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EVALUATING FATIGUE BEHAVIOR OF ASPHALT BINDERS AND MIXES CONTAINING DATE SEED ASH

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Abstract. Fatigue is one of the most occurring distresses in asphalt pavements. Asphalt binder plays a critical role in fatigue behavior of asphalt mixes. Modelling and predicting fatigue behavior of binders will result in more fatigue resistant mixes. In this research, possibility of using Date Seed Ash alongside two commonly used additives (namely, a siliceous and a limestone) as bitumen modifier were investigated. Then, the influence of these additives on fatigue behavior of asphalt binders and mixes was investigated. Linear Amplitude Sweep (LAS) test was carried out and Viscoelastic Continuum Damage (VECD) parameter was determined. In addition, Indirect Tensile Fatigue Test (ITFT) was performed on mixes containing these additives. Correlation equations were developed to link fatigue behavior of binders to those of mixes. The results showed acceptable agreement between binders and mixes fatigue testing results. In addition, with predicted models it was able to obtain the asphalt binders contribution to mixes fatigue resistance. However, in the case of ash modified samples, no good correlation was observed between fatigue behavior of binders and that of mixes.

Keywords: date seed ash (DSA), linear amplitude sweep (LAS), viscoelastic continuum damage (VECD), indirect tensile stiffness modulus (ITSM), indirect tensile fatigue test (ITFT), hot mix asphalt (HMA).

Introduction

Fatigue failure in asphalt mixes occurs as a result of accumulation of damages under repeated loading. Fatigue cracking resistance of asphalt pavements is highly dependent on pavement layers thicknesses, mix volumetrics, mixture type and the structure of the pavement (Safaei *et al.* 2016). Several tests are carried out to evaluate fatigue behavior of asphalt mixes, including Flexural Fatigue Beam and Indirect Tensile Fatigue Tests (ITFT). It is recommended to perform fatigue testing on bituminous mixes at intermediate ambient temperatures (e.g. 20 °C) (Modarres 2013). Experimental assessment of cracks implies that fatigue cracking occurs through the binder phase and will be spread to the whole mix (Safaei *et al.* 2014). As asphalt binder plays a key role in fatigue behavior of asphalt mixtures, many researchers investigated the application of additives in order to improve characteristics of binders in mixes (Khattak *et al.* 2013; Capitão *et al.* 2012; Yang *et al.* 2014). It would be reasonable to utilize both an experimental method alongside with a theoretical model to predict how binders and mixes behave under traffic loading and resist fatigue cracking.

Although the currently applied performance grade specifications of asphalt fatigue resistance (that is based on linear viscoelastic behavior) is adequate for evaluating the overall quality of the binders, the main defect is their inapplicability in characterizing the actual damage resistance of mixes (Hintz, Bahia 2013; Deacon *et al.* 1997; Bahia *et al.* 2001a, 2001b). Furthermore, this grading system cannot be used to characterize modified binders, precisely. Many researchers have criticized the G*Sin parameter (known as fatigue crack parameter), which is the stiffness-based parameter measured in a quite different condition than that in the field (Deacon *et al.* 1997; Bahia *et al.* 2001b; Andriescu *et al.* 2004; Tsai *et al.* 2005). Fixed frequency, few cycles of loading and small shearing strain are among the restricted parameters in which G*Sin is measured (Zhou *et al.* 2012).

Viscoelastic Continuum Damage (VECD) Model is a prevalent approach which has been utilized by many researchers to evaluate fatigue resistance of asphalt mixes (Lee, Kim 1998; Daniel, Kim 2002; Kutay *et al.* 2008; Underwood *et al.* 2010; Sabouri, Kim 2014; Norouzi,

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Kim 2015). This method is used to differentiate damage from time effects related to viscoelasticity by substituting strain with pseudo-strain (Hintz *et al.* 2011a). VECD Model has been simplified (namely, S-VECD) and produced on the basis of uniaxial cyclic direct tension test to predict fatigue life of asphalt pavements (Norouzi, Kim 2015; Schapery 1990). This method, then, became a standard procedure and was known as AASHTO TP-107. Recently, VECD modeling method has been applied to binders (Safaei *et al.* 2014; Hintz *et al.* 2011b). Johnson *et al.* (2009) evaluated the application of VECD method under monotonic constant strain-rate shear loading by DSR which was proposed by Wen and Bahia and demonstrated the inapplicability of this approach for polymer-modified binders.

Thereafter, he applied VECD model on asphalt binders and subjected these to a cyclic loading in DSR testing. Then, Johnson *et al.* (2009) presented the Linear Amplitude Sweep (LAS) test. Others improved the test by recommending continuous increment in amplitude sweep instead of the stepwise case (Hintz, Bahia 2013). This testing method was then standardized in AASHTO TP-101 (2014). Currently the LAS test seems to be the most accurate testing method in predicting bituminous binders fatigue behavior. However, Hintz and Bahia (2013) recommended that it would be better name it a damage tolerance test rather than a fatigue testing.

On the other hand, the application of different additives in bituminous mixes has been widely investigated. These include diverse categories such as polymers, fibers, industrial by-products, waste materials, nanomaterials, catalysts, engineered and natural materials (Whiteoak 1990; Arabani *et al.* 2017a). Among these, Polymer Modified Bitumens (PMBs) are the most widely in high performance mixes (Yildirim 2007). Investigations showed that a single PMB is not able to address all the pavement distresses (e.g. rutting, fatigue cracking, moisture damage and age hardening of mixes lonely) (Read, Whiteoak 2003; Chen *et al.* 2002; Kavussi, Barghabany 2015; Isacsson, Xiaohu 1999). In this study, the feasibility of using Date Seed Ash (DSA) as a bitumen modifier to improve fatigue behavior of bitumen was investigated. Date palm grows in vast areas of the earth, particularly from North Africa to Persian Gulf. Date tree has various byproducts which are dropped into the river or deposited in the farmlands or in most of the cases they will be burnt by the farmers (Chandrasekaran, Bahkali 2013). All the mentioned issues are definitely harmful for human and environment. According to FAO annual reports, Date palm seeds, by-products of date palm tree, constitute about 2 million tons of waste materials that their proper application could be beneficial to the environment (Food F.A.O. 2015).

In this research, bitumen was modified with DSA alongside with two types of commonly used additives in asphalt pavement industry (namely, a siliceous and a limestone). The modified binders were then used to prepare asphalt mixtures. The first objective of this research was to produce DSA from seeds of date tree. The second and main goal of this study was to investigate whether this additive could improve the fatigue behavior of asphalt binders. LAS testing was used to analyze Viscoelastic Continuum Damage properties of the materials. Third, fatigue behavior of asphalt mixtures, containing three types of additives, were assessed applying ITFT method and finally, prediction models were developed to model fatigue behavior of bitumen and asphalt mixes.

1. Background

1.1. Linear amplitude sweep test

The current PG specifications that assess fatigue resistance of asphalt binders lack the ability of defining real damage resistance. Therefore, VECD approach cannot be applied to these testing results. In order to improve PG specifications, Time Sweep test (TS) which is performed using DSR device was introduced in NCHRP Project 9-10. This is different than the SHRP proposed PG tests that consist of applying repeated cyclic loading at fixed amplitude mode in either stress or strain controlled conditions (Safaei *et al.* 2016; Bahia *et al.* 2001a; Martona, Bahia 2008; Hintz *et al.* 2011a). The main problem of Time Sweep test is its rather long testing time. In some cases, testing time takes several hours until the fatigue damage occurs (Hintz, Bahia 2013). The efforts in determining fatigue resistance of binders resulted in two tests; namely Binder Yield Energy Test (BYET) which is a monotonic shear test, performed under constant strain rate loading condition and Linear Amplitude Sweep test (LAS) (Hintz *et al.* 2011a; AASHTO-TP101 2014). It has been proved that LAS test is more practical and appropriate for prediction of fatigue behavior of asphalt binders. Both RTFO and PAV aged binders can be tested under LAS testing. LAS and TS have some similarities in which both can be applied in DSR device using the 8-mm-diameter parallel plate geometry with 2-mm gap setting (AASHTO-TP101 2014). However, in order to accelerate damage accumulation, LAS test consists of oscillatory strain amplitude sweep in which loading amplitudes are linearly increased. In order to utilize VECD analysis, a frequency sweep test should be performed before the strain sweep, in order to determine "alpha" damage parameter. While frequency sweep is a non-damage test, the amplitude sweep test can run directly after the frequency sweep (Hintz, Bahia 2013; AASHTO-TP101 2014). It should be noted that, frequency sweep testing conditions consists of applying a load at 0.1% percent strain level over a range of 0.2–30 Hz. More details of this test can be found elsewhere. As mentioned before, amplitude or strain sweep runs after the frequency sweep, where loading begins and increases linearly with 100 cycles at a rate of 1% increased and the application of stress until 30% strain level is achieved as shown in Figure 1 (Safaei *et al.* 2016; Hintz, Bahia 2013; AASHTO-TP101 2014).

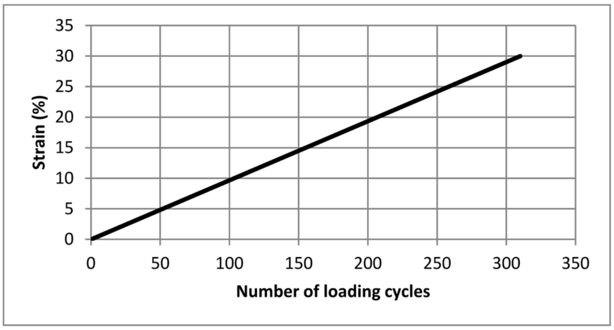


Fig. 1. Loading scheme in linear amplitude sweep test

1.2. VECD modeling approach

Results from LAS test can be used in VECD modeling framework. A brief review is implied herein and more details can be found elsewhere (AASHTO-TP101 2014). As mentioned before, frequency sweep should be performed to determine alpha parameter of undamaged asphalt binder. Thereafter, calculations should be carried out to develop storage modulus from the following equation:

$$G'_{(\omega)} = \left|G^*\right|_{(\omega)} \times \cos\delta_{(\omega)} . \tag{1}$$

In this equation, $G'_{(\omega)}$ is storage modulus and $\left|G^*\right|_{(\omega)}$ and $\delta_{(\omega)}$ are dynamic modulus and phase angle respectively. A diagram is then plotted in that $\log G'_{(\omega)}$ and $\log \omega$ are the vertical and horizontal axis, respectively. From the above the following equation can be obtained:

$$\log G'_{(\omega)} = m\left(\log \omega\right) + b . \tag{2}$$

The m value in the above equation is used to determine α as it follows:

$$\alpha = \frac{1}{m} . \tag{3}$$

Results from LAS testing could be utilized in Eqn (4), known as damage accumulation equation:

$$D_{(t)} \cong \sum_{i=1}^{N} \left[\pi\gamma_0^2 \left(C_{i-1} - C_i\right)\right]^{\frac{\alpha}{\alpha+1}} \left(t_i - t_{i-1}\right)^{\frac{1}{\alpha+1}} . \tag{4}$$

In this equation, C is pseudo-stiffness and indicates material integrity. It is considered to be 1 for a material which behaves in a viscoelastic manner (Safaei *et al.* 2016). $C_{(t)}$, determined from Eqn (5), is a function obtained from dividing $\left|G^*\right|$ at time *t*, to the initial value of $\left|G^*\right|$; γ_0 represents percent of applied stress for a given data point and $\left|G^*\right|$ stands for complex shear modulus:

$$C_{(t)} = \frac{\left|G^*\right|_{(t)}}{\left|G^*\right|_{intial}} . \tag{5}$$

As it can be seen from Eqn (4), the damage induced is a function of time which is achieved by summing $D_{(t)}$ from the beginning ($t = 0$) to the final data point. Similarly, $C_{(t)}$ is calculated applying the same approach. From previous works it is presumed that $C_{(t)}$ at $D_{(0)}$ is equal to 1 and $D_{(0)}$ is considered to be zero (AASHTO-TP101 2014). Therefore, the relationship between $C_{(t)}$ and $D_{(t)}$ can be achieved on the basis of the power law from Eqn (6) below:

$$C_{(t)} = C_0 - C_1 \left(D\right)^{C_2} , \tag{6}$$

where: C_1 and C_2 are the coefficients derived from linearization of power law equation as it follows:

$$\log\left(C_0 - C_{(t)}\right) = \log(C_1) + C_2 \times \log\left(D_{(t)}\right) . \tag{7}$$

Reduction in initial $\left|G^*\right|$ at the peak shear stress represents failure point and $D_{(t)}$ corresponding with this point is known as D_f determined from the following equation:

$$D_f = \left(\frac{C_0 - C_{at\ Peak\ Stress}}{C_1}\right)^{\frac{1}{C_2}} . \tag{8}$$

The binder fatigue performance could be calculated using Eqn (9) below:

$$N_f = A\left(\gamma_{max}\right)^{-B} , \tag{9}$$

where γ_{max} is the percentage of maximum expected binder strain for a given pavement structure. Indexes *A* and *B* are fatigue performance parameters, calculated from Eqn (10) below:

$$A = \frac{f\left(D_f\right)^k}{k\left(\pi C_1 C_2\right)^{\alpha}} , \tag{10}$$

where: f = Loading frequency (10 Hz); $k = 1 + \left(1 - C_2\right)\alpha$, and $B = 2\alpha$.

1.3. Indirect tensile stiffness modulus

Indirect tensile stiffness modulus test is a non-destructive test, used to determine stiffness of asphalt mixes. Stiffness modulus (S_m) is one of the key parameters in asphalt mix analysis, playing a major role in their fatigue behavior. S_m is an important value that shows the ability of asphalt mixes to tolerate stress and strains due to repeated traffic loading (Arabani *et al.* 2017b). In this research, ITSM testing was carried according to AASHTO-TP31 (1996) procedure using a Universal Testing Machine (UTM-14). Specimens were subjected to haversine loading pulses across the vertical axis of each specimen. Figure 2 shows a typical loading scheme of UTM device in ITSM testing in which horizontal deformation is plotted against time. This is measured via three Linear Variable Differential Transducers (LDVTs) attached to the front and back sides of the specimen. All the tests were conducted at 20 °C. Three specimens were prepared for each mix composition and each specimen was tested twice (rotating 180° around x-axis).

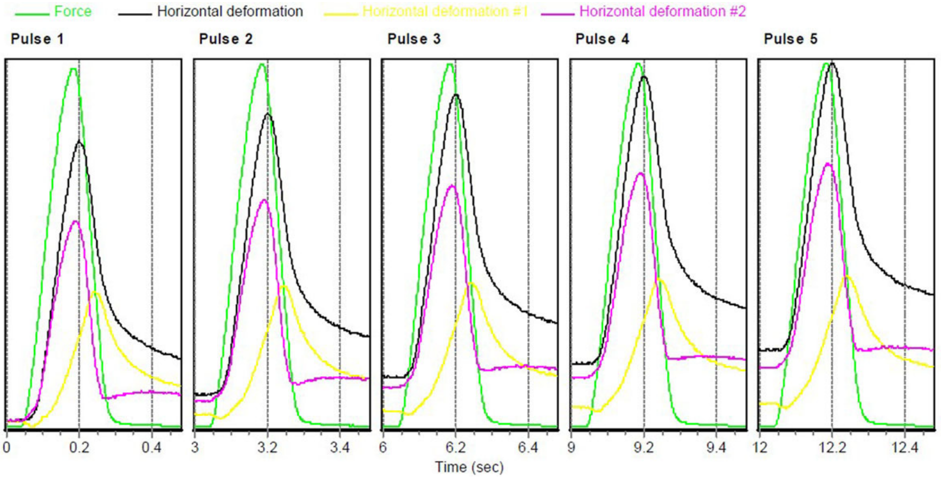


Fig. 2. Loading scheme in ITSM test

UTM device used in this research automatically calculates the stiffness modulus values of the specimens. Stiffness modulus could be determined from the following equation:

$$S_m = \frac{P(\nu + 0.27)}{t \times H}. \tag{11}$$

In this equation, S_m is stiffness modulus (MPa), P is the maximum dynamic load (N), t is average thickness of the specimen, H is horizontal deformation and ν is Poisson ratio (assumed to be 0.35).

1.4. Indirect tensile fatigue test

Fatigue cracking in asphalt pavements usually occur due to repeated loadings (Al-Khateeb, Shenoy 2004; Martona, Bahia 2003). Indirect tensile fatigue test (ITFT) is one of the most efficient tests which is designed to predict fatigue behavior of asphalt mixes. The greater resistance of mixes to fatigue results in fewer fatigue cracks (Arabani *et al.* 2017b). ITFT can be conducted either in strain or stress controlled modes (Arabani, Mirabdolazimi 2011). In this research, the test was conducted in stress controlled mode, according to EN-12697-24 (2004). Failure of the specimens occurred when either the specimen completely fractured or the vertical deformation reached 9 mm and the fatigue life was determined as the total number of loads that caused failure in the specimen (EN-12697-24 2004). The test was carried out at the fixed temperature of 20 °C and at three stress levels of 150, 250 and 400 kPa. Haversine loading was applied during the test with 500 ms repetition time and 100 ms pulse widths.

It has been proved that fatigue cracks at the bottom of the asphalt layer are mainly created due to the concentration of tensile stresses caused by traffic loading (Arabani *et al.* 2017b). As a result, tensile strain at the bottom of the mix is directly related to the number of cycles to failure. As tensile strain of the specimen for each level of stress is given, a relationship between number of loading cycles to failure and tensile strain of the specimen can be determined. Several models are developed to predict fatigue life of asphalt mixes, based on regression analysis of the results. Among these, Wohler's Model is a simple model which is widely accepted and is utilized by researchers (Arabani *et al.* 2017b; Shafabakhsh *et al.* 2015; Sybilski, Bańkowski 2002; Azarhoosh *et al.* 2016). This model, defined in Eqn (12), was used in this research:

$$N_f = a\left(\frac{1}{\varepsilon_t}\right)^b. \tag{12}$$

In this equation N_f is the number of load cycles to failure, ε_t is the applied strain, and a and b are regression coefficients.

2. Materials, mix design and procedure

A PG 58-22 bitumen from Isfahan Refinery was used in this research. In order to prepare the modified binders, three types of additives were added to bitumen at three different levels of 3%, 6% and 9%. The mixing procedure was prepared applying two steps as recommended by some researches (Cuadri *et al.* 2015; Köfteci *et al.* 2014). Firstly, the bitumen was heated to 160 °C and DSA as other additives was poured slowly into the mixing container. Mixing was continued for 10 to 15 minutes at 600 rpm. Second, in order to achieve better homogenous mixtures, mixing speed was increased to 2000 rpm and mixing was kept on for one hour. For simplicity, samples were named with two letters and a number. With this regard, B represents bitumen and the next letter indicates the type of additive. The numbers show the percentages of additive by weight of bitumen. For example, BD3 represents binder with 3% DSA (by weight of bitumen). Similarly, BS and BL represent bitumen modified with siliceous and limestone additives, respectively. Then, the modified bitumen samples were added to the aggregates in order to prepare asphalt mixes. It is to be mentioned that limestone aggregate was utilized to prepare all of the hot mix asphalt samples according to ASTM D6927 standard and optimum bitumen content was determined for control sample (with no bitumen additive) and it was employed for other mixes. Asphalt mixes gradation was based on the continuous type IV scale of the AASHTO (1993) and is depicted in Table 1 (AASHTO 1993).

Table 1. Gradation of aggregates used in the study

Sieve (mm)	19	12.5	4.75	2.36	0.3	0.075
Lower-upper limit	100	90–100	74–77	28–58	5–21	2–10
Passing (%)	100	95	59	43	13	6

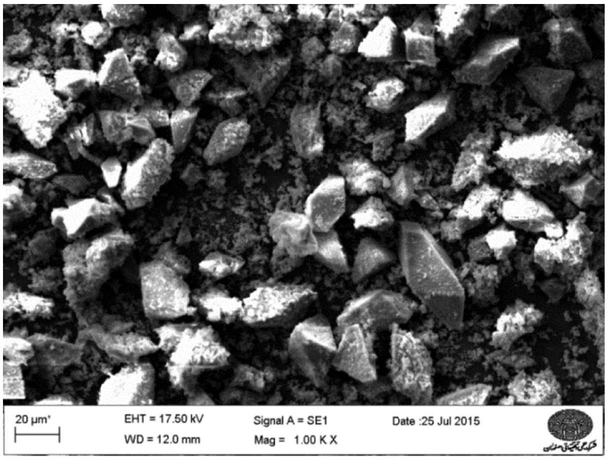
2.1. Production of DSA

The Date Seed Ash that was used in this research, was prepared in two phases. The first phase consisted of burning Date Palm Seeds in order to convert these into date seed coal. In the second phase, the date seed coal was placed in a furnace and was heated to 600 to 800 °C for 1.5 to 2 hours (Mirhosseini *et al.* 2016). Figure 3 shows a sample of DSA that has gray color. As some unburned and rather coarse black particles were observed, the ash was sieved on a No. 200 Sieve. In order to have additives with the same maximum size, siliceous and limestone additives were also passed through Sieve No. 200.

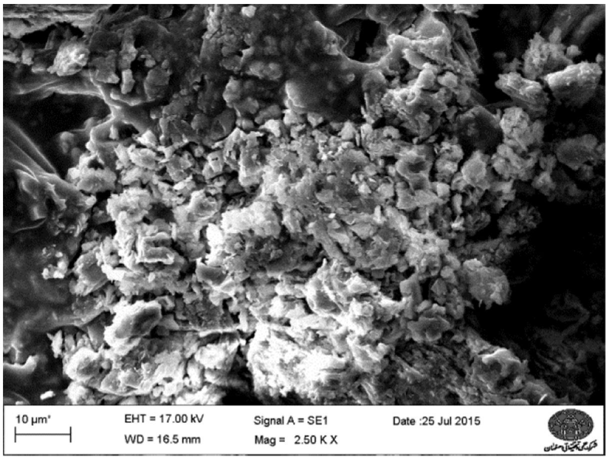
Fig. 3. Date seed ash (DSA); up-right-side: original date seed (Mirhosseini *et al.* 2016)

Table 2. Chemical composition of the three additives (%)

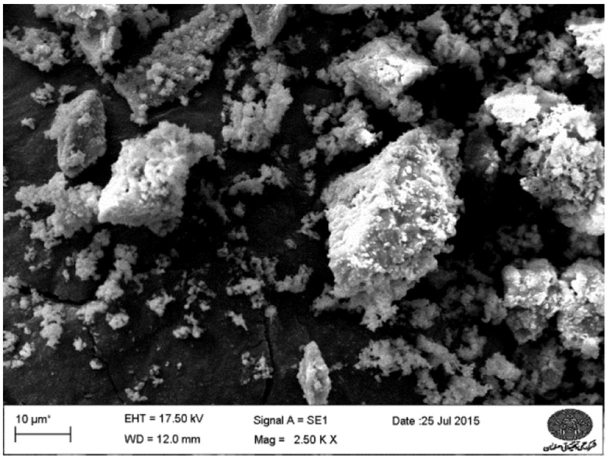
Composition	Siliceous	Limestone	DSA
SiO_2	74.5	4.1	58.6
Al_2O_3	9.8	6.2	4.9
Fe_2O_3	0.7	0.4	7.9
CaO	2.1	69.7	4.8
MgO	3.2	1.1	3.9
Na_2O	–	–	7.2
K_2O	–	–	0.3
SO_3	–	–	0.4
LOI	8.8	18.5	12



(a) DSA



(b) siliceous additive



(c) limestone additive

Fig. 4. SEM images of the additives tested

Figure 4 presents the Scanning Electron Microscopy (SEM) pictures of the three additives tested. In this figure the granular grading and regular geometry of DSA particles can be observed. Additionally, XRF testing was carried out on these additives and their major constituents were determined as reported in Table 2.

3. Results and discussion

3.1. Asphalt binder

3.1.1. Stress-strain curves

As it was mentioned earlier, before the modifications of the loading scheme in LAS testing, strains were applied on the specimens step wised. This type of loading has some disadvantages. For instance, the sudden increased loading amplitude leads to induced sudden increment in crack growth rates (Hintz, Bahia 2013). On the other hand at each stage, crack growth rate decreases and the rate does not correspond with fatigue crack propagation. This procedure results in decreased loading capacity and earlier failure of the specimen (Hintz, Bahia 2013). However, the analysis of cracks development in LAS testing is out of the scope of this research.

In this work, amplitude sweep testing was conducted on binders directly after the frequency sweep test. The results were analyzed using VECD approach. In this method the stress-strain and damage curves (resulted from VECD analysis) are plotted.

Figures 5 to 7 show stress-strain curves for bitumen binders containing the three additives used in this research. As it can be seen in Figure 5, for binders containing 3%, 6% and 9% siliceous additive (i.e. BS samples), adding siliceous additive resulted in a considerable drop in maximum stress, compared with the neat binder. For instance, the maximum stress in BS9 was 170 kPa which is 13% lower than that of the neat binder (being 194 kPa). Adding siliceous additive resulted in lower stresses. With regard to shear stresses, it can be realized that the ultimate presumed strain (i.e. 30%) occurred earlier. This indicates that fatigue life of BS modified binder would be rather short.

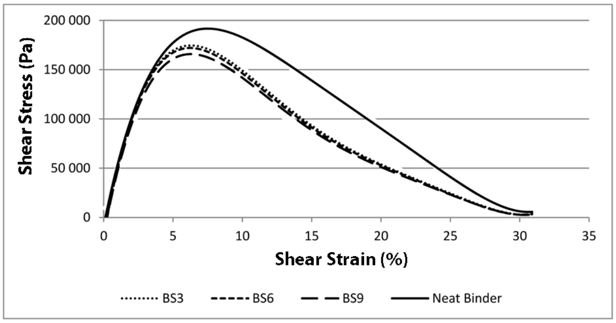


Fig. 5. Stress-strain curves extracted from LAS testing of siliceous modified binders

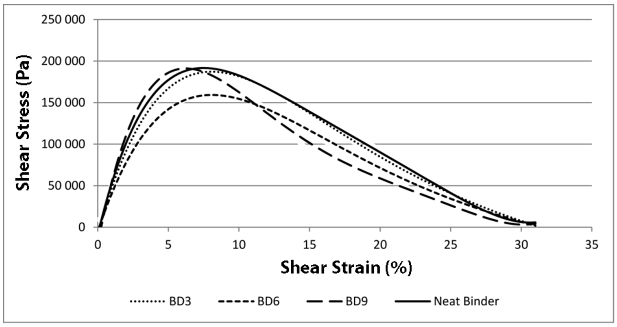


Fig. 6. Stress-Strain curves extracted from LAS testing of DSA modified binders

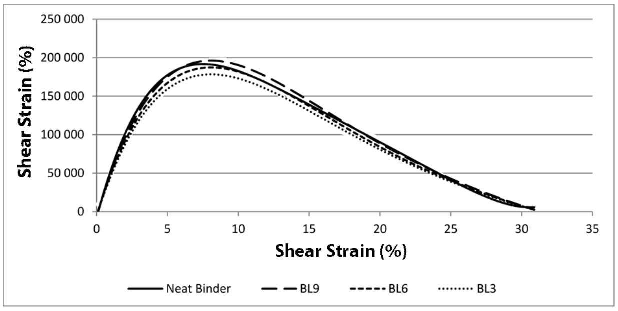


Fig. 7. Stress-Strain curves extracted from LAS testing of limestone modified binders

With reference to Figure 6, it can be seen that there is no particular order in the trends of stress-strain curves for BD samples. BD9 experienced the highest maximum stress among all the other BD binders. In BS specimens, BS9 showed the lowest maximum stress. Mirhosseini *et al.* (2016) investigated the effects of various amounts of DSA on binders and concluded that chemical interactions exist between bitumen binders and DSA. The addition of DSA changed properties of the bitumen binders appreciably. With reference to Figure 6, it can be seen that sample BD3 experienced the maximum stress level of 188 kPa, while this parameter was recorded about 160 and 190 kPa for BD6 and BD9 samples, respectively. Similarly, the stress-strain curves for binders containing limestone additive are reported in Figure 7. As it can be seen, similar behavior was observed on all samples containing this additive. For instance, the highest value of maximum stress belonged to BL9 (with 197 kPa). This is almost equal to that of the neat binder (with 194 kPa). Hence, it is expected that the fatigue behavior of BL samples could be considered similar to the neat binder. Also, the values of maximum shear stress for all samples are shown in Table 3.

3.1.2. Damage characteristics and fatigue failure

In addition to stress-strain curves, the damage curves can also be drawn from LAS testing results. Damage curves are plotted using excel file prepared by some researchers (Kavussi, Barghabany 2015). Damage intensity and material integrity at failure moment are the two key factors

Table 3. Values of shear stress for control and modified binders

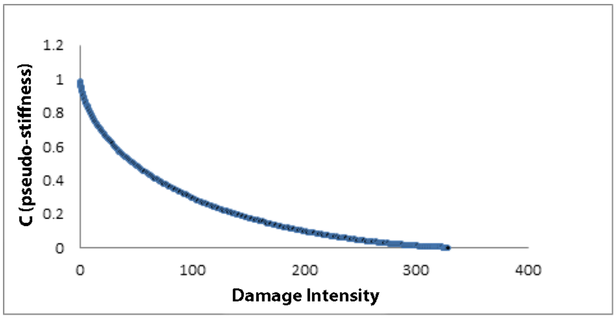
Sample	Control	BS3	BS6	BS9	BD3	BD6	BD9	BL3	BL6	BL9
Stress (Pa)	194.3	179.7	176.4	170.8	196	160.4	187.8	188.8	179.8	197.8

in investigating fatigue resistance of binders (Safaei *et al.* 2014). Figure 8 shows the difference between damage intensity of BD samples, compared with the neat control binder. As previously stated, a higher value of damage intensity at the moment of failure can indicate that the material has a high fatigue resistance (Safaei *et al.* 2014). With reference to Figure 8, it can be observed that BD3 has the lowest damage intensity, compared with that of the control and BD samples. Among the various modified binders, BD6 had the highest damage intensity. Therefore, it could be inferred that BD3 and BD6 have the lowest and the highest fatigue life among the four specimens. The complete details of damage characteristics and fatigue behavior of the investigated samples are reported in Table 4. For a better understanding of the phenomenon, the fatigue life cycles of the control and the modified binders at strain level of 2.5% are illustrated in Figure 9.

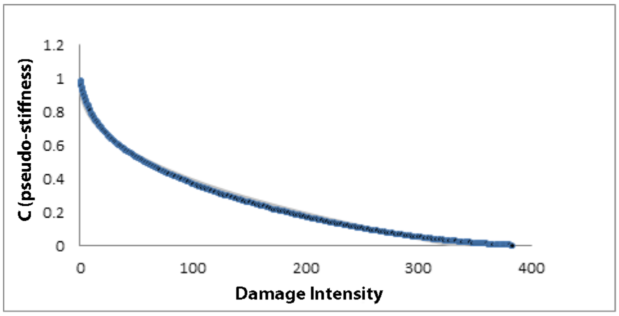
Table 4. Damage characteristics of binders after LAS testing

sample	Damage level	N_f at strain level of		Fatigue model
		2.5%	5%	
Base bitumen	0.423	5889	820	$N_f = 7.9\times10^4(\gamma_{max})^{2.84}$
BS3	0.402	3795	562	$N_f = 4.74\times10^4(\gamma_{max})^{2.75}$
BS6	0.391	3601	525	$N_f = 4.59\times10^4(\gamma_{max})^{2.77}$
BS9	0.391	3545	517	$N_f = 4.51\times10^4(\gamma_{max})^{2.77}$
BL3	0.419	7767	1107	$N_f = 1.02\times10^5(\gamma_{max})^{2.81}$
BL6	0.482	9144	1273	$N_f = 1.24\times10^5(\gamma_{max})^{2.84}$
BL9	0.430	7930	1130	$N_f = 1.04\times10^5(\gamma_{max})^{2.81}$
BD3	0.425	7757	1105	$N_f = 1.01\times10^5(\gamma_{max})^{2.81}$
BD6	0.425	8003	1116	$N_f = 1.08\times10^5(\gamma_{max})^{2.84}$
BD9	0.402	3939	570	$N_f = 5.06\times10^4(\gamma_{max})^{2.78}$

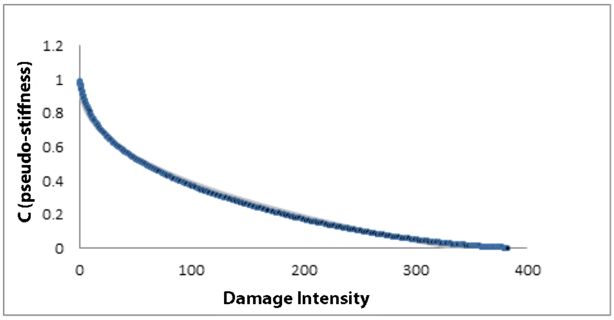
As it can be seen, the fatigue models for all specimens are developed based on VECD analysis. Fatigue life cycle value for each specimen at strain level of 2.5% is shown in Figure 9. It can be recognized that among all the samples, the one containing 6% limestone additive resulted in a 55% increase in fatigue life, compared with the control binder. A decreasing trend was observed in BS samples. In this case, the modified binder containing 9% siliceous additive had a fatigue life of some 40% lower than that of the control binder. Therefore, it can be concluded that the siliceous modified binder has a reduced fatigue life compared with the control binder. This



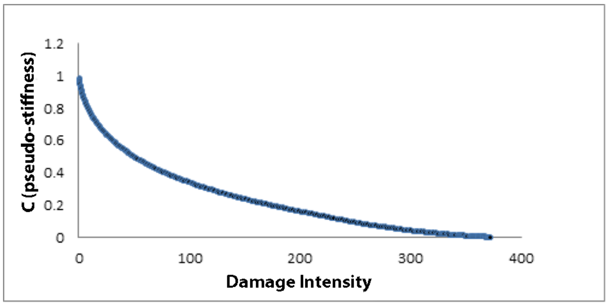
(a) BD3 sample



(b) BD6 sample



(c) BD9 sample



(d) Control neat binder

Fig. 8. VECD damage curves drawn from amplitude sweep testing data

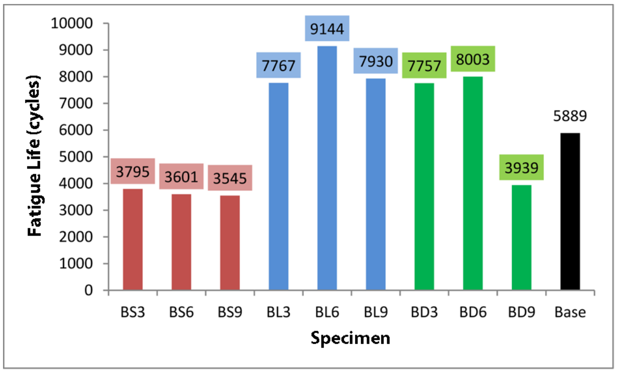


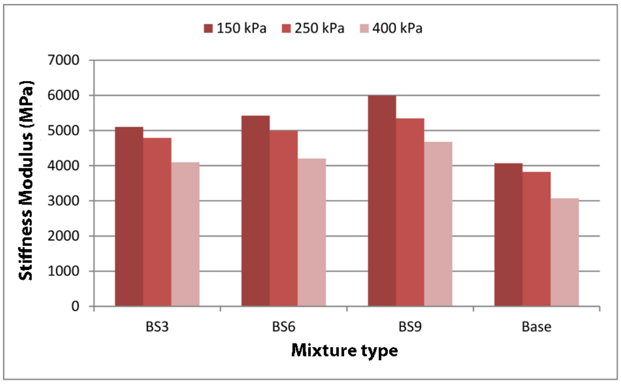
Fig. 9. Fatigue life of various modified binders at strain level of 2.5%

might be due to the higher stiffness of BS samples. The mix with higher stiffness is more prone to fatigue failure (Hinislioğlu *et al.* 2005; Bagampadde *et al.* 2013). Increasing the amount of SiO_2 or additives containing high percent of Silicon to bitumen would enhance stiffness of the binders (Sadeghpour *et al.* 2015; Shafabakhsh, Ani 2015; Rusbintardjo *et al.* 2013). The main reason for that were SiO_2 molecules and this growth occurred through crosslinking process. The silicon molecules cross-linked between asphalt binder molecules when siliceous additive was entered into the binder mass. This results in a dense and hard material with high cross-link density (Aziz *et al.* 2003). In the case of BL samples, the highest fatigue life was achieved in BL6. Fatigue life of BL samples was first increased to 7767; then it was increased to 9144 and then decreased to 7930. Results showed that with adding limestone to bitumen in the investigated range, improved fatigue life will be observed. Finally, investigating the effects of DSA on fatigue behavior of BD samples showed that the maximum amount of DSA to improve fatigue life of binder is 6% by weight of bitumen. As it can be seen, BD6 showed the maximum tolerance in fatigue behavior among all BD samples (with 36% greater fatigue life than the control binder). However, increased amounts of DSA resulted in significantly reduced fatigue life of the DSA containing binder. Utilizing regression analysis resulted in determining optimum values of limestone and DSA in their resistance to fatigue failure. The values were 6.1% and 4.6% for limestone and DSA additive, respectively.

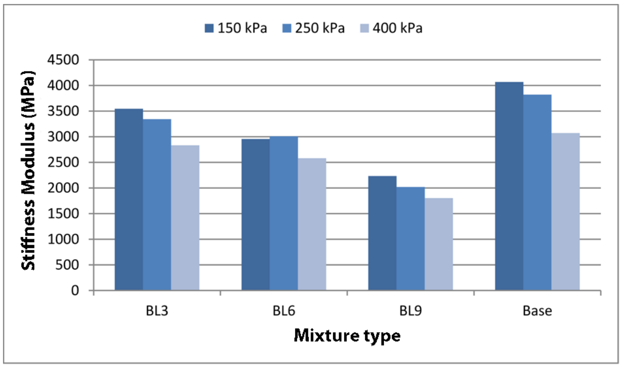
3.2. Asphalt mixtures testing results

3.2.1. ITSM results

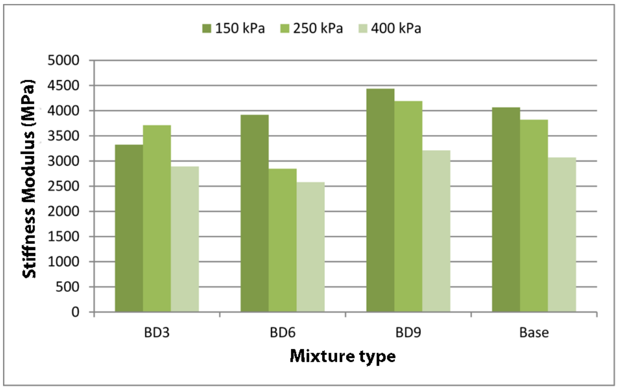
Results of ITSM testing are reported in Figure 10. For each sample, three specimens were prepared and each specimen was tested twice under two different conditions as described above. It can be seen from this figure that stiffness modulus values were decreased with increased stress level. At a same stress level, stiffness modulus of BS samples are greater than that of limestone and DSA modified samples.



(a) Siliceous modified mixes



(b) Limestone modified mixes



(c) DSA modified mixes

Fig. 10. Stiffness modulus of various modified mixes

With reference to Figure 10, an increase in stiffness modulus of BS and BD specimens can be observed with increasing additive amounts. In contrast, BL samples experienced a decreasing trend with increased amounts of the additive. Another important issue is that the increased stress level with result in decreased stiffness modulus. Generally, stiffness modulus of BS samples are greater than that of the other BL samples. The highest value of belonged to BS9 with 5994 kPa at stress level of 150 kPa. While the lowest value was attributed to BL9 sample at stress level of 400 kPa (with 1803 kPa). Stiffness values of BD samples varied from below to above the control specimen. values of BD3 and BD6 specimens were lower than the stiffness modulus of the control specimen

Table 5. ITFT fatigue testing results of mixes containing various amounts of additives

Sample	σ (kPa)	ε ($\times 10^{-6}$)	N_f	Fatigue model	R^2
Control	150	75	6338	N_f = 5E+06 $\varepsilon^{-1.512}$	0.94
	250	134	3285		
	400	166	1760		
BS3	150	60	4213	N_f = 1E+06 $\varepsilon^{-1.402}$	0.95
	250	107	2199		
	400	125	1394		
BS6	150	56	3942	$N_f = 895547\ \varepsilon^{-1.341}$	0.96
	250	102	2038		
	400	122	1302		
BS9	150	51	3773	$N_f = 689330\ \varepsilon^{-1.319}$	0.96
	250	95	1903		
	400	109	1287		
BL3	150	86	6952	$N_f = 745338\ \varepsilon^{-1.047}$	0.98
	250	152	4065		
	400	181	3109		
BL6	150	104	8136	N_f = 1E+07 $\varepsilon^{-1.588}$	0.95
	250	170	4338		
	400	198	2745		
BL9	150	137	9121	N_f = 2E+07 $\varepsilon^{-1.535}$	0.89
	250	253	4617		
	400	284	2554		
BD3	150	92	6892	N_f = 4E+07 $\varepsilon^{-1.93}$	0.97
	250	138	3676		
	400	177	1898		
BD6	150	78	7115	$N_f = 633154\ \varepsilon^{-1.024}$	0.82
	250	180	3992		
	400	198	2241		
BD9	150	69	5921	N_f = 4E+06 $\varepsilon^{-1.541}$	0.94
	250	122	3111		
	400	159	1532		

and BD9 showed higher values at all three stress levels. Increasing stiffness of BS and BD asphalt mixes with increasing the amount of additive might be due to the considerable amount of silicon in their structure. As mentioned before, increasing the amount of SiO_2 or additives containing high percent of Silicon to the mix will stiffen the blend and consequently, the stiffness modulus of the mix will be increased. Besides, as a result of increasing the stiffness modulus of asphalt binder, the adhesion between the aggregates enhances and materials of the mixture can sorely slid. Therefore, the stiffness modulus of the mixture will grow significantly (Arabani, Tahami 2017).

3.2.2. ITFT results

The number of cycles to failure and final strain of asphalt mixtures at different stress levels are reported in Table 5. Generally, it can be observed that with increasing level of the applied stress, fatigue life of the specimens are reduced and the final strains are increased. The table shows that mixtures made with limestone modified binders resulted in a greater fatigue life. Assessing the role of DSA on HMA mixes, shows that the addition of 6% DSA to a mix results in good fatigue life resistance. However, with increasing the amounts of DSA to greater values, considerable decrease in fatigue life results. For instance, at stress level of 150 kPa, the addition of 3 and 6% DSA to bitumen resulted in 8 and 12% increase in fatigue life, respectively. The addition of DSA to bitumen at low levels (i.e. below 6%) will gradually break the structure of bitumen. Then sodium and calcium salts are formed which have more adhesion properties in sticking aggregates together, compared with the control specimens (Mirhosseini *et al.* 2016). In the case of siliceous samples, there will be a reduced trend in fatigue life of mixes with increasing percentages of siliceous additive. As an example, the addition of 3% siliceous additive to bitumen in BS mixes at stress level of 250 kPa, resulted in 33% reduced fatigue life of HMA mixes. On the other hand, fatigue behavior of BL mixes were all improved in the ranges of the studied values. For example, the addition of 9% limestone additive at stress level of 400 kPa improved fatigue life of mixes up to 44% (compared with the control mix).

3.3. Correlation equations

Three relationships were developed, based on fatigue coefficients of the modified binders and asphalt mixes. The models are reported in Table 6. Based on R^2 coefficients reported in Table 6, it can be seen that the predicted model of BS samples can precisely relate the fatigue life of modified binders to those in their HMA mixes. However, R^2 value of BL samples could be considered acceptable but the model developed for BD samples seems to be unreliable to link fatigue parameters to each other.

Table 6. Correlation equations relating fatigue behavior of binders and HMA mixes

Sample type	Regression equation	R^2
BS	$N_f = 0.4798\ln(\varepsilon) - 7.9103$	0.98
BL	$N_f = 0.2558\ln(\varepsilon) - 5.5691$	0.57
BD	$N_f = 0.1809\ln(\varepsilon) - 4.5656$	0.37

Conclusions

Based on the results obtained from using Date Seed Ash in an asphalt mix and investigating the role of two different additive types in mixes, the following conclusions can be drawn:

1. Application of DSA as a bitumen modifier improves fatigue behavior of both bitumen and asphalt mixes to a good extend.
2. Based on LAS testing results, siliceous additive decreased fatigue resistance of bitumen. In contrast, limestone additive increased fatigue life of bitumen to some 12%. With this regard, the addition of 3% and 6% of limestone additive to asphalt mix resulted to increased fatigue life of mixes up to 32% and 55%, respectively.
3. Evaluating the effects of DSA on fatigue life of bitumen showed that there was a peak in the trend. Regression analysis of LAS testing data yielded to an optimum value of 4.6% of the weight of bitumen in order to achieve a better behavior against fatigue failure.
4. ITFT results showed that siliceous additive had a detrimental effect on fatigue life of asphalt mixes. At stress level of 150 kPa, for example, the addition of 3% and 9% siliceous additive to bitumen, resulted in 33% and 40% decrease in fatigue life of mixes, respectively.
5. Similar to LAS testing, with adding DSA to an asphalt mix, its fatigue life will first increase, and then it will decrease. Hence, an optimum amount of DSA should be determined to be added to HMA mixtures.
6. Regression models were developed, based on fatigue coefficients in logarithmic scale in order to show a meaningful relationship between fatigue properties of bitumen and that of asphalt mixes. However, a logical relationship between fatigue behavior of modified bitumen and HMA mixes could not be established. The sources of errors or uncertainties of precisions in performing laboratory tests might have caused this incompatibility.

Disclosure statement

No potential conflict of interest was reported by the authors.

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