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Development Of A Fatigue Model For Hot Mix Modified Asphalt Based On The Critical Temperature Of Asphalt Rheology

Raden Hendra Ariyapijati[1]

[1]Teknik Sipil-Fakultas Teknik-Universitas Mercu Buana, Jakarta
email: raden.hendra@mercubuana.ac.id

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Abstract

External factors that affect the structure of the road pavement are the loads of traffic and the environment (temperature, weather). Fatigue cracking is one of three major distresses for asphalt pavement. One method used for fatigue analysis is classical fatigue. This method is used to obtain an equation model which predicts the service life of a road pavement. Apart from problems like this, there needs to be innovation both in terms of materials and road pavement planning, namely by modifying the asphalt mixture, such as adding buton asphalt and crumb rubber. This research is intended to develop a Monismith model that is used to predict the fatigue life of a road pavement material. Three types of asphalt, namely 60/70 penetration asphalt, buton modified asphalt and crumb rubber modified asphalt were used in this research. The fatigue test used the Four Point Bending Test (4PBT) tools. The specimen which used to fatigue test with 4 variations of asphalt mixtures, 4 variations of temperatures at 15°C, 20°C, 25°C and 30°C. The results of the four-point bending test showed that the N_f value (maximum number of repetitions) at a temperature of 30°C was 394,400 cycles, with 15% crumb rubber modified asphalt. The development of a fatigue model with a critical temperature approach to asphalt mechanistic rheology has resulted from this research.

Keywords: *Fatigue, modified asphalt, stiffness*

INRODUCTION

Fatigue is a well-known process that relates to material failure due to the repeated loading and unloading at a stress level that is below the ultimate strength of the material. For bituminous materials, this is due to vehicles traveling over the pavement, each wheel passing on the pavement can be considered as a loading cycle. Fatigue causes progressive damage in the asphalt, which will lower the material's strength and stiffness, before finally resulting in premature failure (Fallon, Mcnally, & Gibney, 2016).

Fatigue cracking is a load associated cracking that is caused due to repeated traffic loading. This type of cracking is considered to be one of the most significant distress modes in flexible pavements. The fatigue life of an asphalt pavement is directly related to various engineering properties of hot mix asphalt mixtures (Ziari, Babagoli, Ameri, & Akbari, 2014).

With the increase in heavy traffic volume, crack fatigue from the asphalt layer has become one of the main types of road damage in flexural hardening, associated with repetitive traffic loads. Fatigue cracking reduces the structural capacity of the pavement and increases maintenance costs. Furthermore, after fatigue cracks propagate through the entire thickness of the asphalt, water and aggressive materials can infiltrate the pavement layer, greatly accelerating the breakdown process. Therefore, understanding the fatigue cracking phenomenon and measuring the fatigue properties of asphalt concrete are important for flexible pavement design (Luo, Xiao, Hu, & Yang, 2013).

Load related factors include the loading frequency which relates to the vehicle speed and load induced strain at the bottom of the asphalt layer. Material related factors include hot mix asphalt properties and asphalt binder properties. Of course, temperature affects all these material properties. Effects of these factors such as loading frequency and strain level on fatigue life of HMA have been studied for a long time (Dehghan & Modarres, 2017). Increasing air temperatures, especially in tropical countries, can increase the temperature of the road surface. Meanwhile, an increase in traffic volume and load on vehicle wheels require asphalt mixtures that are resistant to increased temperatures and loads. Some researchers have engineered new materials from the conventional asphalt mixture by introducing additives.

Currently, the demand for good asphalt mixture performance is increasing and the need to protect ecosystems has led designers of pavement structures to develop new technologies, use new materials, improve analysis models, and improve asphalt mixture design methods for pavements. The criterion is to promote the use of available resources more rationally and consider low environmental impact techniques (Shadman & Ziari, 2017).

Fatigue cracks mostly occur at medium and low temperatures because reducing the temperature increases the bitumen stiffness and at these temperatures asphalt mix tends to behave like a brittle material. Most standards of fatigue testing propose to analyze the fatigue response of asphalt-mix at moderate temperatures (e.g. 25ºC). At lower temperatures, due to material stiffening, for a constant load the number of loading applications lead to cracking will be too high. However, at higher initial strains sudden cracking is a dominant phenomenon (Modarres & Hamedi, 2014).

The conventional asphalt mixes, unavoidably encounter aged-hardening due to oxidation of the asphalt. The bitumen in asphalt mixes hardens as a result of the ageing process, thus increasing the mix stiffness. Hardening was primarily associated with loss of volatiles in asphalt during the construction phase, and progressive oxidation of material in the field (Q. Liu, Yu, & Wu, 2017). Evaluation of the binder properties influencing associated mixture fatigue resistance and its field performance can be a good criterion. During the Strategic Highway Research Program (SHRP) project, researches proposed to use binder's shear modulus (G*) and its phase angle (δ) as the mixture fatigue index to evaluate asphalt pavement performance (Ameri, Nowbakht, Molayem, & Mirabimoghaddam, 2016).

The overall history of the development of fatigue models can be subdivided into five main categories/approaches as follows: the phenomenological approach, the continuum damage mechanics approach, the fracture mechanics approach, the energy and dissipated energy approach (Saboo, Das, & Kumar, 2016). This study focusses on analyzing the phenomenological approach. Traditionally the failure in this approach is defined to be reduction in 50% of the initial stiffness of the material.

The use of standard materials and the use of new materials as additives to improve the performance of asphalt mixes, especially against the effects of temperature changes or other environmental changes. Two primary components exist in a road pavement: a combination of asphalt binder and aggregates as a mixture that serves to realize excellent performance. However, several other factors such as water penetration, traffic loading, poor asphalt, and aggregate binding can cause the collapse of bonds between the asphalt binder and aggregate particles (Davar, Tanzadeh, & Fadaee, 2017).

The asphalt mixture modified with CR from used tires in hot asphalt mixes have become a promising technique for performance improvement in recent years. Two techniques used to add CR to bituminous mixes are wet and dry processes. From these two methods, the dry process is less popular because it produces poor results initially (Moreno-navarro, Sol-sánchez, Rubio-gámez, & Segarra-martínez, 2014). The wet-processed CR mixture is stronger than the dry mixture in indirect tensile strength (Jeong, Lee, Amirkhanian, & Kim, 2010).

Variant analysis indicates that among the three factors of CR type, particle size, and content, content is the primary factor that influences the performance of CR-modified asphalt, followed by the type of CR and particle size (S. Liu, Cao, Fang, & Shang, 2009). The dosage and percentage of CR used, the addition of wet and dry process-CR process to asphalt mixed with conventional asphalt increases its resistance to plastic deformation. This also increases the stiffness modulus, creep modulus, and its resistance to plastic deformation caused by vehicle traffic loads (Moreno, Sol, Martín, Pérez, & Rubio, 2013). Penetration, ductility, and asphalt binder phase angles decreased, and softening points, elastic recovery, viscosity, complex modulus, and asphalt rutting parameters increased when CR was added to asphalt. A high CR swelling rate is advantageous for preparing a successful CR as a modification of the asphalt binder (Cong, Xun, Xing, & Chen, 2013). Natural asphalts are another kind of additive used in hot mix asphalts. Natural asphalts are the most widely used natural binder modifiers. Various studies have shown that use of natural asphalt in hot mix asphalts enhances their properties (Yilmaz & Ertug, 2013).

The material aggregate consisted of course, medium, and fine aggregate with the largest size of 19 mm, and the composition is shown in Fig. 1.

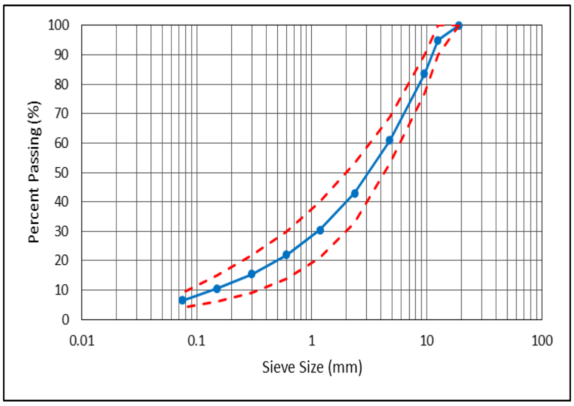

Figure 1. Aggregate distribution on gradation chart.

The increasing number of vehicles has increased the number of used vehicle tires. The utilization of used tires includes processing them into new materials, such as rubber powder. Rubber tires can be used as an additive in asphalt cement to improve hollow roads (Lavasani, Latifi, & Fartash, 2015). CR is made from used tire rubber, in the form of fine powders through no. 30 (0.6 mm). For the CR modification asphalt preparation process, asphalt binder is heated when it reaches 177 ˚C and CR powder (5%, 10% and 15% of the total weight of asphalt) is added gradually into the asphalt in a high rotary mixer at a speed of 700 rpm until it reaches a homogeneous mixture (Shafabakhsh & Tanakizadeh, 2015).

The Buton asphalt originates from the rock asphalt on Buton Island, Southeast Sulawesi, Indonesia. This type of asphalt has been used widely in Indonesia with various processing methods because deposits of almost 677 million tons exist while the production is still low. It can be used directly as a lightweight traffic surface layer material, and through processing for moderate and heavy traffic, because it still contains large amounts of minerals. The asphalt content in Buton asphalt varies between 20–30%. Buton asphalt contains high aromatic and resin that increase its adhesion and flexibility. In this study, the Buton asphalt used was the result of extracting Buton asphalt, by separating the asphalt from its mineral content.
The main objective of this study is to evaluate the fatigue lives of hot mix modified asphalt with crumb Rubber and Buton natural asphalt additives.

RESEARCH METHODOLOGY

The research conducted is an experiment in the laboratory. The pavement material to be studied is a modified Hot Mix Asphalt.

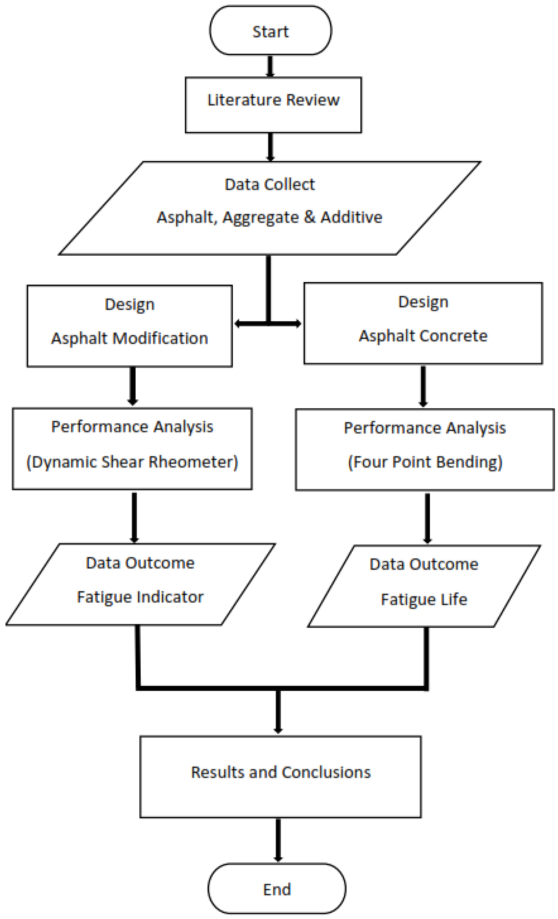

Figure 2. Research Flow Chart.

Laboratory experiments conducted refer to the Indonesian National Standard, the American Association of State Highway and Transportation Officials (AASHTO) and the American Society for Testing Materials (ASTM). The research variables that influence it are the independent variables, namely: asphalt content, additive content and temperature. While the dependent variables consist of stress, strain, modulus, deformation and fatigue life.
To analyze the data obtained from dynamic tests conducted on modified asphalt with dynamic shear rheometer tests and on asphalt mixtures tested with four-point bending. Analysis was carried out by combining the rheological properties of asphalt with the properties of the aggregate asphalt mixture material. In analyzing the asphalt mixture, the characteristics obtained are the behavior of the asphalt because the aggregate in the mixture is locked (fixed variables).
The characteristics resulting from the analysis of fatigue were tested statistically with multiple regression and correlation tests, so that conclusions were obtained that answered the research objectives.

Table 1. Modified Asphalt

No.	Modified Asphalt Code	Asphalt + Additive	
		Base	Additive
1	C1	95%	5% crumb rubber
2	C2	90%	10% crumb rubber
3	C3	85%	15% crumb rubber
4	B1	92%	8% Buton asphalt
5	B2	90%	10% Buton asphalt
6	B3	88%	12% Buton asphalt
7	O	100%	0%

RESULTS AND ANALYSIS

Rheological of Modified Asphalt is used widely to measure the consistency of bitumen at a certain temperature; it is a method to establish a classification rather than a measure of quality. Penetration is related to viscosity, and empirical relationships have been developed for Newtonian materials. Based on the analysis of kinematic viscosity of each binders, the mixing and compaction temperature for asphalt mixture can be determined.

The rheology parameter such as G* (complex shear modulus), G' (storage modulus), G" (loss modulus) and δ (phase angle) can be obtained from dynamic shear rheometer (DSR) test. G* is the ratio of total shear stress to total shear strain. This G* parameter is a fundamental property of materials.

Fig.3 shows the change of complex shear modulus to the temperature sweep at the PAV condition (aged) in laboratory. At this temperature sweep test, the angular frequency of 10 rad/sec or equivalent with traffic speed of 55 mph (90 km/hour) was selected.

In the PAV (aged) bitumen condition, it is clear that with increasing temperature, the complex shear modulus (G*) decreases. The complex shear modulus G* for the modified asphalt is lower than that of the 60/70 pen base asphalt at various low temperatures, except that the modified asphalt with the addition of 15% and 5% CR has a higher G* value. 15% CR asphalt has the highest complex shear modulus and low phase angle compared to base asphalt. It has a viscous characteristic, when stretched and released it tends to recover its original shape and makes the binder more flexible.

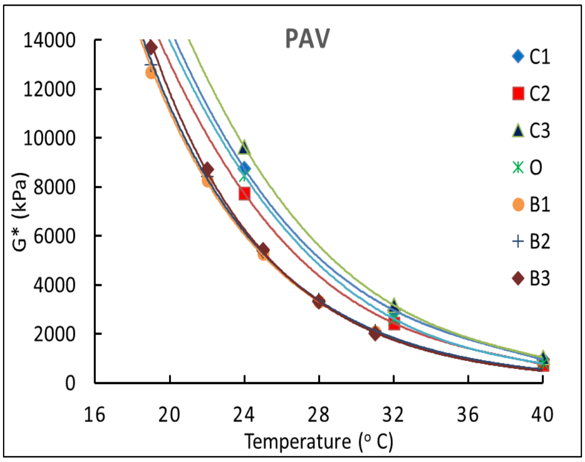

Figure 3. Change of G* at temperature sweep

From these results it can be seen that the modified asphalt with the addition of CR increases G* which helps to resist damage. CR 10% gives the best results this is because the oil in the asphalt absorbs into the CR. The modified bitumen is completely stable and the increase in rheological properties is due to the increase in the elasticity and tensile strength of the asphalt. Using a CR modifier increases the elasticity of the asphalt binder at high temperatures and increases flexibility at low temperatures.

It is known that there are four types of chemicals used to classify the composition of bitumen. Understanding the chemical composition helps to know how the CR modifier affects the properties of the bitumen. The main chemical compositions are asphaltenes, resins, aromatics and saturates, each component affecting the properties of bitumen. Resin, aromatics and saturation make up the maltenes fraction of the asphalt. In order to obtain harder bitumen with less liquid bitumen, the asphalt content must be increased.

When CR is added to the bitumen, the elastomer absorbs all the maltenes component of the bitumen leaving the remaining bitumen containing more asphaltenes. The crumb rubber modified asphalt is harder than base asphalt.

The application of the lighter fraction of CR to the asphalt in greater quantities, subsequent changes in asphalt rheology also have a detrimental effect on cohesion, improved rheological properties should lead to increased resistance to routine asphalt at high temperatures and fatigue cracking at low temperatures.

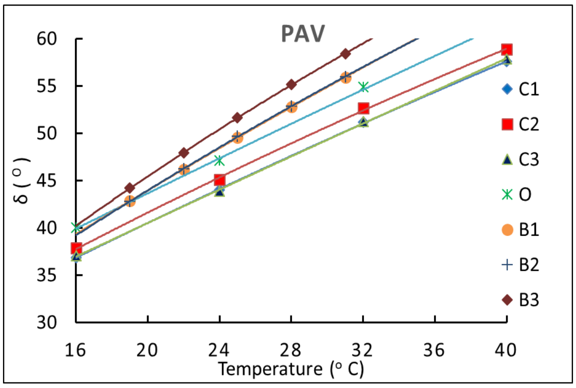

Figure 4. Change of δ at temperature sweep

The bitumen is tested with the DSR to determine the fatigue cracking potential of hot mix asphalt. The fatigue potential is measured by the fatigue factor, defined as G* sin δ. This is done because it can be shown that under a strain-controlled process, the work done for fatigue is proportional to G* sin δ. Hence a lower value of G* sin δ means slower potential of fatigue cracking. This can be explained by the fact that as G* decreases, the asphalt binder becomes less stiff and is able to deform without building up large stresses, and as δ value decreases, the asphalt binder becomes more elastic and hence can regain its original condition without dissipating energy. An upper limit is set on the G* sin δ value in the Superpave specification, in order to minimize the potential of fatigue cracking (Bahia and Anderson, 1995). Since the asphalt binder becomes stiffer due to aging during its service life and becomes more susceptible to cracking, the DSR test for fatigue factor determination is conducted on PAV-aged samples.

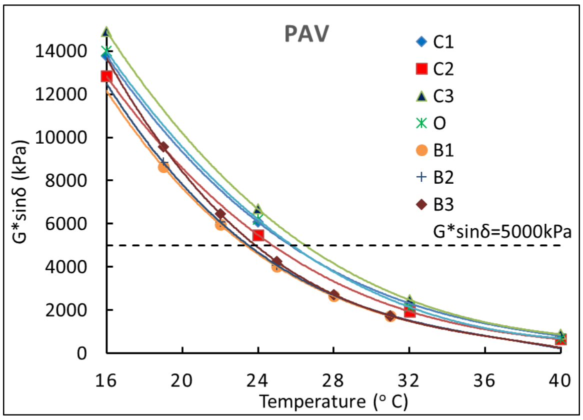

Figure 5. The change of G* sin δ (fatigue indicator)

Asphalt resistance to fatigue under aged conditions is indicated by the value of G*sin δ, where the value must be less than 5000kPa. From Figure 5, it can be seen that the critical temperature value for fatigue resistance. Asphalt with CR 5% shows a critical temperature value at 26˚C, and Asphalt with CR 10% shows a critical temperature value of 25˚C, Asphalt with CR 15% shows a critical temperature value of 27˚C and Asphalt base has a critical temperature value 26˚C. It can be concluded that the addition of CR to asphalt for aged conditions resulted in widening the range of critical asphalt temperatures. The critical temperature is lower than the base asphalt, except for asphalt with 15% CR additives. This has a positive impact because fatigue cracking will occur at lower temperatures. For asphalt with Buton asphalt additives (8%, 10% and 12%), the critical temperature is much lower than for other modified asphalts, it's at 24˚ C. This indicates fatigue cracking will occur at lower temperatures. Resistance to fatigue damage is better than others.

Four point bending fatigue test was conducted following the AASHTO T 321 protocol to evaluate the fatigue behavior of the mix. Fig. 6 shows the setup for four point bending fatigue test. Beam samples were prepared using a kneading compactor. The beam samples were 380 mm length, 63 mm width and 50 mm height. The samples were loaded under strain-controlled conditions using sinusoidal loading. According to the standard, the sample stiffness at 50th cycle is defined as the initial stiffness. Samples were tested at three strain levels: 700 600 500 at loading frequencies of 10 Hz. In this study, the failure criteria were a 50% reduction of the initial stiffness value.

Figure 6. Test device for 4PB

Phase angle occurs due to viscoelastic asphalt materials, where the immediate response is elastic and the response is delayed from the viscous material. There is a time lag between the applied stress and the resulting strain. Elastic material there is no phase difference between the applied stress and the resulting strain, Phase angle 0° means the material is elastic while phase angle 90° means it is viscous. At low temperatures and high frequencies, small phase angles are found because bitumen is close to elastic behavior. On the other hand, at high temperature and low frequency it shows a high value of the phase angle because the bitumen is close to viscous.

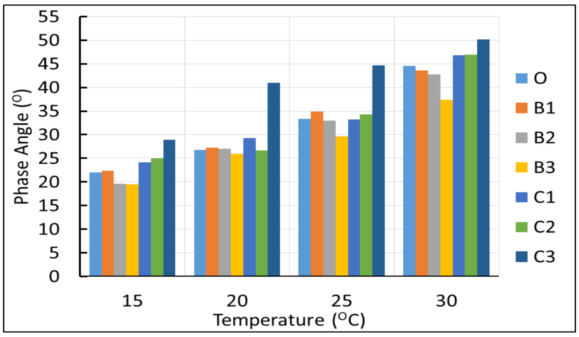

Figure 7. Phase angle on various modified asphalt and temperatures

Figure 7 shows that at a temperature of 30°C, the highest phase angle value in the mixture with 15% CR additive is more viscous, compared to asphalt mixture with 12% BNA additive which is more elastic. From the figure it can also be seen that the lower temperature has a smaller phase angle value than all types of mixtures, which means it becomes more elastic. On the other hand, asphalt mixtures with high temperatures will be more viscous.
The value of the Phase angle is inversely proportional to the value of the flexural stiffness modulus, where the smaller the value of the phase angle, the greater the flexural stiffness modulus. Vice versa, as the phase angle value increases, the flexural stiffness modulus decreases. The larger the phase angel value, the material tends to approach viscous properties, so the value of the flexural stiffness modulus will decrease. From the test results, it can be seen that the lowest phase angel value (tends to be elastic) at low temperatures (15°C).

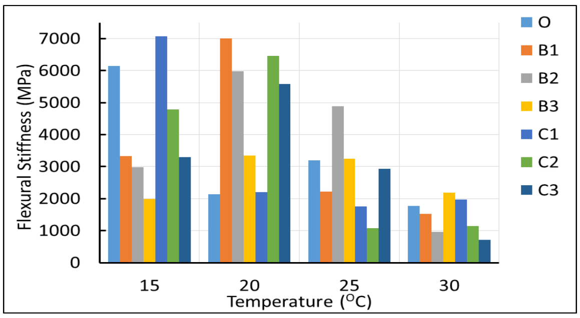

Figure 8. Stiffness on various modified asphalt and temperatures

The test results show that the Flexural Stiffness value in the mixture with 5% CR additive has the highest value at low temperatures (15˚C), at higher temperatures (30˚C) a mixture with 12% Buton asphalt additive has a stiffness modulus value. High Flexural Stiffness. The greater the value of the Flexural Stiffness of the asphalt mixture, the greater the area of the stress distribution to the lower layer.
Fatigue life is obtained based on strain control, so that fatigue occurs when the stiffness value is reduced by 50% from the initial stiffness value. The 4PB test results show that the fatigue life increases with increasing temperature. It is well known that pavement damage due to fatigue occurs at low temperatures. From the graph it is also known that the addition of CR to asphalt results in an increase in fatigue life, it can be said that the addition of CR has an effect on increasing strength against fatigue. The addition of Buton asphalt to asphalt base also increases the fatigue life, but the value of the increase is lower than that of pavement materials with CR modified asphalt.

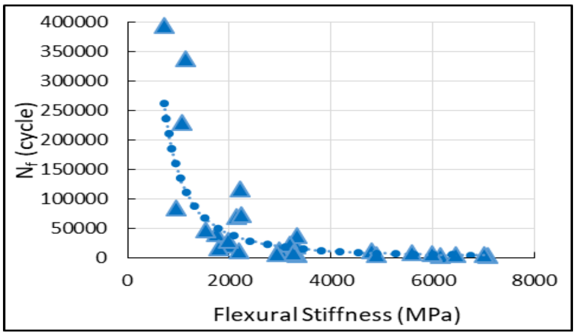

Figure 9. Fatigue life at various values of Flexural Stiffness

The test results with Four Point Bending (4PB) obtained fatigue life (N_f). The graph plots various values of Flexural Stiffness on fatigue life. The graph shows the relationship in the form of a power function.
Fatigue is defined as the phenomenon of material deterioration (reduction in stiffness and strength, ending in fracture) under repeated loads. With the increase in heavy traffic volumes, fatigue cracking (fatigue) of the asphalt layer has become one of the main types of road damage in flexible pavements, associated with repeated traffic loads. Fatigue crack prediction is usually based on the concept of cumulative damage. The number of load repetitions permitted is related to the tensile strain at the bottom of the asphalt pavement layer. Damage is calculated by the ratio of the predicted number of repetitions of the load to the number of repetitions allowed. The overall history of fatigue model development can be divided into five main approaches as follows: phenomenology, continuum damage mechanics, fracture mechanics, energy and dissipated energy.

Fatigue life model relating the number of load repetition to failure. The failure in this approach is defined as a 50% reduction in the initial stiffness of the material.

The experimentation part to determine how many repetitions of the tensile stress or strain the pavement can sustain before there is damage. This needs the development of a model, based on statistical analysis of experimental data, of the following form:

$$N_f = K (\varepsilon_t)^a (E)^b \quad (1)$$

$$\text{Log } N_f = \log K + a \log(\varepsilon_t) + b \log(E) \quad (2)$$

The equation (2) reduces to the following:

$$Y = c + a X_1 + b X_2 \quad (3)$$

Table 2. Multiple regression

Eq	Multiple Regression	Coeff.	R^2
O	Intercept	-2.9288	0.949
	Variable X1	-2.8006	
	Variable X2	-0.5885	
B1	Intercept	16.86723	0.984
	Variable X1	0.98711	
	Variable X2	-2.64309	
B2	Intercept	8.375087	0.999
	Variable X1	-1.31807	
	Variable X2	-2.28818	
B3	Intercept	-0.69329	0.987
	Variable X1	-2.9683	
	Variable X2	-1.27284	
C1	Intercept	-15.849	0.999
	Variable X1	-7.16486	
	Variable X2	-0.80697	
C2	Intercept	3.750188	0.947
	Variable X1	-1.86184	
	Variable X2	-1.64205	
C3	Intercept	-17.3032	0.999
	Variable X1	-7.98606	
	Variable X2	-1.18047	

Table 3. Coefficient value of each type of mixtures

Eq.	T_c	c	a	b
O	26	-2.9288	-2.8006	-0.5885
B1	23	16.8672	0.9871	-2.6430
B2	24	8.3750	-1.3180	-2.2881
B3	24	-0.69329	-2.9683	-1.2728
C1	26	-15.8490	-7.1648	-0.8069
C2	25	3.75019	-1.8618	-1.6420
C3	27	-17.3031	-7.9860	-1.1804

From *Multiple Regression* results:

(1) $c = -7.9\ T_k + 196.9639$

(2) coef. $X1 = a = -1.9688\ T_k + 45.918$

(3) coef. $X2 = b = 0.4242\ T_k - 12.095$

So that Y in the Tk function in equation 3. becomes:

$$Y = (-7.9\ T_k + 196.9639) + (-1.9688\ T_k + 45.918)\ X_1 + (0.4242\ T_k - 12.095)\ X_2 \quad (4)$$

The final model was given by:

$$\mathbf{Nf = 10^{(-7.9\ Tk + 196.9639)} (\varepsilon_t)^{(-1.9688\ T_k + 45.918)} (E)^{(0.4242\ Tk - 12.095)}} \quad (5)$$

Where:

N_f = number of load repetition (cycles)

ε_t = tensile strain (μ)

E = stiffness (MPa)

T_k = critical temperature (^{O}C)

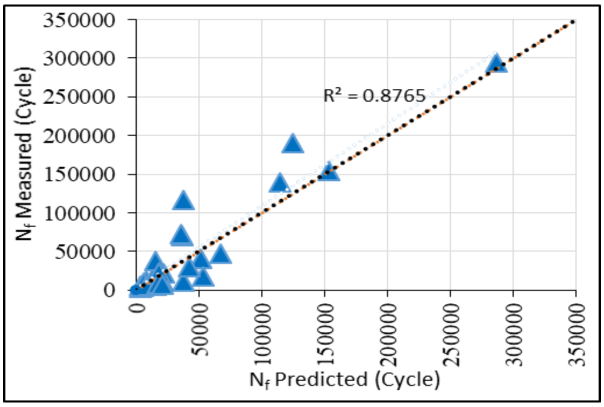

Figure 10. Fatigue life prediction results against measurement results

Comparison between the experimental results and calculations using the model confirmed the appropriateness of the strong relationship shown in Fig. 10 with a value of $R^2 = 0.8765$.

CONCLUSION

The following conclusions can be drawn based on the results and discussions above:

The fatigue life (N_f) of the asphalt-aggregate mixture as a pavement material can be seen from the relationship between asphalt rheology and the performance of asphalt-concrete mixtures based on the results of measurements of mechanical performance on test objects that have the same aggregate composition. Asphalt concrete mix pavement material with 15% crumb rubber additive has a fatigue life of N_f = 394,400 cycles, as the best mixture to deal with fatigue. The development of the Monismith model with a performance grade critical temperature approach from modified asphalt mechanistic rheology obtained the following model:

The final model was given by:

$$\mathbf{N_f = 10^{(-7{,}9\ Tk + 196.9639)} (\varepsilon_t)^{(-1{,}9688\ Tk + 45{,}918)} (E)^{(0{,}4242\ Tk - 12{,}095)}}$$

The model confirmed the appropriateness of the strong relationship.

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