INVESTIGATING FATIGUE PERFORMANCE ON THE FOAMED ASPHALT SPECIMENS GENERATED USING DIFFERENT FOAM PROPERTIES

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Abstract

An evaluation of fatigue resistance for foamed asphalt mixture is very demanding since the binder is not continuously distributed on the aggregate surface and this mixtures contains water, the content of which dramatically affects the mechanical properties. This paper discusses the results of laboratory fatigue testing on the foamed asphalt mixtures in which the specimens are generated using three different foamed bitumen properties. Foamed bitumen as the binder was produced at three different foaming water content (FWC) at a temperature of 180^{o}C using a 70/100 pen. The aggregates were mechanically mixed with foamed bitumen using a Hobart mixer. The resulting mixtures were then compacted using a gyratory compactor to generate specimen with diameter of 100 mm. The specimens were fatigue tested at various stress levels at a temperature of 20^{o}C following a curing period of 3 days at 40^{o}C. Overall, fatigue performance of foamed asphalt can be identified based upon both stress and strain for mixtures produced at FWC 1%, 5%, and 10%.

Keywords: fatigue performance, foamed asphalt, binder, foaming water content.

Abstrak

Evaluasi ketahanan lelah untuk campuran yang menggunakan *foamed asphalt* sangat penting karena *foamed asphalt*, sebagai bahan pengikat, tidak terdistribusi secara menerus pada permukaan agregat dan campuran ini mengandung air, yang sangat mempengaruhi sifat mekanik campuran. Makalah ini membahas hasil pengujian laboratorium terhadap kelelahan campuran yang menggunakan *foamed asphalt*, menggunakan benda uji dengan menggunakan tiga sifat *foamed asphalt* yang berbeda. *Foamed asphalt*, sebagai bahan pengikat, dibuat dengan tiga kadar air yang berbeda pada temperatur 180^{o}C menggunakan aspal Pen 70/100. Agregat dicampur secara mekanis dengan *foamed asphalt* menggunakan pencampur Hobart. Campuran yang dihasilkan kemudian dipadatkan menggunakan alat pemadat giratori untuk menghasilkan benda-benda uji dengan diameter 100 mm. Kemudian benda-benda uji tersebut diuji kelelahannya dengan berbagai tingkat tegangan pada temperatur 20^{o}C setelah diperam selama 3 hari pada temperatur 40^{o}C. Secara keseluruhan, kinerja kelelahan *foamed asphalt* dapat diketahui berdasarkan tegangan dan regangan untuk campuran-campuran yang dibuat dengan kadar air 1%, 5%, dan 10%.

Kata-kata Kunci: kinerja kelelahan, *foamed asphalt*, pengikat, kadar air *foaming.*

INTRODUCTION

Foamed asphalt as a road material has considerable advantages. This material has both environment and engineering advantages. The use of this mixture conserves aggregates and bitumen, decreases energy usage, minimises waste and reduces fuel consumption and greenhouse gas emission. This mixture can therefore significantly reduce the overall cost of construction. Engineering advantages include the possibility to use a wide variety of aggregates, the binder increases the strength compared to a granular material, exhibiting more flexibility compared to cement treated materials, giving faster strength gains compared to emulsion mixtures and possible early opening to traffic (Muthen, 1999).

This material has been firstly successful implemented in Pantura (Pantai Utara Jawa) road in which the foamed bitumen as a binder was utilised to improve performance of the existing road recycling material (Widajat, 2009). This material had also been discussed by Widyatmoko and Sunarjono (2007) and Yamin et al (2008) in terms of considerations to implement this technology for road construction in Indonesia.

Foamed bitumen is commonly characterised in terms of its maximum expansion ratio (ERm) and half-life (HL). During the bitumen foaming process, the foamed bitumen would expand to a maximum volume and then the bubbles would collapse rapidly. ERm is defined as the ratio between maximum volume achieved in the foam state and the volume of bitumen after the foam has completely dissipated. HL is the time that the foam takes to collapse to half of its maximum volume. Value of ERm and HL is controlled by percentage of added water by mass of bitumen or called as foaming water content (FWC). If value of FWC increases, it is normally followed by increasing ERm value and decreasing HL value. Therefor at a given temperature, there is an optimum FWC that produces the most effective ERm and HL of the foamed bitumen (Sunarjono et al, 2007).

Unfortunately, the performance of foamed asphalt is still poorly understood. The overall behaviour during the mixing, compaction, and curing process is not well understood; nor are the fundamental properties of stiffness, fatigue and deformation resistance fully defined. Addressing the lack of understanding of how the binder works in the mixture is crucial for implementation. It is noted that laboratory investigation have been conducted by the author to open the fundamental properties of foamed asphalt, e.g. stiffness properties (Sunarjono, 2010) and rutting performance (Sunarjono, 2009).

This paper discusses fatigue performance of foamed asphalt under laboratory testing in which the specimens with different foamed bitumen properties (different FWC) were tested using indirect tensile fatigue test (ITFT) at various stress level. The fatigue performance investigation is really demanding since the unique properties of foamed asphalt should be explored in terms of fundamental characteristics. It could be that foamed bitumen properties affect the mixture performance. It is then interesting to know how large the effect of binder properties on the fatigue resistance of a mixture is. It is expected that this discussion provide an up-to-date evaluation of foamed asphalt performance, especially the effect of binder properties on fatigue resistance performance.

TEST PROCEDURE

The ITFT can be performed in accordance with BS DD ABF: 2000 and BS DD ABF: 2003. The test is carried out at a standard temperature of $(20\pm1)^{o}$C using (100±3) mm diameter specimen. A thickness of (40±5) mm is recommended. The test is performed at various stress levels at a rate of 40 pulses/minute. Each specimen is repeatedly loaded until it fails by cracking or a vertical deformation of 9 mm has been achieved. A number of specimens from each mixture are tested at a range of applied loads resulting in different target stress levels at the centre of each specimen. Therefore the results can be plotted as the maximum stress against the number of cycles to failure (N_f) using logarithmic scales. Linear regression analysis is used to describe the resultant fatigue relationship. The test configuration can be seen in Figure 1. In this study, the procedure used for establishing fatigue characteristics is as follows:

- Prepare cylindrical specimens (at least 10 samples);
- Determine ITSM value for each specimen using either stress mode or horizontal deformation target;
- Determine the maximum horizontal stress for each specimen using Eq.1 (for horizontal deformation target);
- Calculate the initial maximum horizontal strain for each specimen using Eq. 2;
- Conduct ITF test at stress level determined from the ITSM test; and
- Establishing N/vertical deformation vs N plot, Stress vs N plot, and Strain vs N plot.

$$\sigma_{hx(\max)} = \frac{2P}{\pi.d.t} \quad \text{................................ Eq. 1}$$

$$\varepsilon_{hx(\max)} = \frac{\sigma_{hx(\max)}.(1+3v)}{S_m} \quad \text{................................ Eq.2}$$

MATERIALS USED AND SPECIMEN PREPARATION

The aggregate used in this study was virgin crushed limestone (Figure 2 Left). Particle gradation (shown in Figure 2 Right) was designed to be within the ideal grading envelope for foamed asphalt as recommended by Akeroyd and Hicks (1988). The maximum aggregate size was 20 mm with 51.20% fines (< 6 mm) and 8.60% filler. This aggregate has a low Plasticity Index (PI) i.e. 2.7%. The maximum dry density (MDD) and optimum moisture content (OMC) were found to be 2.242 Mg/m3 and 6.4% respectively, determined in accordance with BS EN 13286-2: 2004 (modified Proctor).

This study used bitumen grade of Pen 70/100 which has properties as shown in Table 1. The bitumen viscosities were measured using a Dynamic Shear Rheometer (DSR) at a frequency of 0.1 Hz for temperatures of 20^{o} and 40^{o}C and a Brookfield rotary viscometer for temperatures of 140^{o}C to 180^{o}C. Foamed bitumen was generated using a laboratory mobile foaming plant type Wirtgen WLB 10 in which the bitumen was foamed at a water pressure of 6 bars and an air pressure of 5 bars. The characteristics of foamed bitumen were varied by applying different foaming water contents (FWC) and temperatures.

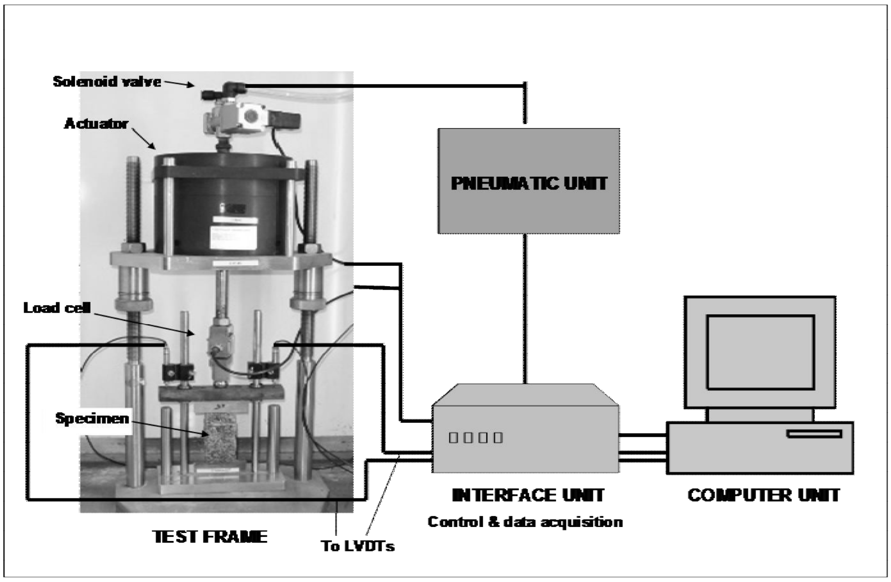

Figure 1 Indirect Tensile Fatigue Test (ITFT) Configuration

In the specimen preparation of foamed asphalt, it should be understood that the mixing technique, the compaction method and the curing process hold an important key. These three aspects will only combine to produce an optimum performance mixture when aggregate gradation, water content and foamed bitumen characteristics are designed correctly.

Figure 2a Virgin crushed limestone aggregate

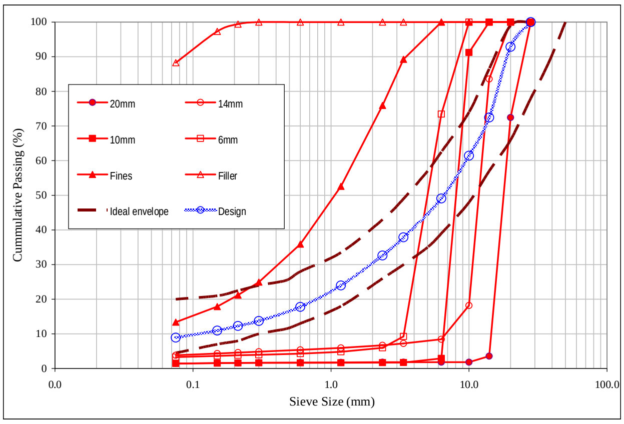

Figure 2b Gradation

Foamed bitumen as the binder was produced at three different foaming water content (FWC) at a temperature of 180°C using a 70/100 pen. The FWCs selected are 1%, 5%, and 10%. The aggregates were mechanically mixed with 4.6% of water before they were mixed with 4% of foamed bitumen using a 20 quarts Hobart mixer. The resulting mixtures were then compacted using a gyratory compactor to generate specimen with diameter of 100 mm. Compaction setting was fixed at 600 kPa, angle of 1.25°, and gyration number of 200. The specimens were fatigue tested at various stress levels at a temperature of 20°C following a curing period of 3 days at 40°C.

Table 1 Properties of Bitumen Pen 70/100

Test Property	Result
Specific gravity	1.03
Penetration (25 ^{o}C, 100g, 5s) (0.1 mm)	85 - 93
Softening Point (ring and ball) (^{o}C)	45 - 49
Viscosity at 20^{o}C (DSR 0.1 Hz, kPa.s)	257
Viscosity at 40^{o}C (DSR 0.1 Hz, kPa.s)	5.54
Viscosity at 140^{o}C (mPa.s)	262
Viscosity at 160^{o}C (mPa.s)	114
Viscosity at 180^{o}C (mPa.s)	57

RESULTS AND DISCUSSION

Three different specimen types, i.e. specimens produced at FWC of 1%, 5%, and 10% have been investigated. Ten or eleven specimens were produced for each type. The ITSM values of specimens at FWC 10% were determined prior to ITFT testing at various stress levels, i.e. from 100 kPa to 300 kPa at intervals of 50 kPa. Based on these tests, a correlation between stress level and ITSM value was developed. Due to the possibility of specimen damage when tested at high stress loading, it was therefore decided to test the specimens using low stress loading. Subsequently the specimens produced at FWC values of 1% and 5% were tested at a horizontal deformation of 5 microns (stress level around 100 kPa to 150 kPa). The correlation developed at FWC of 10% was then utilised to correct the ITSM values of FWC 1% and 5% specimens. It is noted that both ITSM and ITFT were performed at a temperature of 20^{o}C. The results can be seen in Table 2 and Table 3, and also in Figure 3 to Figure 6.

Fatigue characteristics were identified using a plot of number of cycles (N) against N divided by vertical deformation (N/vd). These two values were recorded during testing. Basically, this plot was used by Read (1996) to define the initiation and propagation phases of fatigue. In this study, this plot was utilised to characterise the fatigue life of the material. The N value at which the N/vd reached its highest value was termed $N_{critical}$ (N_{cr}). The N value at which the specimen failed was termed $N_{failure}$ (N_f). Table 2, Figure 3 and Figure 4 show the fatigue characteristics of foamed asphalt materials. Increasing the applied stress level significantly reduces both N_{cr} and N_f as shown in Figure 3. It can also be seen in Figure 4 that the specimens with FWC of 5% performed better in fatigue at a stress level of 100 kPa than specimens with FWC of 1% and 10% since the stiffness at FWC of 5% is higher than both at FWC of 1% and 10%. Higher stiffness in foamed asphalt mixture means the specimen is better in bider distribution. However, although having lower stiffness, the specimens produced at FWC of 1% exhibited slightly better fatigue life than at FWC of 10%, although this may be due to scatter of ITFT data as commonly found by researchers. Table 2 indicates that for all cases N_{cr} was about 60% to 66% of N_f.

Figure 5 expresses the results in the form of a plot of N_f against the applied stress level. A power trend line was developed for each data set and hence the equation of a fatigue line and its R^2 value can be determined as shown in the figure. As an example, for FWC of 1%, the equation of the fatigue line is $y= 1239x^{-0.2636}$. This equation means that for monotonic loading (at N=1), the specimen should fail at a stress of 1239 kPa. The slope of the fatigue line is –0.2636, the negative sign meaning that the stress decreases with N_f. Greater slope or steeper fatigue line indicates that specimen performance is more sensitive to the applied stress. It can be seen that the fatigue lines for specimens produced at FWC of 1% and 5% are comparable, the line for FWC of 1% being slightly steeper than that for FWC of 5%, whereas the fatigue line for specimens at FWC of 10% appears far steeper than the other two. It was also found that data of the lower FWC give higher R^2 values.

Table 2 The Number of Cycles To Reach Critical Point ($N_{critical}$) and Failure ($N_{failure}$) at Various Stress Levels and Foaming Water Content Applications.

Specimen type and stress level (kPa)		$N_{failure}$	$N_{critical}$	% N_{cr}= 100*(N_{cr}/N_f)
FWC 5%	100	18603	12020	65
	150	9565	5720	60
	200	3255	2060	63
	250	1172	770	66
	300	128	80	63
FWC 1%	100	10944	7070	65
FWC 10%	100	9660	6090	63

When the results are plotted in the form of N vs strain, the fatigue line for FWC of 5% is clearly better than the two others as shown in Figure 6. It can be seen in Table 3 that specimens produced at FWC of 5% will have better fatigue performance at strains lower than 200 microstrain, whereas for strains higher than 200 microstrain the specimens produced at FWC of 10% performed better than the others. A comparison between foamed asphalt (FA) and hot-mix asphalt (HMA) is given in Figure 7, in which the bitumen volume of HMA (20mm DBM) was slightly higher than that of FA (FWC 5%). It can be seen that the fatigue life of foamed asphalt is very short in comparison with HMA. At 200 microstrain, the fatigue life of FA is about 650 cycles whereas that of HMA is about 30000 cycles. This can be understood since HMA is a fully bonded material, with less void content and hence more resistance to fatigue.

Overall, the specimens produced at FWC of 10% exhibit the poorest fatigue performance, but these specimens were tested at relatively high stress to determine their ITSM value prior fatigue testing. It may be that their performance would not be significantly poor than that of specimens at FWC of 5%, if their condition was fresh at ITF testing. In practice, it is recommended to implement FWC of 5% in order to produce the best mixture which has the best in binder distribution, stiffness, and life performance.

Table 3 Fatigue Characteristics of Foamed Asphalt Materials Produced at Foaming Water Content of 1%, 5% and 10%.

Specimen type	Equation based on strain	Strain at 10^3 cycles	Strain at 10^4 cycles	Strain at 10^5 cycles
FWC 1%	$\varepsilon = 1590.5N^{-0.3118}$	185	90	44
FWC 5%	$\varepsilon = 1048.3N^{-0.2618}$	172	94	51
FWC 10%	$\varepsilon = 3881N^{-0.4183}$	216	82	31
	Equation based on Number of cycles	Cycles at 50 microstrain	Cycles at 100 microstrain	Cycles at 200 microstrain
FWC 1%	$N= 1.43E+10\ \varepsilon^{-3.15}$	63618	7169	807
FWC 5%	$N= 7.39E+10\ \varepsilon^{-3.50}$	83608	7390	653
FWC 10%	$N= 7.24E+10\ \varepsilon^{-2.15}$	16105	3629	818

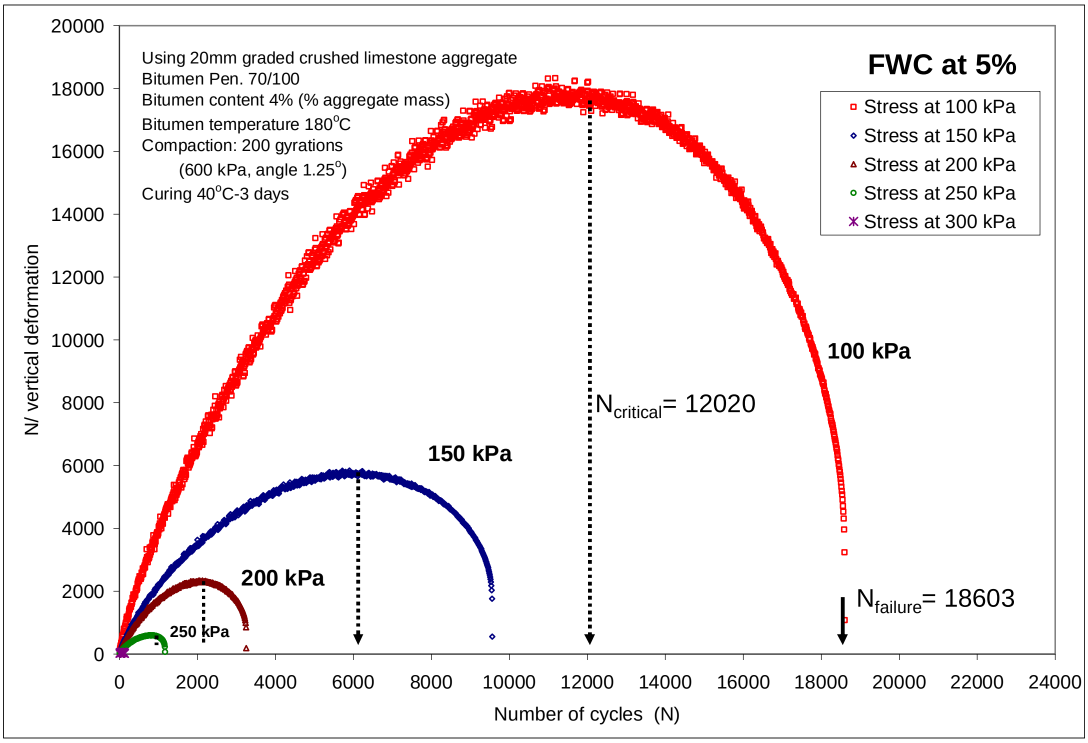

Figure 3 Fatigue Characteristics of Foamed Asphalt Materials at Different Stress Levels (Specimens Produced at FWC of 5%)

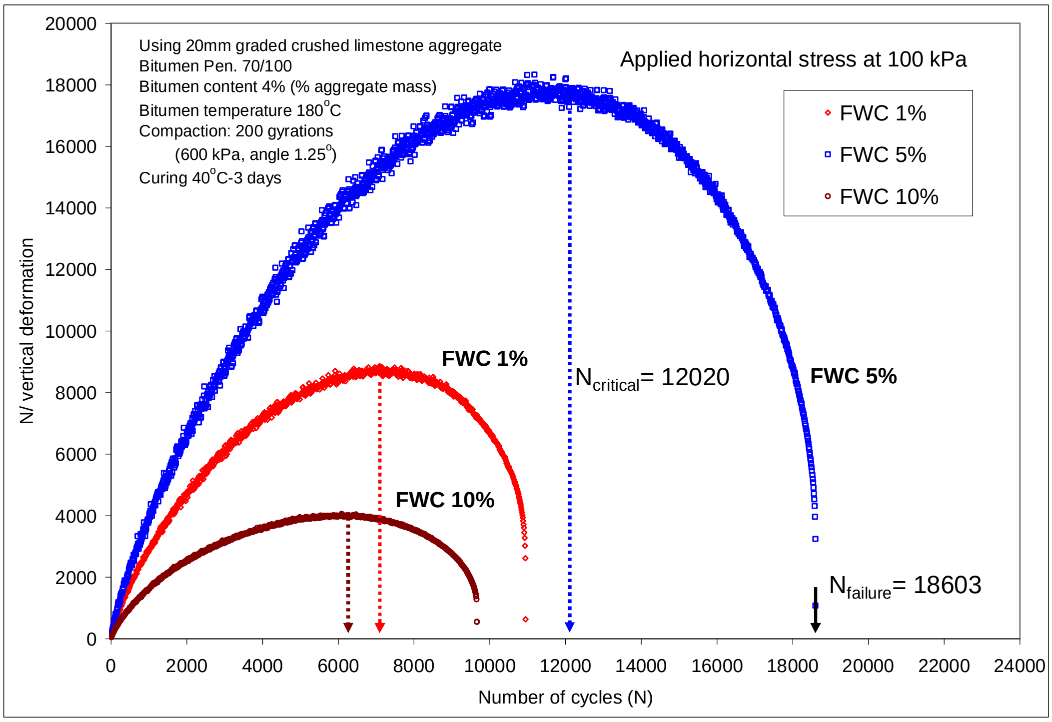

Figure 4 Effect of Foaming Water Content on the Fatigue Characteristics at a Stress Level of 100 Kpa

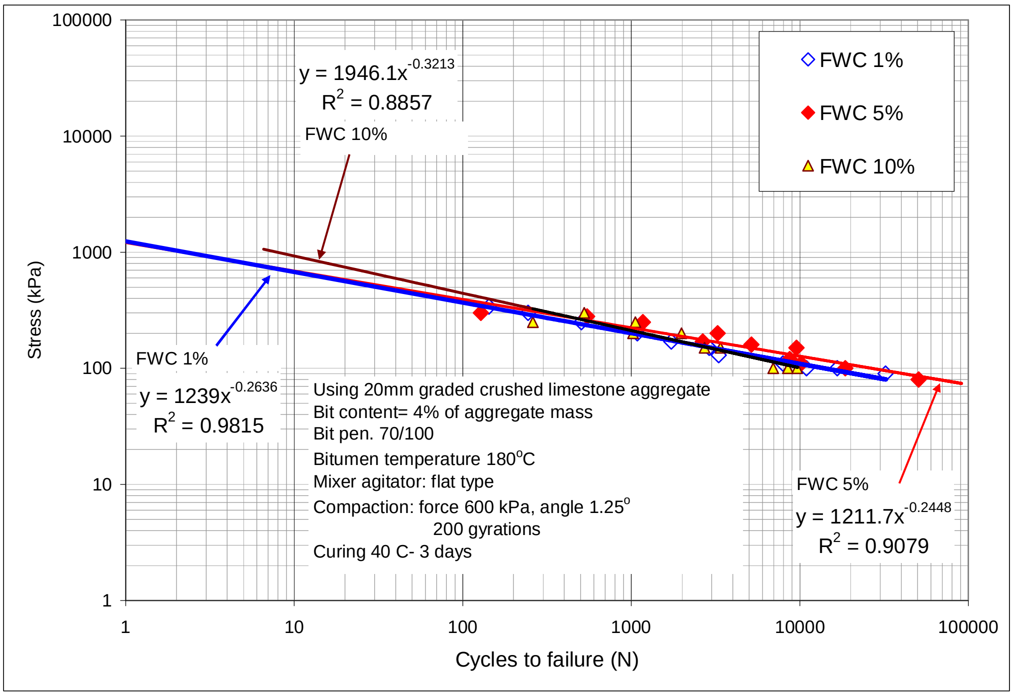

Figure 5 Fatigue Characteristics of Foamed Asphalt Materials Based on Stress for Specimens Produced at FWC Of 1%, 5%, and 10%

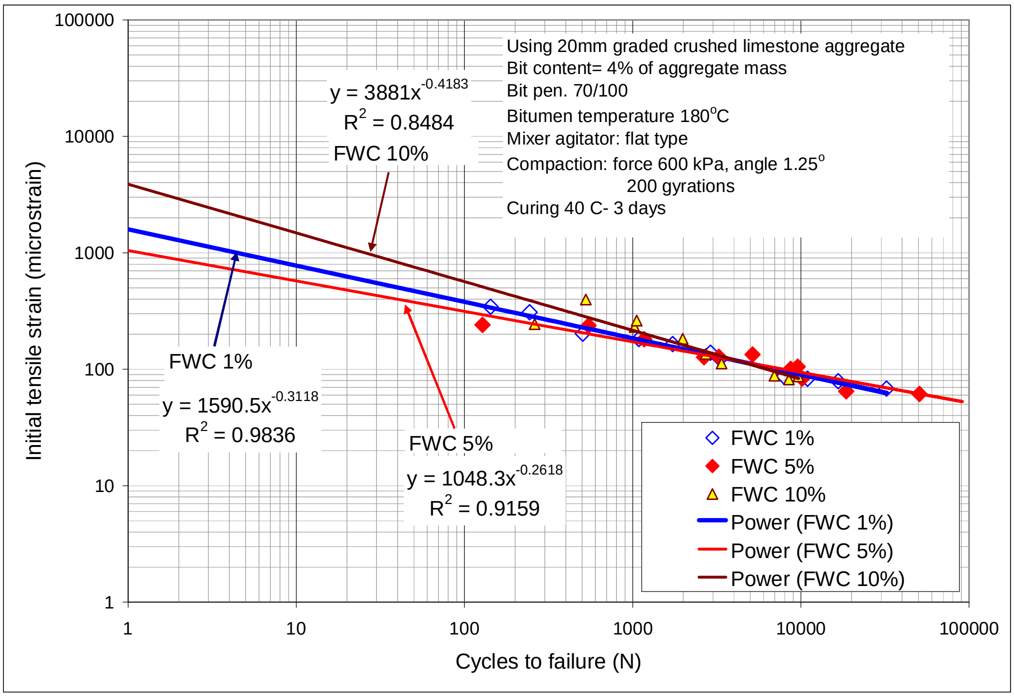

Figure 6 Fatigue Characteristics of Foamed Asphalt Materials Based on Strain For Specimens Produced at FWC Of 1%, 5%, and 10%

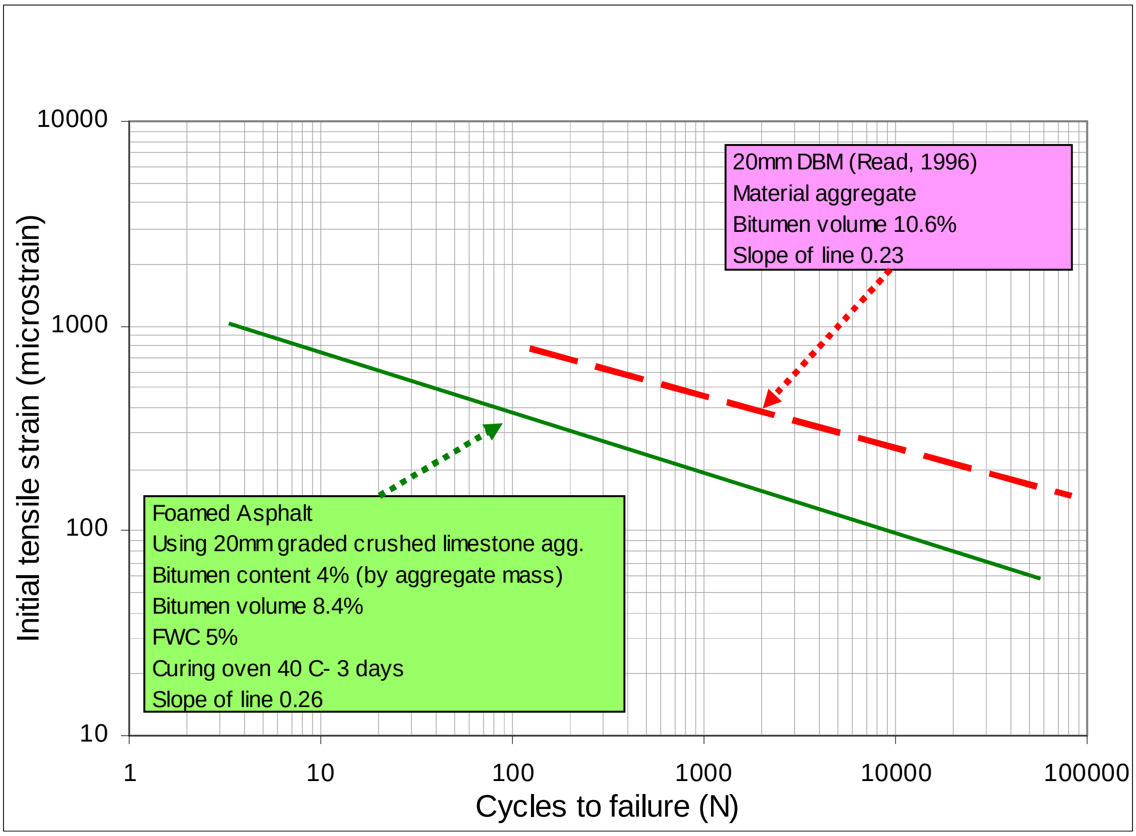

Figure 7 Comparison of Fatigue Characteristics between Foamed Asphalt and Hot Mix Asphalt (20mm DBM)

CONCLUSIONS

Following the work described in this paper, it can be deduced that the fatigue characteristics of foamed asphalt are as follows:

1. The fatigue life was found to be very short in comparison with hot-mix asphalt materials (e.g. 20 mm dbm), about (600-800) cycles at 200 microstrain. The $n_{critical}$ value (number of cycles (n) at the peak value of n/vertical deformation) was generally about 60 %-66 % of $n_{failure}$. This value is about 90 % for HMA mixtures (Read, 1996). It means, following Read's (1996) idea, that foamed asphalt materials will initiate cracking faster than HMA, but have a longer crack propagation life.
2. The fatigue life was significantly affected by applied stress level and clearly linked with the stiffness value. Based on the developed fatigue lines, the specimens produced at FWC of 5% were found to have the lowest slope (best performance) and the specimens produced at FWC of 10% were the steepest (worst performance). However their fatigue lives at 200 microstrain were comparable. It can be therefore deduced that in the field the fatigue performance of foamed asphalt materials with various FWC values is not significantly different.

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