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EVALUATION OF THE FATIGUE BEHAVIOR OF STONE MASTIC ASPHALT MODIFIED BY DOMESTIC WASTE BIO-ASPHALT

*Dr. Sady Abd Tayh[1], Dr. Ratnasamy Muniandy[2], Salihudin Hassim[3], Dr. Fauzan Mohd Jakarni[4]

1) Lecturer, Highway and Transportation Engineering Department, Al-Mustansiriayah University, Baghdad, Iraq.
2) Dr. Prof., Department of Civil Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia.
3) Associated Prof., Department of Civil Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia.
4) Dr., Department of Civil Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia.

Abstract: This paper presents the results of a laboratory study based, upon evaluating the fatigue characteristics of Stone Matrix Asphalt (SMA) Mixtures using different percent of bio-oil produced from pyrolysis process of house hold waste. The indirect tensile fatigue (ITFT) test was used to study fatigue behavior. The fatigue tests were performed at three temperatures (15, 20, and 25°C) using one asphalt binder, 80/100 penetration asphalt. The outcomes demonstrated that the addition of DWBO has slightly lowered the resilient modulus, and reduced the fatigue performance of the SMA Mixtures. For the effect of the temperature on fatigue life of 80/100 bio-binders, it is reasonable to use DWBO in asphalt mixture as an additive in cold to moderate temperature regions. The study shows that the DWBO can be used with petroleum binders in the pavement industry with a percent not exceeding 3% by weight of the base binder.

Keywords: *Bio-oil; Indirect Tensile Fatigue Test; SMA; Energy Ratio.*

تقييم تصرف الكلل للخلطات الاسفلتية الحجرية المحسنة بالزيت الحيوي

الخلاصة: هذه الورقة البحثية تبين النتائج المستندة على الدراسة المختبرية من خلال تقييم خواص الخلطات الاسفلتية الحجرية باستخدام نسب مختلفة من الزيت الحيوي المنتج من مخلفات المنازل. طريقة الشد الغير مباشر استعملت لدراسة تصرف الكلل. فحص الكلل اجري بثلاث درجات حرارة (15، 20، و 25°م) باستخدام نوع واحد من الاسفلت (80\100). مخرجات البحث بينت ان اضافة الزيت الحيوي قد قلل معامل اللدونة تقليلا طفيفا، كما قلل من تصرف الكلل للخلطة الاسفلتية. بالنسبة لتأثير درجة الحرارة على تصرف الكلل للخلطة الاسفلتية المعدلة بالزيت الحيوي، فانه من الممكن استخدام الزيت الحيوي في الخلطات الاسفلتية كمضاف في مناطق الاجواء الباردة و المعتدلة. هذه الدراسة بينت بأن الزيت الحيوي يمكن يستخدم مع المواد الرابطة التقليدية في صناعة التبليط الاسفلتي بنسبة لا تتجاوز 3% من وزن المادة الرابطة الاساسية.

* saabta75@yahoo.com

1. Introduction

The restricted reserves of crude petroleum have driven the asphalt industry recently to confront the rise in prices and conceivably supply deficiency. Various analysts are researching the topic of reducing the employment of crude asphalt. The first thought of this approach is to get materials that have comparative properties as the petroleum-based asphalt binders and utilize them within the pavement construction.

Bio-Saphalt binder could be defined as an "asphalt binder alternative, derived from non-petroleum based renewable resources, which should not rival any food material, and have environmental and economic benefits" [1]. Based on this definition, bio-oils are these materials that can be delivered from biomass materials such as urban yard waste [2], tea and coffee residue [3,4], corn stover [5], rapeseed and soybean [6,7], etc. The bio-oils have been introduced to the asphalt pavement structure either as a modifier or as a partial replacement for asphalt binders [5,8-11].

The introduction of polymers into the bio-oils from various sources (oakwood, switchgrass, and cornstover) have been investigated by many researchers. It is found that the rheological performance of modified bio-binders changed essentially after adding polymer modifiers, and the low-temperature performance grade for the produced bio-binders may fluctuate altogether from that of the bitumen binders [12-14]. Depending on the conclusions of these studies, the use of bio-oil as a modifier for asphalt binder was very favorable.

The use of bio-binder produced from swine waste may reduce the asphalt binder stiffness and enhance the low temperature performance [9,15]. In addition, the employment of bio-oil as an additive to the crude oil asphalt binders can decrease the production temperature of the asphalt pavement, which can in turn reduce fuel consumption and greenhouse discharge and enhance work site conditions for laborers [16-18]. The utilization of bio-oil also can greatly enhance the asphalt mixture fatigue performance and has no critical impact on the rutting performance and dynamic modulus, however can marginally affect the tensile strength [19].

In spite of all the significant study advancements in the use, application, and development, there is little existing research in direct relation to the performance evaluation of asphalt mixtures modified by bio-oils, especially in SMA Mixtures. Thus, this study tries to make an investigation of the fatigue performance of SMA Mixtures modified by DWBO through laboratory evaluation.

In this study, one base asphalt binder utilized as a control group was modified by adding 3, 6, and 9% Domestic Waste Bio-Oil (DWBO) by weight of the base asphalt to be tested for fatigue performance at three temperatures, namely 15, 20 and 25 °C. This range is the most critical for fatigue distress to take place at modest climate regions.

2. Materials And Methods

2.1. Aggregate

Granite aggregates from Kajang Road Stone Quarry are chosen to be used in the asphalt mixture of this study.The basic properties of the granite aggregates are determined to ensure that they comply with the requirements of this study. One gradation was selected within the specifications of JKR SMA NMS 12.5mm as shown in Figure 1.The mineral filler was limestone dust. The properties of granite aggregate are shown in Table 1.

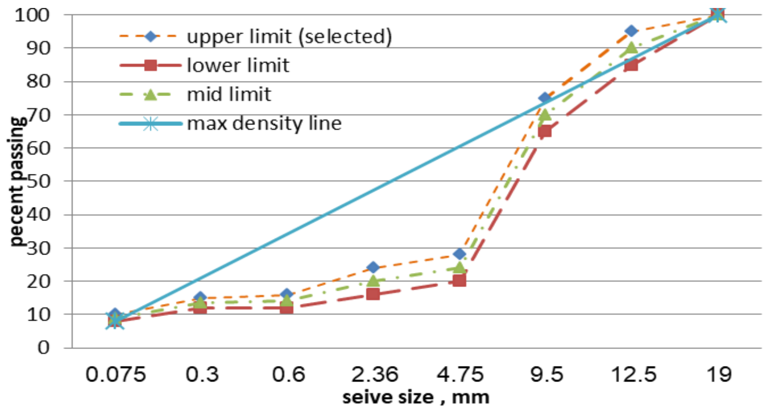

Figure 1. Gradation of Aggregate Used

Table 1. Physical Properties of the Granite Aggregates

Type of Test	Standard Used	Results Obtained	Requirement	Remarks
Los Angeles Abrasion (LA)	ASTM C131	26.27 %	<30%	Suitable
Aggregate Impact Value (AIV)	BS812: part3	7.8%	<15%	Suitable
Polished Stone Value (PSV)	ASTM C88-83	50.75	>40	Suitable
Soundness	BS812: part3	5.23	<20	Suitable
Flakiness Index	BS812: part3	18.1%	<20%	Suitable
Elongation Index	BS812: part3	6.9%	<20%	Suitable
Specific Gravity	ASTM C127	2.622	>2.60	Suitable
Absorption (%)	ASTM C127	0.42	-	-

2.2. Asphalt Binder

The commonly used 80/100 penetration grade soft binder was intentionally selected as the base binder in this study to produce SMA Mixtures. The physical and rheological properties of base asphalt binder are shown in Table 2.

Table 2. Physical and Rheological Properties of the Base Binders Used

Type of Test	Standard Used	Test Results
Penetration @ 25 °C	*ASTM D5	81.7
Softening point, °C	ASTM D36	45
Flash point, °C	ASTM D92	280
Fire point, °C	ASTM D92	310
Specific Gravity	ASTM D70	1.036
Viscosity @ 135 °C (cpoise)	ASTM D4402	332
Viscosity @ 165 °C (cpoise)	ASTM D4402	111
Penetration after RTFOT	ASTM D5	41.7
Softening point after RTFOT	ASTM D36	50.3

*American Society for Testing and Material
**American Association of State Highway and Transportation Officials

2.3. Domestic Waste Bio-Binder

To produce bio-oil from house hold waste, the fast pyrolysis procedure was performed, where waste bio-mass materials are heated rapidly in a vacuum device to transform them into fractures like bio-char, aerosols, and vapors. Prior to introducing the biomass (waste materials) into the pyrolysis process, the domestic wastes materials should be dried at about 100°C for 24h period, then the pyrolysis process was done at about 500°C. Quick vaporization was then done on the product from the pyrolysis stage to be condensed utilizing cooling method to get the ultimate bio-oil product [20].

The water content of this kind of bio-oil was around 15–35% by weight. The high water content is because of the origin of the biomass sustain stock. The physical properties of original DWBO are shown in Table 3 [20].

Table 3. Physical Properties of Original Bio-Oil from Domestic Waste

Physical property	Test value
Specific gravity	1.09
pH	6.3
Moisture content (wt%)	15-35
Rotational viscosity at 135 °C (Pa.S)	0.10

Since the bio-oil has high percent of water content, an upgrading process has been performed to reduce the water content to be less than 10% throughout dehydration process by heating the bio-oil indirectly in a suitable oven at 100°C. The next step to introduce the treated DWBO into the base asphalt binder to give bio-binder. The blending procedure was done at a constant rotation speed of 1000 rpm utilizing medium shear blender at a temperature 120-125°C until steady state were accomplished.

3. Theory and Calculations

3.1. Fatigue Criteria for the HMA Mixtures

The general definition of fatigue life is the number of load repetitions to failure for an asphalt mixture. Fatigue resistance normally demonstrates asphalt pavement capability to resist repeated cyclic loading that causes break [21].

During the formation of fatigue cracking, there are two phases of the degradation process which could occur. The first stage is denoted as crack initiation which relates to degradation coming about due to damage that is consistently distributed throughout the material. This stage is showed by the start and proliferation of a network of micro-cracks which causes a decrease in stiffness modulus of the material. The second stage is denoted as crack propagation which begins with the coalescence of these micro-cracks and the presence of macro-cracks which engender within the asphalt material [22].

As a compacted asphalt mixture specimen is repeatedly loaded during a fatigue test, it releases energy. From controlled strain fatigue tests conducted in the simple bending test, there is a clear change in behavior at N_1 when the energy ratio is plotted versus the number of load application cycles, as can be seen in Figure 2. Generally, the formation of cracks may occur at this point.

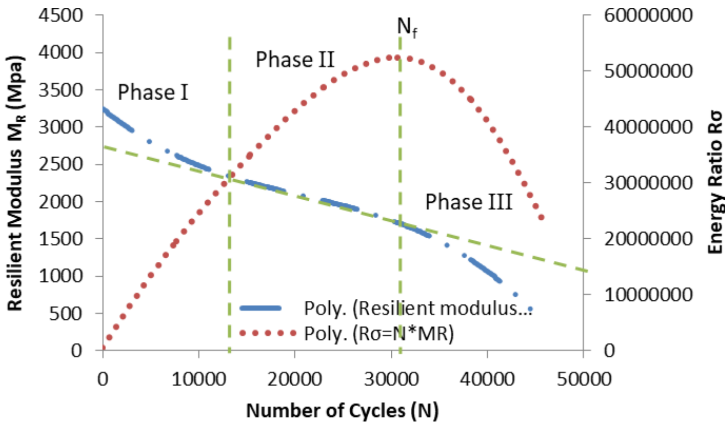

Figure 2. Expected Typical Fatigue Failure Point for Indirect Fatigue Test [22]

Dissipated energy is given by Equation 1:

$$W = \pi.\sigma.\varepsilon.\sin\phi \tag{1}$$

where σ, ε and Φ are the stress, strain, and their phase lag between them, respectively. However also, the energy ratio could be put as in Equation 2:

$$\text{Energy Ratio (ER)} = \frac{\mathrm{N}(\pi\,\sigma_0\,\varepsilon_0 \sin\Phi_0)}{(\pi\,\sigma_i\,\varepsilon_i \sin\Phi_i)} = \frac{\mathrm{NW}_0}{\mathrm{W}_i} \tag{2}$$

This Equation is for controlled strain bending tests. If further approximation were to be made for a controlled stress test, to simplify the equation, Rσ will be produced as in Equation 3:

$$\mathrm{R}_\sigma \cong \mathrm{N}\,\mathrm{E}_i^* \tag{3}$$

where Rσ is the equivalent energy ratio, which when plotted versus number of repetition of load, produces a curve as can be seen in Figure 2.

For the ITFT test in this research, controlled stress test mode is used and the modulus measured directly during the progress of the test is Resilient Modulus (MR), thus, the approximation for Energy Ratio will be as in Equation 4:

$$R_\sigma = N_i \times M_{R_i} \tag{4}$$

where M_{Ri} is the Resilient Modulus (MPa) at cycle i. Fatigue failure was then considered to occur at the maximum value (peak) of equivalent energy ratio (Rσ) against N plot. This demonstration of fatigue failure is considered a more exact and sensible method of characterizing fatigue failure than simply deciding failure as an arbitrary condition, for example, full fracture of the sample, or a 50 or 90% reduction in initial stiffness.

For this study, based on the EN-12697-24 [23] standard, fatigue life of the cylindrical specimen corresponds to the peak point of the energy ratio (cycle number multiplied by resilient modulus) ($N.M_R$) diagram as shown in Figure 2.

During a fatigue test, stiffness modulus value diminishes, the first stage (phase I) demonstrates a sharp fall in stiffness modulus because of repetitive load excitation encountering fast damage in the early stage of a test. Phase II demonstrates a semi straight diminishing in stiffness; where the rate of damage remains to some extent through a constant representing controlled micro-cracking. After that, the specimen encounters an accelerated period of damage and begins to crack quickly at the time of phase III because of non-consistency in the strain field [22,24,25].

3.2. Indirect Tensile Fatigue Test

The fatigue test was performed by applying a repetitive load of 3.0 kN, with 0.1s loading time and 0.4s rest time. A universal testing machine (UTM), made by Industrial Process Control (IP Global), was utilized for this reason. The loading frame was kept in a conditioning chamber in order to keep temperature constant prior and amid the process of the test. The deformation values of the diametral samples were measured using LVDTs. A cyclic compressive load was shed to the samples over the vertical cross section along the depth of the sample utilizing two loading strips 12.5 mm in width.

The relationship between the vertically applied compression load and the subsequent tensile stress is calculated according to Equation 5. The resultant ultimate tensile strain at the horizontal axis of the center of the sample was ascertained utilizing Equation 6.

$$\sigma_{\max} = \frac{2P}{\pi Dt} \tag{5}$$

$$\varepsilon_{\max} = \frac{\sigma_{\max}\,(1-3v)}{S_m} * 1000 \tag{6}$$

where σ_{max} is the maximum tensile stress at the center of specimen (kPa); ε_{max} the maximum tensile strain at the center of specimen (microstrain); S_m the indirect tensile stiffness modulus at σ_{max} (Mpa); P the dynamic vertical load applied (kN); D the diameter of specimen (m); t the height of specimen (m) and v is the Poisson's ratio and assumed to be (0.35).

4. Test Results And Discussion

This segment is made to deal the testing outcomes and shown her based on the examination directed on the indirect tensile fatigue test raw data in this study.

4.1. The Effect of DWBO on Resilient Modulus

The resilient modulus test results of mixtures are shown in Figure 3. The results indicate that addition of DWBO in SMA Mixtures produced lower resilient modulus, where the values denote the mean of three specimens.

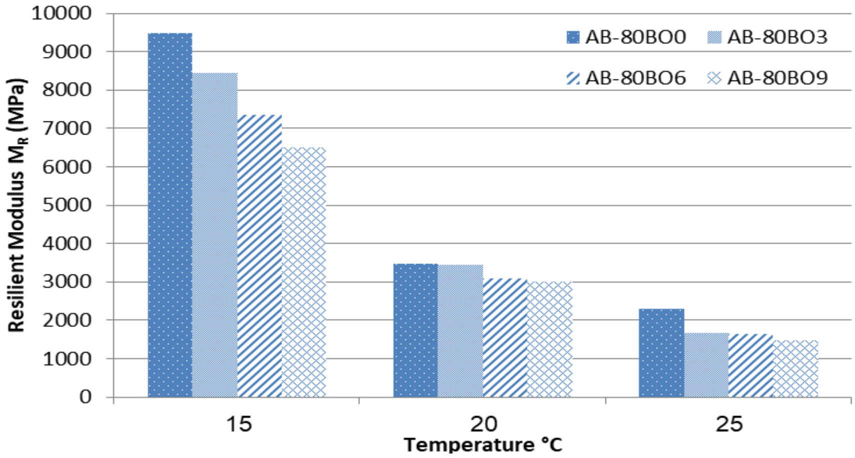

Figure 3. Resilient Modulus Versus Temperature for 80/100 DWBO SMA at 15, 20, and 25°C

Figure 3 illustrates the resilient modulus variation versus temperature for mixture samples containing different percentages of DWBO. Results have shown that , in general, the resilient modulus of the tested samples reduced with the increase temperature. This case is due to effect of the reduced viscosity of the binder with the increase in bio-oil percent and with respect to temperature.

The higher temperature led to particle slippage in the asphalt mixtures, which in return lead to decrease the resilient modulus of overall DWBO modified mixture [26]. In addition, the resilient modulus of DWBO modified asphalt mixtures was lower than that of unmodified mixtures as due to the presence of DWBO that gives the softening effect to the asphalt mixture due to its low viscosity. However, the rate of resilient modulus decrease with the increase of the DWBO percentage in the base asphalt is lower than that of unmodified samples.

From the results of the resilient modulus of SMA Mixtures, the stiffness decreases with the increase in DWBO content; this decrease might be considered unfavorable for fatigue resistance performance at temperatures in the upper limit of the intermediate temperature range (between 15–30°C).

It is clear from Figure 3 that, by decreasing the temperature, the resilient modulus of asphalt mix samples has an increasing rate. Although, this rate increase is not the same for asphalt mixture samples that contain various proportions of DWBO. As the temperature decreases to a lower degree, the asphalt mixture tends to become less ductile.

4.2. The Effect of Bio-Oil on Fatigue Life at Different Temperatures

The combined effect of DWBO and temperature on fatigue life of SMA was obtained from comparing stiffness modulus, fatigue life and accumulated strain of asphalt mixture specimens prepared using different percentages of DWBO at controlled loading magnitude of 3.0 kN and at different temperatures of 15, 20 and 25°C was conducted to 80/100 DWBO binders to measure the susceptibility of SMA Mixtures modified with bio-oil to the change in temperature. The test results are summarized in Table 4.

Table 4. Summary of ITFT results for 80/100 Bio-binders at 15,20 and 25°C

Temperature °C	Binder Type	Average initial strain (μm/m)	Average initial stiffness (Mpa)	Average stiffness @ failure point (Mpa)	Average N_f
15°C	AB-80BO0	27.94	9468	3745	679253
	AB-80BO3	30.08	8447	3212	610347
	AB-80BO6	32.86	7356	3207	374400
	AB-80BO9	36.68	6506	3056	212427
20°C	AB-80BO0	272.34	3456	1751	40134
	AB-80BO3	353.24	3453	1621	34893
	AB-80BO6	460.97	3097	1287	18213
	AB-80BO9	499.43	2999	1427	16293
25°C	AB-80BO0	432.94	2284	1251	8927
	AB-80BO3	1463.81	1660	916	2433
	AB-80BO6	1520.74	1626	935	2224
	AB-80BO9	1713.15	1463	713	1833

From Table 4, the stiffness of asphalt mixtures samples was decreased with the increase in bio-oil proportion in pavement mixture. However, at temperatures below 20 °C, namely 15°C, there was less decrease in the stiffness; the way that makes the asphalt mixture less susceptible to bio-oil percent at lower temperatures and hence, less sensitive to fatigue cracking. Thus, the results were highly dependent on the test temperature and this is supported by Minhoto *et al.* (2009) [27]. The change in fatigue life resistance between the various bio-oil content was lower at lower initial strain levels compared by that at higher initial strain.

To compare the fatigue results at the three test temperatures (15, 20 and 25°C), the number of cycles to fatigue failure was plotted versus the strain level for the three temperatures in the same plot as shown in Figure 4. This figure clearly showed that the fatigue life decreased with the increase in temperature from 15 °C to 25 °C. The power model was the best function to fit the scatter data in this figure at the three temperatures with a coefficient of simple determination (R2) of 0.96, 0.92, and 0.99, respectively [28]. At a temperature of 25 °C, the difference in fatigue life (N_f) between the various bio-oil content samples was found to be higher with higher initial strain than that at lower temperatures with lower initial strain levels.

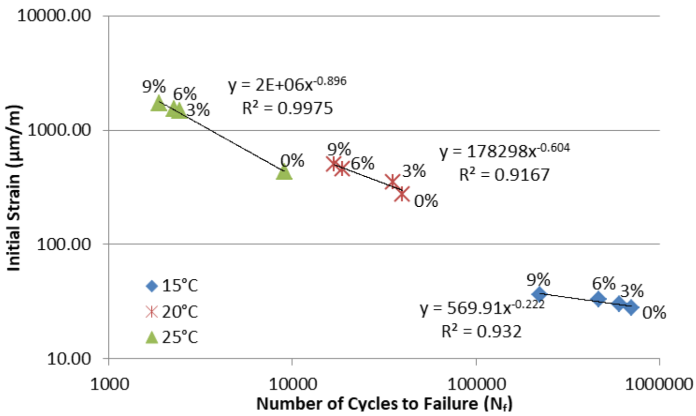

Figure 4. Number of cycles to failure (N_f) versus initial strain (ε_{in}) at Temperatures 15, 20 and 25 °C for 80/100 Bio-binders

5. Conclusions

The purpose of this research is to assess the effectiveness of the use of DWBO on the dynamic properties of SMA mixtures by adding bio-oil produced from domestic waste to the base asphalt binder (80/100) at proportions of 0, 3, 6, and 9% by the weight of the base asphalt binder. Based on the test results, the following conclusions were made:

- The addition of DWBO resulted in reducing the fatigue performance of SMA Mixtures by reducing the number of repetition to failure in ITFT.
- The addition of DWBO has slightly negative effect on the stiffness modulus of the SMA due to the softening effect of the bio-oil on the base asphalt binder.
- The fatigue life is highly dependent on temperature and the effect of the DWBO concentration at higher temperature (25°) is higher than at lower temperature (15°C).
- The fatigue results conform with the hypothesis that stress controlled fatigue tests favor stiffer materials. However, the ranking of mixtures may change if a strain controlled fatigue test is conducted.

Overall, bio-oil generated from domestic waste resources can be one candidate as a replacement for the petroleum asphalt binders when low bio-oil fraction is used, where the DWBO is about 3% by weight of asphalt binder at cold to moderate climate regions.

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