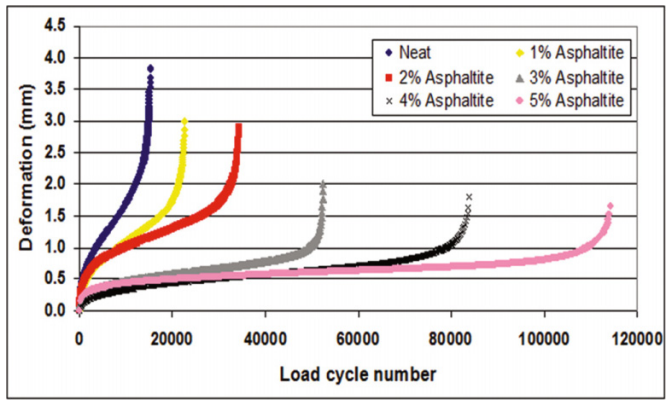
stage in this curve is taken as the flow number. The flow number could also be obtained from the load cycle versus creep modulus $\times$ load cycle plot, where the peak value of the graph is used for its calculation (Goh and You 2009). It was determined that flow numbers calculated by the latter method are more repeatable compared to the slope method described above. Hence, in this study the second method is utilized to determine the flow number values.

Results and discussions

Results of the indirect tensile stiffness modulus test

Indirect tensile stiffness modulus tests were performed on both short-term aged (STA) and long-term aged (LTA) specimens at three different temperatures, i.e., 20 °C, 30 °C, and 40 °C. The results of the ITSM tests are given in Fig. 3, where each value denotes the mean value of three specimens.

Fig. 4. The variation of deformation with load cycle number for LTA mixtures at the stress level of 300 kPa.



As seen in Fig. 3, ITSM values increase with increasing asphaltite content at all temperature levels. However, increasing temperature results in lower ITSM values, holding all other factors constant. Further examinations of the ITSM data also show that the stiffness of the mixtures escalates when the aging is long term.

The study points out that the amount of asphaltite addition is also decisive on ITSM values. At all temperature levels, the lowest and highest values of ITSM were measured in the control mixture and the 5% asphaltite containing mixture, respectively. However, the difference between maximum and minimum values slightly depends on the temperature at which the experiment was conducted, i.e., for STA specimens, 2.3 times at 20 °C, 2.2 times at 30 °C, and 2.1 times at 40 °C; for LTA specimens 1.7 times at 20 °C, 2.0 times at 30 °C, and 1.9 times at 40 °C. The obtained results demonstrate that the entrainment of asphaltite enhanced the stiffness of HMA at all temperature levels, while the increase is less pronounced for LTA specimens.

Indirect tensile fatigue test results

The indirect tensile fatigue test was performed on pure (control) mixture and asphaltite added HMA mixtures of five different asphaltite contents, from 1% to 5%, at room temperature. Including LTA and STA samples, in total 108 specimens with 3 specimens for each type of mixture were examined by this method. Three different stress levels (300 kPa, 375 kPa, and 450 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.

Figure 4 shows the accumulated deformation versus load cycle graph at 300 kPa stress level for LTA specimens. The corresponding values of N_f and δ_f as well as N_{max} and δ_{max} are given in Fig. 5 and Fig. 6, respectively. The coefficients of Wohler's fatigue prediction model and r_p values are presented in Table 4.

Figures 4, 5, and 6 show that the load cycle number increases with increasing amount of asphaltite. At all stress levels, it was

Fig. 5. The variation of N_f and δ_f values of (a) STA and (b) LTA mixtures with the stress level and asphaltite content.

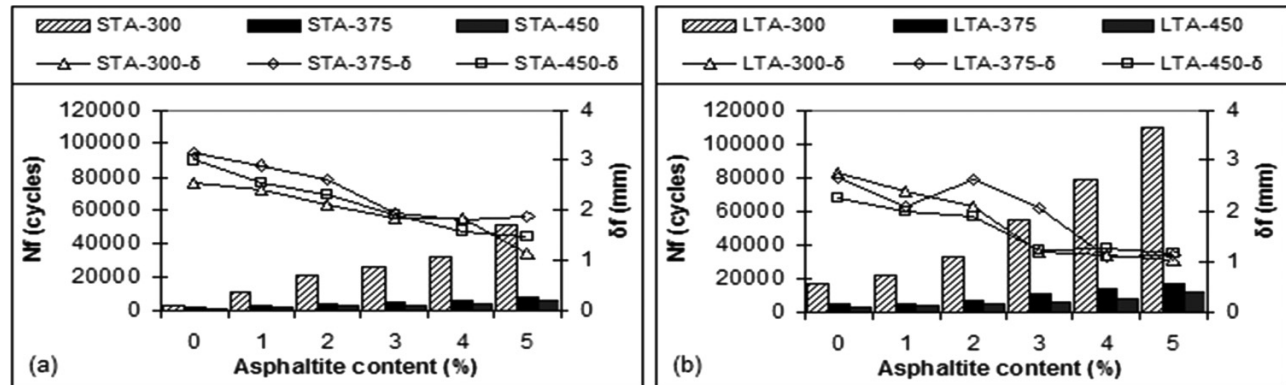


Fig. 6. The relation between N_{max} and δ_{max} values with the stress level and asphaltite content.

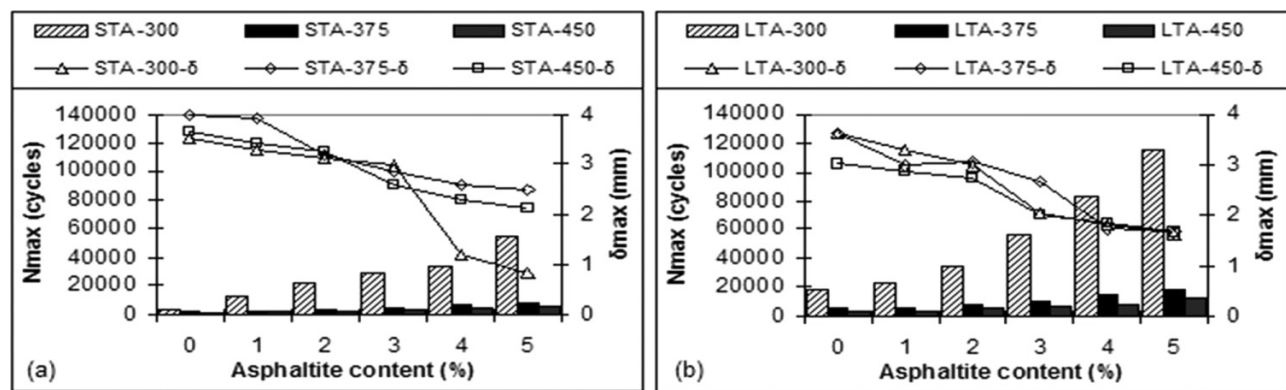


Table 4. Indirect tensile fatigue test results.

Asphaltite content (%)		r_p (cycles/mm)			k_1	k_2	R^2
		300 kPa	375 kPa	450 kPa			
0	STA	1111	645	384	1.09E+10	2.62	0.9350
	LTA	5941	1644	1343	7.35E+14	4.31	0.9702
1	STA	3972	952	1071	2.54E+14	4.21	0.9221
	LTA	8184	2511	1711	1.25E+15	4.37	0.9344
2	STA	8537	1327	1172	1.15E+17	5.17	0.9089
	LTA	15263	2549	2476	5.55E+15	4.56	0.9204
3	STA	14180	1909	1702	1.42E+17	5.17	0.9005
	LTA	47227	4636	4054	6.82E+17	5.31	0.9277
4	STA	16889	3255	2471	2.45E+17	5.22	0.9301
	LTA	63345	10181	6182	7.71E+18	5.68	0.9271
5	STA	44362	4373	3195	3.86E+17	5.24	0.8863
	LTA	102391	13038	8251	1.59E+19	5.75	0.9028

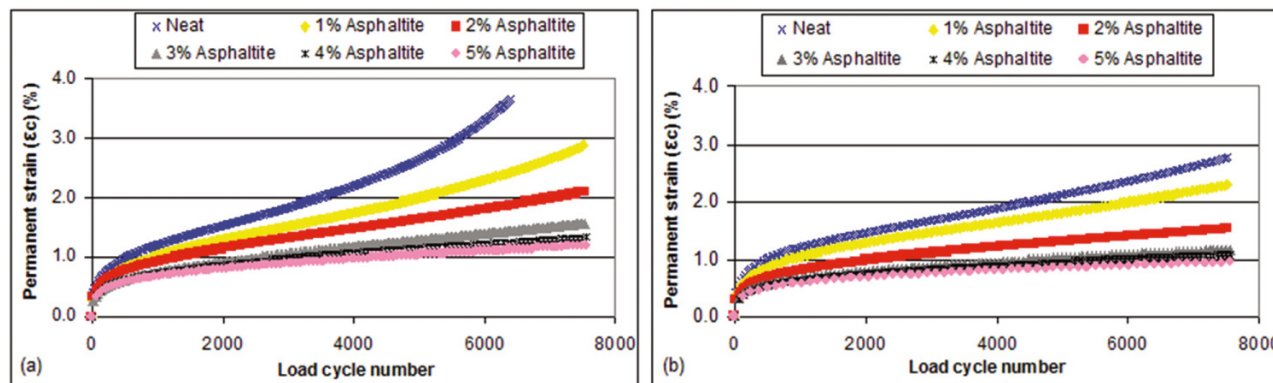
observed that the highest and the lowest N_f values were obtained from 5% asphaltite containing mixture and the pure mixture, respectively. In fact, the variation in the N_f value when the asphaltite content is increased from 0% (pure mixture) to 5% remarkably depends on the level of applied stress. For STA mixtures, using 5% asphaltite content enhanced the N_f value by 14.5 times, 4.0 times, and 5.2 times compared to the pure mixture, at a stress level of 300 kPa, 375 kPa, and 450 kPa, respectively. For LTA mixtures, the increase is 6.7 times, 3.2 times, and 3.9 times for the same respective stress levels. It should be noted that the variation in N_{max} value has a similar trend with N_f values.

The δ_f and δ_{max} values obtained from deformation measurements point out that the amount of deformation generally decreases as the asphaltite content increases. This observation implies that the use of asphaltite induces a more brittle behavior

to the mixtures. The r_p values showed that crack propagation rate increases with increasing asphaltite content. Meanwhile, it was detected that the application of the long-term aging is effective on the amount of the deformation. It was determined that the application of long-term aging causes an increase in r_p values. The highest spike in the r_p values of the mixtures compared to the control specimen was observed in the STA 5% asphaltite containing mixture at 39.9 times. Collectively, crack propagation rates demonstrate that entraining asphaltite as into the filler enhances the resistance against crack propagation. However, performing strain-controlled fatigue tests on pure and asphaltite added mixtures can be useful to reach a solid conclusion.

Analyzing the data in Table 4 compiled from the fatigue life relationships, it can be seen that there is a high level of coherency in the values and the coefficient of determination (R^2) is higher

Fig. 7. The amount of permanent deformation for (a) STA and (b) LTA mixtures up to 7500 cycles.



than 0.90 in all mixtures. It was also found that the values of the coefficients k_1 and k_2 increase with increasing asphaltite content and with the application of long-term aging. A high value of the coefficient k_2 derived from the slope of the fatigue line indicates a brittle behavior possessed by the mixtures, whereas a low value implies a more resilient behavior (Molenaar and Medani 2000). The fatigue test results show that the fatigue life of the mixtures increases as a result of asphaltite usage and long-term aging, albeit at the cost of exhibiting more brittle behavior.

Results of the cyclic creep test

Cyclic creep tests were performed at 50 °C to determine the resistance of hot mix asphalts against permanent deformation. The stress level was selected as 500 kPa so that the primary, secondary, and tertiary stages could be observed separately (Tapkin et al. 2009). 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 the stress level of 10 kPa for 90 s prior to the commencement of the test. In the study, the repeated load was applied until the point of failure in the specimens. The flow numbers were determined by fitting 2nd degree polynomial equations into the creep modulus $\times$ load cycle number against cycle number plots. In the study, the permanent strain (ϵ_c), resilient modulus (E_r), and creep modulus (E_c) values were investigated at the end of the 7500th cycle and at a specified flow number. Up to the 7500th cycle, the variations of ϵ_c , E_r , and E_c are given in Fig. 7, Fig. 8, and Fig. 9, respectively. The presented data are the average values obtained from the three specimens of the same type.

The detailed examination of Fig. 7a and 7b shows that ϵ_c values in both STA and LTA mixtures decrease with increasing asphaltite content up to first 7500 cycles. The highest and lowest values of ϵ_c belong to the pure mixture and mixture with 5% asphaltite, respectively. Except for STA pure mixture and the 1% asphaltite containing mixtures, the tertiary stage was not observed up to 7500 cycles. In this cycle period, mixtures with 3%, 4%, and 5% asphaltite show severe resistances against permanent deformation. Among STA mixtures, the level of ϵ_c at the end of 7500 load cycles reduced by 2.6 times in the 3% asphaltite containing mixture and 3.5 times in the 5% mixture. As for the LTA mixtures, the ϵ_c values fell by 2.2 times for the mixture containing 3% asphaltite and 2.7 times for the 5% mixture.

Figures 8a and 8b show that the resilient moduli (E_r) of the mixtures increases after the primary loading. The following trend, however, show variation with the type of the mixture; a clear decline in the cases of pure and 1% asphaltite containing mixture whereas a constant trend in the cases of 4% and 5% asphaltite containing mixtures. This situation indicates that the pure and 1% asphaltite containing mixtures display a more elastic behavior after 1000–2000 cycles despite the emergence of early deformation. At the completion of the first 7500 pulses, it was

determined that the highest resilient modulus belonged to the 4% asphaltite containing mixture, which was 39.7% higher than the pure mixture prior to long-term aging. The increase in the value is 44.5% in case of long-term aging.

When the creep modulus values after the first 7500 load cycles are compared, see Fig. 9a and 9b, a steady decline in E_c values could be clearly observed due to the increase in the number of load pulses and the level of ϵ_c . The experimental data show that creep modulus values increase with increasing asphaltite content. Among the LTA mixtures, the creep moduli for the pure and the 1% asphaltite containing mixtures exhibited similar variations with those of the 3%, 4%, and 5% asphaltite containing mixtures along with the increase in load cycle number. At the conclusion of 7500 cycles, creep moduli of the mixture containing 5% asphaltite increased by 3.21 times compared to the pure mixture prior to long-term aging. There is a 2.71 fold increase in the value in the case of long-term aging.

It was determined that the flow number value of 5% asphaltite containing LTA specimens is greater than the maximum value (65 000) allowed by the software. For this reason, the flow number of these particular specimens was derived from the curve fitted on the plot of the creep modulus $\times$ load cycle vs. load cycle number while the corresponding ϵ_c , E_r , and E_c variables could not be obtained. Nevertheless, it is seen from Table 5 that the flow numbers display a steady rise with increasing asphaltite content. Among STA mixtures, it was determined that the flow number of 3% asphaltite containing mixture is 2.32 times higher than that of the pure mixture, whereas the corresponding increase for the 5% mixture is 5.51 times. As for LTA mixtures, using 3% asphaltite enhanced the flow number by 3.84 times while using 5% asphaltite increased the same value by 8.40 times.

In view of the permanent strain (ϵ_c) values at the flow number, the highest value belongs to the pure mixture whereas the lowest one belongs to the mixture with 3% asphaltite. The analysis of the resilient moduli (E_r) at the flow number shows that the moduli increase with increasing asphaltite content. The lowest resilient modulus value belongs to the pure mixtures for both STA and LTA mixtures. The maximum value, on the other hand, is reached at 5% asphaltite addition in STA mixtures while it is obtained at 4% addition in LTA samples. These results imply that at the load cycle giving the same flow number, the mixtures containing higher proportions of asphaltite (3%–5%) display more inelastic behavior, while the pure mixture possesses the highest elasticity among all.

Analyzing the creep modulus (E_c) values at the flow number, an escalation was observed as the asphaltite content increased. Among the STA mixtures, the creep modulus value at the flow number increased by 18.6% relative to the pure mixture for the 3% asphaltite containing mixture, while the corresponding increase was 10.4% when 5% asphaltite was used. As for the LTA mixtures,

Fig. 8. Resilient modulus values of (a) STA and (b) LTA mixtures up to 7500 cycles.

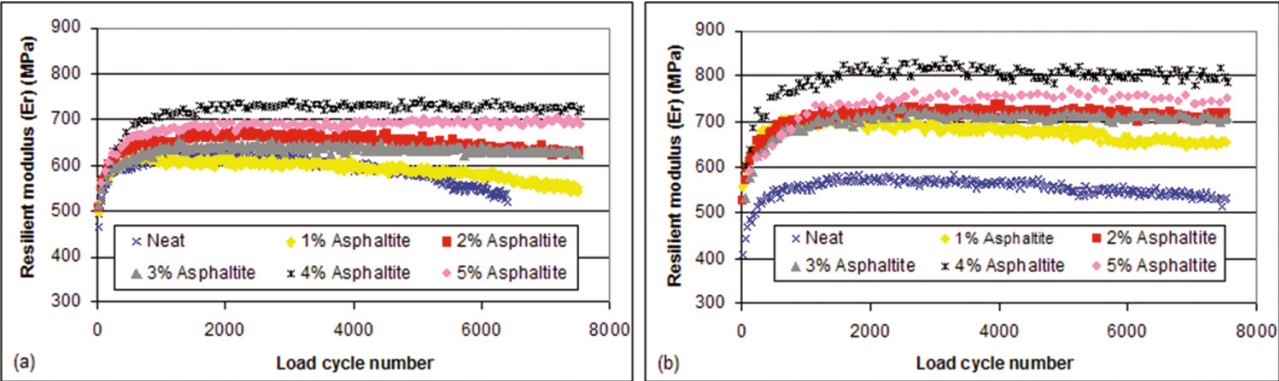


Fig. 9. Creep modulus values of (a) STA and (b) LTA mixtures up to 7500 cycles.

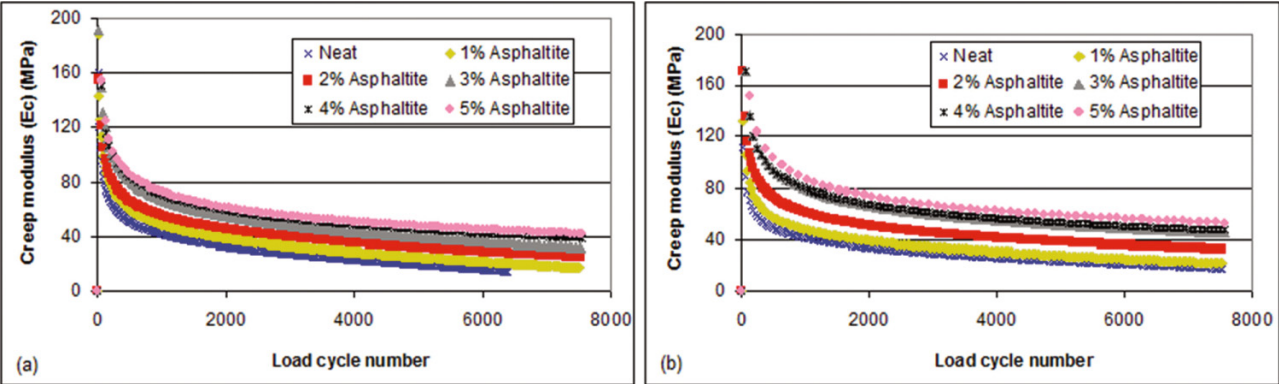


Table 5. Dynamic creep test results.

	Asphaltite content (%)											
	0		1		2		3		4		5	
	STA	LTA	STA	LTA	STA	LTA	STA	LTA	STA	LTA	STA	LTA
FN	5153	8093	6698	9707	9735	16340	11966	31112	23699	40683	28375	67984
ϵ_c @ FN (%)	2.62	2.94	2.53	2.80	2.52	2.46	2.22	2.38	2.53	2.52	2.37	—
E_r @ FN (MPa)	579	526	560	623	600	661	605	669	657	742	676	—
E_c @ FN (MPa)	19.1	17.0	19.8	17.9	20.4	20.3	22.7	21.9	20.7	20.0	21.1	—

the highest rise in creep modulus compared to the pure mixture was determined in the 3% mixture as 29.2%. In this context, the increase in the flow number and creep moduli with increasing asphaltite content shows that the resistance of hot mix asphalts against permanent deformation is augmented by the use of asphaltite, while the rise in resilient modulus indicates a reduction in elastic behavior.

Conclusions

In this study, five different proportions of asphaltite were entrained as filler into the HMAs. Both asphaltite filler containing and control HMAs were subjected to three different mechanical tests to elucidate their long-term mechanical performances. The effect of short and long-term aging on mechanical performance of the mixtures was also examined in this context. Based on the results obtained from this study, the following conclusions could be drawn:

- It was demonstrated by ITSM tests conducted at 20, 30, and 40 °C that the stiffness of the mixtures rises to higher values as the asphaltite content is increased.
- Fatigue life (N_f) and the maximum number of load cycles (N_{max}) increase with increasing asphaltite content. The decline in the

- δ_f and δ_{max} values with increasing asphaltite content points out an increase in the brittleness.
- The increases in flow number and creep modulus with increasing asphaltite content indicate to an improved resistance of hot mix asphalts against permanent deformation, while the rise in resilient modulus implies a decrease in the elasticity.
 - Long-term aging increases the ITSM, fatigue life, flow number, creep and resilient modulus values.

As a comprehensive assessment of the overall results obtained in the study, it can be concluded that the use of asphaltite would reduce the bitumen requirement, enhance the resistance against permanent deformation and fatigue, while it increases the brittleness of the mixtures.

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References

- Abo-Qudais, S., and Shatnawi, I. 2007. Prediction of bituminous mixture fatigue life based on accumulated strain. *Construction and Building Materials*, **21**(6): 1370–1376. doi:10.1016/j.conbuildmat.2005.09.004.
- Airey, G.D. 2002. Rheological evaluation of ethylene vinyl acetate polymer modified bitumens. *Construction and Building Materials*, **16**(8): 473–487. doi:10.1016/S0950-0618(02)00103-4.
- Alavi, H.A., Ameri, M., Gandomi, A.H., and Mirzahosseini, M.R. 2011. Formulation of flow number of asphalt mixes using a hybrid computational method. *Construction and Building Materials*, **25**(3): 1338–1355. doi:10.1016/j.conbuildmat.2010.09.010.
- Al-Hadidy, A.I., and Yi-qiu, T. 2011. Effect of styrene-butadiene-styrene on the properties of asphalt and stone-matrix-asphalt mixture. *Journal of Materials in Civil Engineering*, **23**(4): 504–510. doi:10.1061/(ASCE)MT.1943-5533.0000185.
- Aragao, F.T.S., Lee, J., Kim, Y.R., and Karki, P. 2010. Material specific effects of hydrated lime on the properties and performance behaviour of asphalt mixtures and asphaltic pavements. *Construction and Building Materials*, **24**(4): 538–544. doi:10.1016/j.conbuildmat.2009.10.005.
- Bell, C.A., Wahab, A.Y., Cristi, M.E., and Sosnovske, D. 1994. Selection of laboratory aging procedures for asphalt-aggregate mixtures. Strategic Highway Research Program, SHRP-A-383, National Research Council, Washington D.C.
- BS DD 213. 1993. Method for determination of the indirect tensile stiffness modulus of bituminous mixtures. Draft for Development, British Standards Institution, London, United Kingdom.
- BS DD ABE. 1997. Method for determination of the fatigue characteristics of bituminous mixtures using indirect tensile fatigue. Draft for Development, British Standards Institution, London, United Kingdom.
- ELE. 1994. Universal materials testing apparatus for asphalt and unbound specimens, Reference and Operating Manual, ELE International Ltd., Hertfordshire, UK.
- Geckil, T. 2008. Research on the effect of carbon black on the features of hot mix asphalt. Ph.D. thesis, Department of Civil Engineering, Firat University, Elazig, Turkey (In Turkish).
- Ghile, D.B. 2006. Effects of nanoclay modification on rheology of bitumen and on performance of asphalt mixtures. M.Sc. thesis, Department of Road and Railway Engineering, Delfth University of Technology, Delfth, Netherlands.
- Goh, S.W., and You, Z. 2009. A simple stepwise method to determine and evaluate the initiation of tertiary flow for asphalt mixtures under dynamic creep test. *Construction and Building Materials*, **23**(11): 3398–3405. doi:10.1016/j.conbuildmat.2009.06.020.
- Isacsson, U., and Lu, X. 1995. Testing and appraisal of polymer modified road bitumens - state of the art. *Materials and Structures*, **28**(3): 139–159. doi:10.1007/BF02473221.
- Kavak, O. 2011. Organic geochemical comparison of asphaltites of Sýrnak area with the oils of the Raman and Dincer fields in southeastern Turkey. *Fuel*, **90**(4): 1575–1583. doi:10.1016/j.fuel.2010.10.055.
- Khalid, H.A. 2000. A comparison between bending and diametral fatigue tests for bituminous materials. *Materials and Structures*, **33**(7): 457–465. doi:10.1007/BF02480666.
- Khodaii, A., and Mehrara, A. 2009. Evaluation of permanent deformation of unmodified and SBS modified asphalt mixtures using dynamic creep test. *Construction and Building Materials*, **23**(7): 2586–2592. doi:10.1016/j.conbuildmat.2009.02.015.
- Kim, K.W., Kweon, S.J., Doh, Y.S., and Park, T.S. 2003. Fracture toughness of polymer-modified asphalt concrete at low temperatures. *Canadian Journal of Civil Engineering*, **30**(2): 406–413. doi:10.1139/l02-101.
- Kok, B.V., and Yilmaz, M. 2009. The effects of using lime and styrene-butadiene-styrene on moisture sensitivity resistance of hot mix asphalt. *Construction and Building Materials*, **23**(5): 1999–2006. doi:10.1016/j.conbuildmat.2008.08.019.
- Kok, B.V., and Colak, H. 2011. Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt. *Construction and Building Materials*, **25**(8): 3204–3212. doi:10.1016/j.conbuildmat.2011.03.005.
- Liu, J., and Li, P. 2008. Experimental study on gilsonite-modified asphalt. In *Proceedings of the 2008 Airfield and Highway Pavements Conference*, 15-18 October 2008. American Society of Civil Engineers, Bellevue, Washington, pp. 222–228.
- Lu, X., Isacsson, U., and Ekblad, J. 1999. Rheological properties of SEBS, EVA and EBA polymer modified bitumens. *Materials and Structures*, **32**(2): 131–139. doi:10.1007/BF02479440.
- Molenaar, A.A.A., and Medani, T.O. 2000. Rational testing methods for performance based specifications, In *Proceedings of the 1st International Conference World of Asphalt Pavements*, 7–10 July 2000. Australian Asphalt Pavement Association, Sydney, Australia, pp. 484–500.
- Nejad, F.M., Aflaki, E., and Mohammadi, M.A. 2010. Fatigue behavior of SMA and HMA mixtures. *Construction and Building Materials*, **24**(7): 1158–1165. doi:10.1016/j.conbuildmat.2009.12.025.
- Roque, R., Birgisson, B., Drakos, C., and Sholar, G. 2005. Guidelines for use of modified binders. Florida Department of Transportation, Project Number: 4910-4504-964-12, Florida.
- Simms, S.A. 1998. Use of coal fly ash in asphalt concrete mixes. M.Sc. thesis, Department of Civil Engineering, Dalhousie University, Daltech, Canada.
- Subagio, B.S., Karsaman, R.H., Adwang, J., and Fahmi, I. 2005. Fatigue Performance of HRA (Hot Rolled Asphalt) And Superpave® Mixes Using Indonesian Rock Asphalt (Asbuton) As Fine Aggregates And Filler. *Journal of the Eastern Asia Society for Transportation Studies*, **6**: 1207–1216.
- Tapkin, S. 2008. Mechanical evaluation of asphalt-aggregate mixtures prepared with fly ash as a filler replacement. *Canadian Journal of Civil Engineering*, **35**(1): 27–40. doi:10.1139/l07-082.
- Tapkin, S., Uşar, Ü., Tuncan, A., and Tuncan, M. 2009. Repeated creep behavior of polypropylene fiber-reinforced bituminous mixtures. *Journal of Transportation Engineering*, **135**(4): 240–249. doi:10.1061/(ASCE)0733-947X(2009)135:4(240).
- Tayfur, S., Özen, H., and Aksoy, A. 2007. Investigation of rutting performance of asphalt mixtures containing polymer modifiers. *Construction and Building Materials*, **21**(2): 328–337. doi:10.1016/j.conbuildmat.2005.08.014.
- Yilmaz, M., Kok, B.V., and Kuloglu, N. 2011. Effects of using asphaltite as filler on mechanical properties of hot mix asphalt. *Construction and Building Materials*, **25**(11): 4279–4286. doi:10.1016/j.conbuildmat.2011.04.072.