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Influence of post - processing methods for ranking of fatigue life of bituminous mixture

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Abstract

In this study, four point beam tests were conducted on bituminous mixture sample pertaining to Bituminous Concrete (BC) grade II as per MORTH specification. The samples were produced using unmodified binder and modified binders. Two types of modified binders, one with crumb rubber and other with polymer were used. A beam sample of size 450×150×160 mm was fabricated using PReSBOX shear compactor with 4% air voids. This sample was cut into samples of size 380×63×50 mm and tested in a four point beam bending equipment. Tests were performed in a controlled displacement mode using sinusoidal waveform with strain amplitude of 200, 400 and 600 microstrain and at a frequency of 10 Hz. The entire test was carried out at 0˚C. The load and displacement data as a function of time for every cycle was recorded at the time interval of 1/100th second. The stiffness modulus, normalized stiffness modulus, phase angle, energy dissipation and cumulative energy dissipation were calculated from the load-displacement data and fatigue life was calculated using all the aforementioned approaches. It was observed that considerable disparity existed between the results. The present investigations threw light on the difference in the fatigue life of the bituminous concrete mixture obtained using these different methods of analysis. Also, the ranking of different bituminous mixture for unmodified and modified binders based on the fatigue life was carried out.

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Keywords: Bituminous concrete, fatigue, stiffness modulus, normalised modulus, dissipated energy

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1. Introduction

Bituminous pavements are subjected to mainly two types of distresses and they are rutting and fatigue cracking. In the mechanistic-empirical pavement design method, distress transfer functions are used to quantify the expected performance of the pavements as far as these distresses are concerned (MEPDG, 2008). Laboratory investigations and field observations are required for establishing these distress functions. This investigation reports the ongoing laboratory investigations currently being carried out at IIT Madras towards quantifying the fatigue behaviour of unmodified and modified binder mixtures.

Fatigue distress in the bituminous mixtures occurs due to repeated loading. Fatigue distress is normally characterised in the laboratory through beam bending tests. These include two/three/four point beam bending techniques (Baburamani, 1999). The recent technique used is the four point bending test. In four-point bending test, beams of 380×63×50 mm size are clamped at two outer ends in such way that its vertical movement is restricted. The beam is subjected to repeated sinusoidal/haversine loading for a given amplitude and frequency at two inner points in the direction perpendicular to the longitudinal axis of the beam. Such experiments are conducted under controlled load or displacement condition and the fatigue life (number of load cycle) is defined for a preselected magnitude of stress or strain (SHRP A 404, 1994).

The stress and strain amplitude from the sinusoidal/haversine waveform and the phase lag between the stress and strain data are post-processed to define the fatigue life of the bituminous mixture. Different guidelines exist for fatigue damage quantification and the post-processing of fatigue test data based on these guidelines are different. Three different standards widely used include AASHTO T321-07, ASTM D7460-10 and EN 12697:24-2004. All these standards record the evolution of damage based on some predefined parameters. One such parameter is the stiffness modulus. Stiffness modulus within the realm of linearised elasticity as far as beam bending is concerned is defined as a ratio of maximum tensile stress to maximum tensile strain. As the fatigue damage accumulates due to repeated loading, the stiffness modulus of the bituminous mixtures reduces. The fatigue life of bituminous mixture as per AASHTO T321-07 is defined as the number of cycles corresponding to 50% of initial stiffness modulus. AASHTO T321-07 (2007) suggests the use of exponential relationship for parametric comparison of stiffness modulus data. Here, AASHTO considers the initial stiffness as the stiffness modulus corresponding to 50^{th} cycle. However, EN 12697:24-2004 standard considers the initial stiffness as the stiffness modulus corresponding to 100^{th} cycle. ASTM D7460-10 approach is based on Miner's equation. In this approach, the failure point is considered as the peak of normalized modulus versus cycles curve. These standards assume the bituminous concrete as a linearised elastic material and linearised elasticity is used to calculate the stiffness modulus, notwithstanding the fact that such analysis has limitations since bituminous concrete mixtures behave like viscoelastic material.

In addition to this, energy dissipation and cumulative energy dissipation are used to quantify the fatigue damage (Shen and Carpenter, 2005 and Pais et al., 2009). The damage due to loading in the bituminous mixture is assumed to occur due to relative amount of energy dissipation between consecutive loading cycles. The ratio of dissipated energy change (RDEC) is defined as the change in dissipated energy with the loading cycles. Figure 1 shows the schematic of RDEC as a function of loading cycles. In the first stage of the curve, RDEC decreases as a function of loading cycles. In stage two (plateau), RDEC value is constant over number of loading cycles indicating that as the loading cycle increases, the energy dissipated is constant. This plateau stage lasts till there is sudden increase in the RDEC. This signifies the onset of third stage in which the major amount of input energy is dissipated indicating the starting of fatigue failure (Shen and Carpenter, 2007). According to this approach, the fatigue life of bituminous concrete is related to plateau value (PV) energy parameter, which corresponds to the RDEC value at 50% of initial stiffness. Studies conducted by Shen and Carpenter (2007) demonstrated that the plateau value is uniquely related to the fatigue life of the bituminous mixtures irrespective of the testing conditions.

Fatigue of bituminous mixture is a complex process to unravel and the definitions are always rife with inconsistencies. Different guidelines exist for fatigue test and fatigue damage quantification. However, few unresolved issues exist related to post-processing of fatigue test data. It is not clear how the collected data should be analysed to arrive at an acceptable value. The issue gains prominence when a wide range of modified binders are used since the material property and damage accumulation are completely different for modified binders. It is also noted that the fatigue life depends on different test parameters including temperature. Kim et al. (2013) evaluated the fatigue performance of the Styrene- Butadiene- Styrene (SBS) modified mastic bituminous mixtures and observed that the SBS modified mastic bituminous mixtures have high flexural resistance at -10°C and comparable at 20°C. Studies conducted as part of National Highway Research program (NCHRP - 646, 2010), indicated that the fatigue lives of mixtures with modified binders were an order of magnitude greater than the fatigue life of mixture with unmodified binder, produced from the same source as the base binder used to create the modified binder. The base binder properties appear to be important in the performance of the modified binders. It was also seen that mixtures made with unmodified binder with low temperature susceptibility, had approximately two to three times the fatigue life of the polymer modified mixtures.

In summary, there appears to be significant historical data indicating that the laboratory fatigue performance of modified bituminous mixtures is greater than the mixtures made with unmodified binders. The fatigue characteristics appear to be dependent on the base bituminous binder used for modification. Such dependence is seen in terms of the test temperature, amplitude and frequency of loading.

The present study is focused on determining the fatigue life using the aforementioned methods and understanding the influence of the post-processing methods on fatigue life of the bituminous concrete. The influence of modified binders on the fatigue life of the bituminous mixtures for the selected test conditions is also investigated.

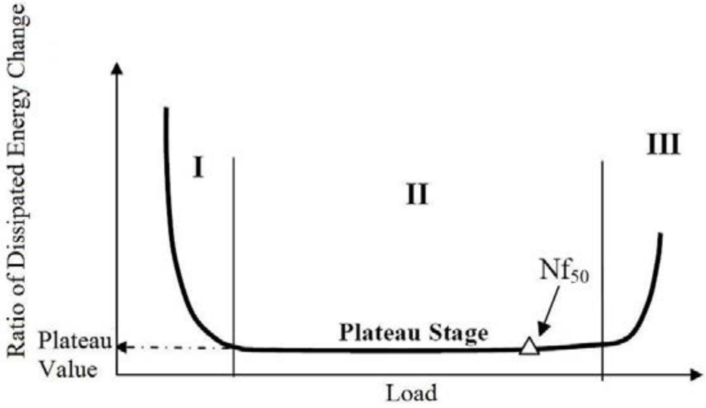

Fig. 1. Schematic of change in energy dissipation (Shen and Carpenter, 2007)

2. Experimental investigation

In this study, four point beam tests were conducted on bituminous mixture sample pertaining to Bituminous Concrete (BC) grade II as per MORTH specification. The samples were produced using unmodified binder and modified binders. Two types of modified binders, one with crumb rubber (CRMB-60) and other with polymer (PMB-40) were used. A beam sample of size 450×150×160 mm was fabricated using PReSBOX shear compactor with 4% air voids. This sample was cut into samples of size 380×63×50 mm and tested in four beam bending equipment. Tests were performed in a controlled displacement mode using sinusoidal waveform with strain amplitude of 200, 400 and 600 microstrain at a frequency of 10 Hz. All the materials were subjected to 20, 00,000 cycles of loading or the number of cycles corresponding to 20% of initial stiffness whichever occurred earlier. The entire test was carried out at 0 ˚C. The load and displacement data as a function of time for every cycle was recorded at a frequency of $1/100^{th}$ second. The stiffness modulus, normalised stiffness modulus, phase angle, energy dissipation and cumulative energy dissipation were calculated from the load-displacement data and results were presented in the next section.

3. Results and discussions

Figure 2a shows 200th cycle displacement and load waveform corresponding to 200 micro-strain test of bituminous mixture produced using CRMB binder. The normalized load and displacement plot is shown in figure 2b. A small variation in tensile peak and compression peak was observed. Also, the phase lag between the load and displacement in a particular cycle was found to be non-uniform. The peak strain and peak stress are calculated corresponding to tensile peak displacement and peak load as per ASTM D7460-10 and used in the fatigue life determination.

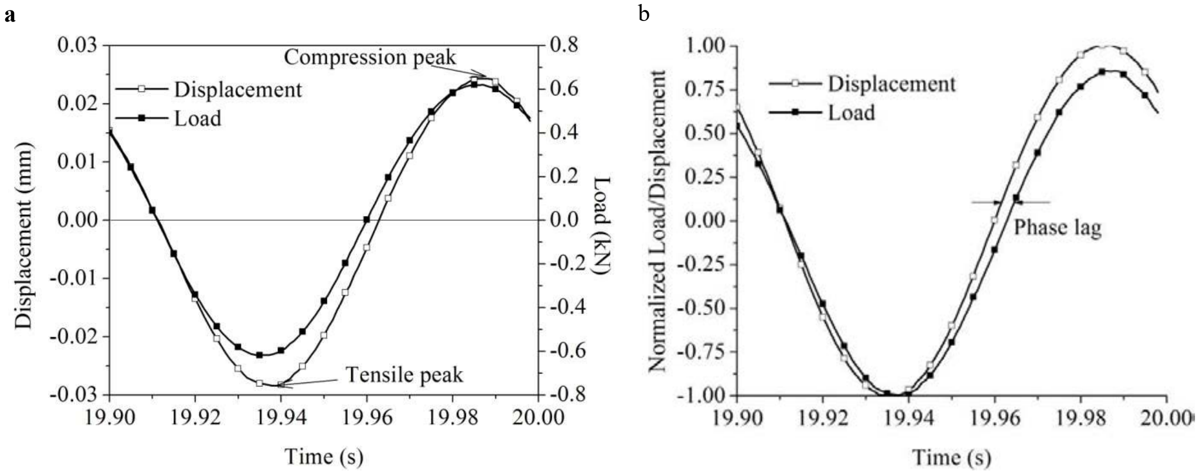

Fig. 2. (a) Sample displacement and load waveform; (b) normalised displacement and load waveform

The maximum tensile strain and maximum tensile stress calculated for VG30 sample at 400 micro-strain is shown in figure 3a. Due to repeated load application, the tensile stress decreases. The stiffness calculated for VG30 sample for different strain level is shown in figure 3b. The flexural stiffness of beam sample prepared with CRMB and polymer modified binder are shown in figure 3c and 3d. From figure 3b, 3c and 3d it is clear that for the same testing condition, the stiffness varies with the binder used. Figure 4a and 4b compares the flexural stiffness of various binders at different strain level. From figure 4a, the initial stiffness of VG30 binder was observed to be higher when compared to the sample produced with CRMB and PMB. However, the rate of reduction in stiffness due to repeated load application was higher in VG30. Hence the fatigue life of the beam with VG30 binder was observed to be lesser based on the fatigue life defined corresponding to 50% of initial stiffness. As discussed earlier, AASHTO considers the initial stiffness as the flexural stiffness corresponding to 50th cycle and EN 12697:24-2004 standard considers the initial stiffness as the stiffness modulus corresponding to 100th cycle. Since there was no considerable reduction in stiffness between 50th and 100th cycle, the fatigue life determined as per AASHTO T321-07 and EN 12697:24-2004 was observed to be the same. The fatigue life of bituminous beam produced using different binder for various strain level is documented in Table 1. From figure 4a and Table 1, the fatigue life of bituminous beam with modified binders at 400 micro-strain was much higher when compared with the bituminous beam produced using VG30 binder. However, the flexural stiffness at 600 micro-strain did not capture the increase in fatigue life of modified binder (refer Table 1 and figure 4b).

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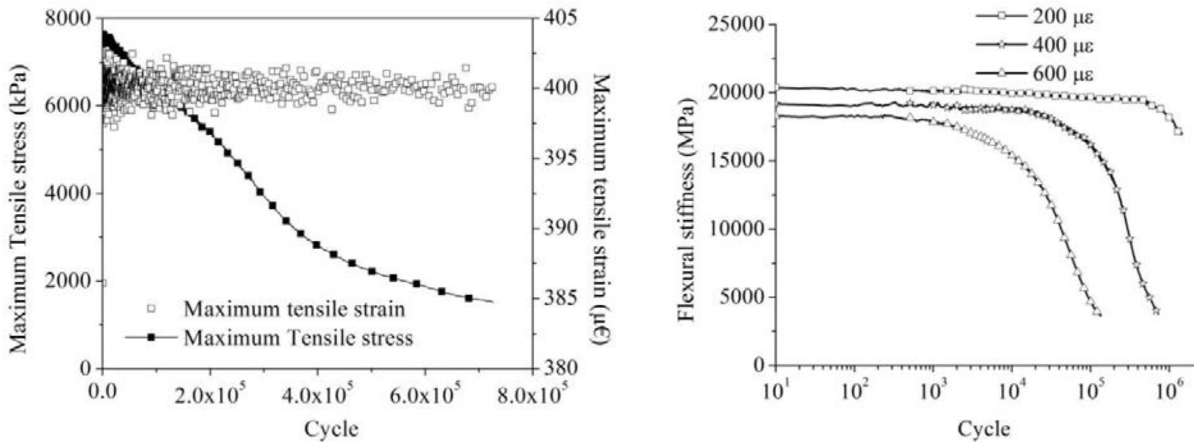

Fig. 3. (a) Maximum tensile strain and stress for VG30 sample; (b) Flexural Stiffness for VG30 sample at 0 ˚C

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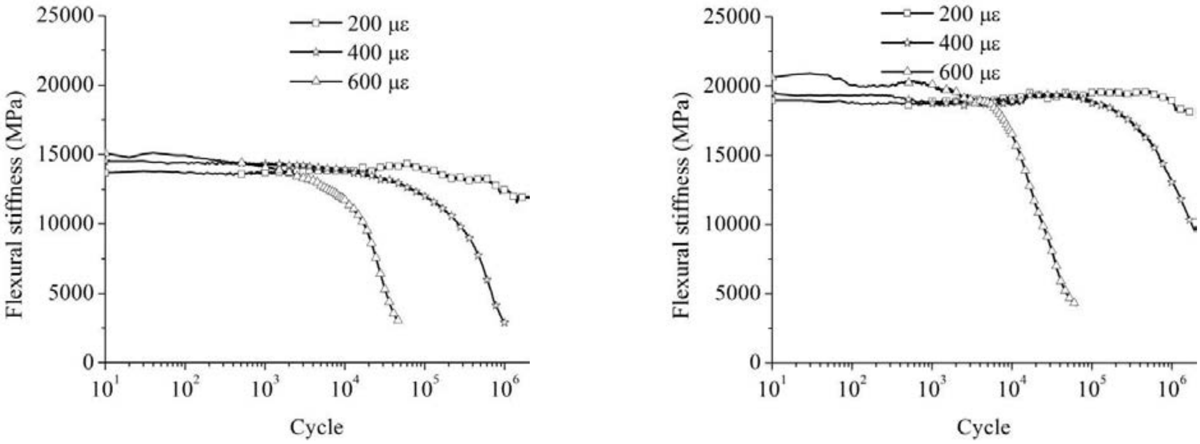

Fig. 3. (c) Flexural Stiffness for CRMB sample at 0 ˚C; (d) Flexural Stiffness for PMB sample at 0 ˚C

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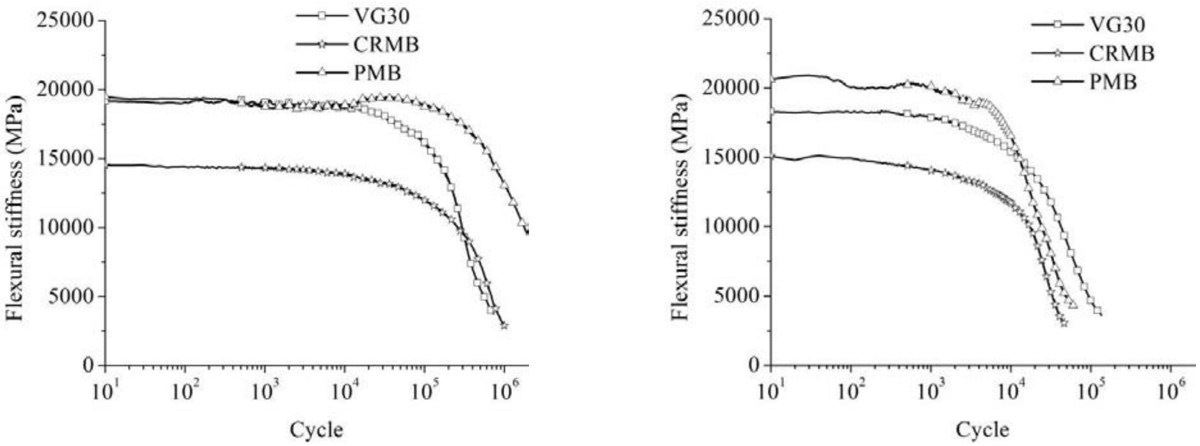

Fig. 4. (a) Comparison of flexural stiffness of different binders at 400 micro-strain; (b) Comparison of flexural stiffness of different binder at 600 microstrain

Even with 20, 00,000 cycles, the reduction in stiffness at lower strain did not reduce to 50 % of initial stiffness. In such cases, the flexural stiffness as a function of load cycles was fitted to an exponential function $S = Ae^{bn}$, where S represents the flexural stiffness, n represents number of load cycles and A and b are model constant. The number of load cycles corresponding to the fatigue life is obtained from the exponential fit. The sample fit is shown in figure 5 and the fatigue life calculated from the exponential fit is tabulated in table 1.

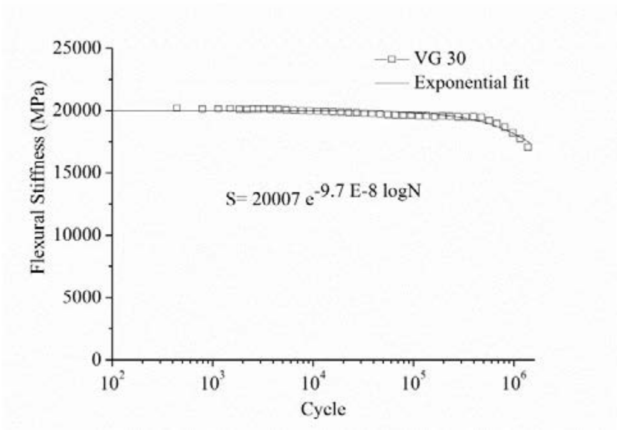

Fig. 5 Exponential fit for BC with VG30 at 200 micro-strain

Determination of fatigue life as per ASTM D7460-10 is based on Miner's equation. As per ASTM D7460-10, the failure point is considered as the peak of normalised modulus versus cycles curve. The normalised modulus can be calculated using the equation;

$$NM = \frac{S_i}{S_o} \times \frac{N_i}{N_o}, \quad (1)$$

where, NM represents normalised modulus, S_i represents flexural beam stiffness at cycle i, N_i represents i^{th} cycle, S_o represents initial flexural beam stiffness at 50^{th} cycle, N_o represents number of cycles where the initial stiffness is estimated (50^{th} cycle). The flexural stiffness value of different cycles was normalised with reference to the initial stiffness and the number of cycle corresponding to the peak normalised modulus was recorded as a fatigue life. The normalised modulus of different sample for 400 microstrain is shown in figure 6a. In the case where the peak of the normalised modulus curve was outside the duration of the test run, the failure point was determined by fitting Weibull distribution to the data set. The two parameter Weibull cumulative distribution function has explicit equation of the form,

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \quad (2)$$

where, F (t) = Probability of failure at time t, η = characteristics life or scale parameter and β = slope or shape parameter. The parameter β shows how the failure rate develops as a function of time. Taking logarithm of negative logarithm of reliability function, the number of cycles to failure is calculated by solving the equation (3).

$$Ln\,(-Ln\,(SR)) = \gamma \times Ln\,(N) + Ln\,(\Lambda), \quad (3)$$

where, Ln (-Ln (SR)) = natural logarithm of the negative of the natural logarithm of SR, SR = flexural beam stiffness ratio, N = number of cycles, γ = slope of the linear regression of the Ln (-Ln (SR)) versus Ln (N), Ln (Λ) = intercept of the linear regression of the Ln (-Ln (SR)) versus Ln (N). The failure point is estimated by solving equation (3) for N where SR = 0.5. The sample fit of equation (3) is shown in figure 6b. The fatigue life obtained from the test result and fit were tabulated in table 1 against fatigue life as per ASTM D7460-10. Fatigue life estimated using ASTM standard was found to different from that of EN standard and AASHTO standard. This difference is more in case the peak of the normalized modulus curve lies outside the duration of the test run.

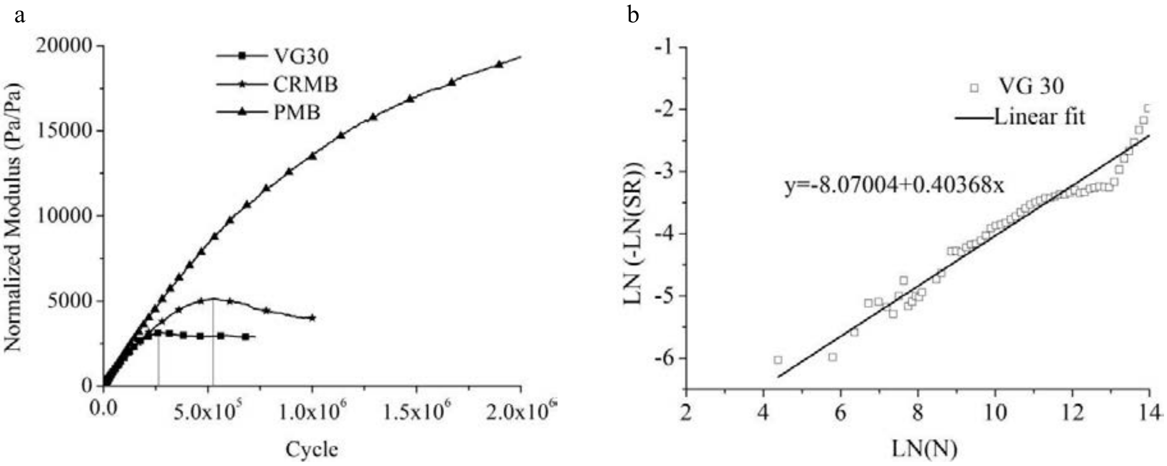

Fig. 6. (a) Normalised modulus at 400 micro-strain; (b) Sample fit for Weibull distribution, BC with VG30, 200 micro-strain

Table 1. Fatigue life of different bituminous mixtures

Sample	Strain Amplitude (με)	Fatigue life as per		
		AASHTO T321-07	EN 12697:24-2004	ASTM D7460-10
VG30	200	7,00,445*	6,98,212*	19,33,47568**
	400	3,10,210	3,10,350	2,77,540
	600	48,470	48,614	86,650
CRMB	200	7,00,248*	7,09,385	-
	400	5,10,890	5,11,620	5,30,880
	600	24,540	24,600	25,180
PMB	200	39,20,806*	39,33,969	-
	400	18,86,050	18,90,730	5,60,97,924**
	600	23,140	24,040	32,770

The energy dissipation in the viscoelastic material was also used to study the fatigue life of the bituminous mixture. The damage due to loading in the bituminous mixture is assumed to occur due to relative amount of energy dissipation between consecutive loading cycles. The ratio of dissipated energy change (RDEC) was calculated using the expression given in equation 4 (Shen and Carpenter, 2007).

$$RDEC = \frac{DE_a - DE_b}{DE_a\,(b-a)}, \qquad (4)$$

where, a and b represents loading cycle, DE_a and DE_b represents dissipated energy at cycle a and b. Shen and Carpenter, 2007 used the expression in equation (4) to calculate the fatigue damage in airfield pavement. In this three stage curve, at stage II the constant value of RDEC indicates that at every increase in loading cycle, a constant amount of input energy being turned into damage. The initiation of stage III represents the fatigue failure.

The energy dissipation for each cycle is obtained by calculating the area enclosed by a stress-strain loop. The energy dissipation for different mixture at 400 and 600 microstrain is shown in figure 7a and 7b. The ratio of dissipated energy change calculated using equation (4) for the sample with VG30 binder is shown in the figure 7c and 7d. The initiation of stage III as found in the schematic was not observed within the number of loading cycles used for testing.

a b

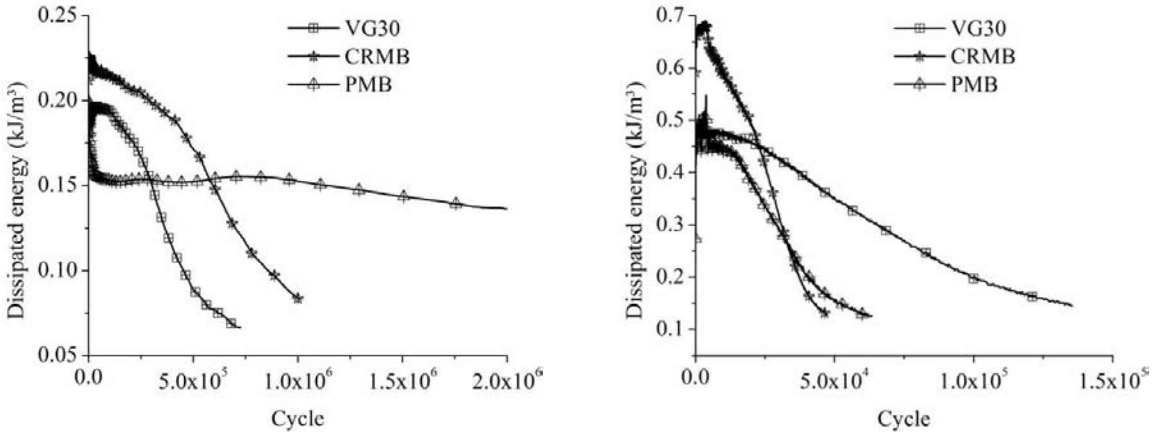

Fig. 7. (a) Energy dissipation at 400 microstrain; (b) Energy dissipation at 600 microstrain

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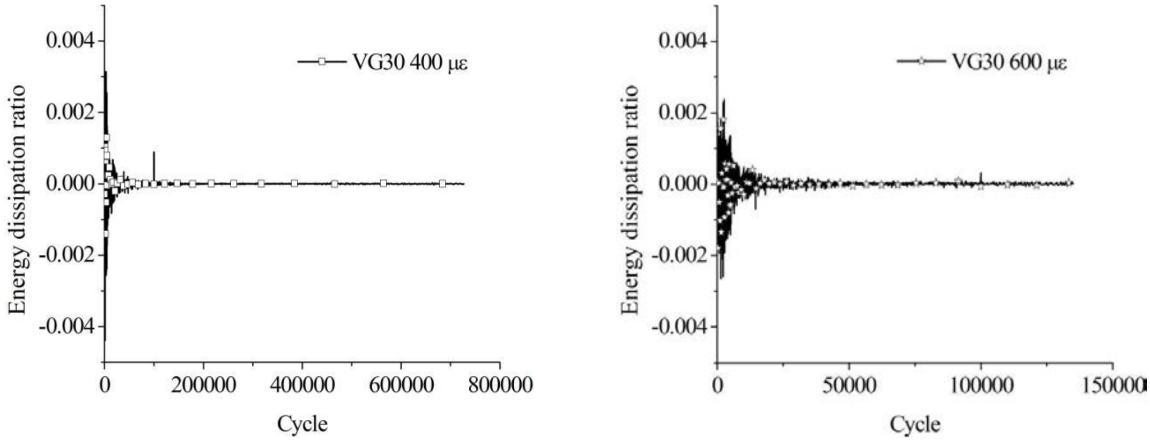

Fig. 7. (c) Energy dissipation ratio at 400 microstrain; (d) Energy dissipation ratio at 600 microstrain

4. Conclusion

We reported here some interesting preliminary results of an ongoing investigation to quantify the influence of modified binders on the fatigue response. It was clearly seen that the fatigue life of bituminous mixtures is defined differently using different standards. The fatigue life is normally defined based on the reduction of stiffness modulus to a predefined value or based on the rate of energy dissipated for every loading cycle. The ASTM, AASHTO and EN standards base their analysis on the evolution of stiffness modulus. From the analysis of the results, it was found that at lower strain levels of 200 and 400 microstrain, PMB exhibited higher fatigue life than VG30 and CRMB. At higher strain level of 600 microstrain, CRMB and PMB exhibited identical fatigue life with VG30 binder showing superior performance. Using the RDEC concept, quantification of fatigue damage was not possible since within the loading cycles applied, the material did not show the third stage. However, observing the dissipated energy as a function of number of cycles, conclusions can be arrived similar to the reduction of stiffness modulus as per ASTM, AASHTO and EN standards.

5. Acknowledgement

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