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EFFECT OF REST PERIOD AND TEMPERATURE ON THE ESTIMATION OF FATIGUE LIFE OF BITUMINOUS MIXTURE

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Abstract. This paper reports the experimental investigation conducted to study the influence of temperature and rest period on different methods of estimation of fatigue life of the bituminous mixture. Four-point beam bending tests were conducted on the bituminous mixture prepared with one unmodified binder and two different modified binders (crumb rubber modified and elastomer modified binder). The test was conducted at 20 °C and 0 °C using continuous loading and a rest period between two load cycles. The fatigue life was estimated using stiffness modulus and energy dissipation. The performance of three different bituminous mixtures was ranked—ranking a bituminous mixture based on the fatigue performance varied with temperature and loading condition. In addition, the ranking also varied with different post-processing methods adopted.

Keywords: bituminous mixture, energy dissipation, fatigue life, flexural modulus, normalised modulus, rest period, temperature.

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Introduction

The fatigue damage in the bituminous mixture occurs due to repeated loading. Micro-crack occurs at the initial loading cycles, and on continuous loading, micro-crack coalesces to form macro-crack. This onset of macro-crack is indicated as the fatigue damage in the material. Repeated loading generally simulates the fatigue damage of bituminous mixture in the laboratory. The mode of testing commonly adopted includes direct tension-compression loading, indirect tension test or beam bending test (Di Benedetto et al., 2004). These tests are generally conducted in the strain-controlled mode with repeated sinusoidal or haversine loading patterns and under controlled temperature (Baburamani, 1999). The number of cycles to failure indicates the fatigue life of the bituminous mixture. The damage in the material is identified through the evolution of material properties such as modulus, phase angle and energy dissipation. These test results were further used to rank bituminous mixtures and design the pavement based on the Mechanistic-Empirical Pavement Design approach (American Association of State..., 2008).

Two main factors govern the fatigue life of bituminous mixtures. One is the selection of test parameters such as temperature and rest period between loading cycles (Bonnaure et al., 1982). Another factor is the post-processing methods adopted to compute fatigue damage in the bituminous mixture (Moreno-Navarro & Rubio-Gámez, 2016; Varma et al., 2016, 2019). *AASHTO T 321 Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending, ASTM D8237-21 Standard Test Method for Determining Fatigue Failure of Asphalt-Aggregate Mixtures with the Four-Point Beam Fatigue Device*, and *EN* standards (*BS EN 12697-24 Bituminous Mixtures – Test Methods for Hot Mix Asphalt. Part 24: Resistance to Fatigue*) recommend conducting the test using sinusoidal loading without providing any rest period between consecutive loading cycles to simulate the fatigue damage in the mixture at a laboratory scale. However, it is advantageous to experiment with a rest period between two load cycles to simulate the real-time traffic loading condition. Various literature has captured the influence of the rest period on the fatigue life of bituminous mixtures at the typical testing temperature of 20 °C (Bonnaure et al., 1982; Groenendijk et al., 1997; Hsu & Tseng, 1996). Baaj et al. (2018) reported the detrimental effect of the rest period on the fatigue life of a bituminous mixture at a lower temperature. Ayar et al. (2018) observed that a rest period between loading cycles extended the fatigue life of the bituminous mixture. The rest period influences the fatigue life only when provided at its initial loading cycles. The influence of the rest period is expected to be more pronounced at 20 °C, where the response of the material is viscoelastic. As the temperature reduces, the material becomes more elastic. At such a lower temperature, though one expects reduced fatigue life due to increased material stiffness, the influence of the rest period at such temperature, especially for the bituminous mixtures with a modified binder, is unknown (Ayyar et al., 2019).

On repeated loading, the material damage occurs, and the damage in the material is identified based on the evolution of modulus or energy dissipation. Various post-processing methods exist for estimating the fatigue life of the bituminous mixture. *EN* standard (*BS EN 12697-24 Bituminous Mixtures – Test Methods for Hot Mix Asphalt. Part 24: Resistance to Fatigue*) recommends using a number of cycles corresponding to 50% of the initial stiffness modulus as the fatigue life of the bituminous mixture. *AASHTO T 321* of 2010 (inactive) also recommended following a similar approach in estimating fatigue life. However, *AASHTO T 321* recommends using the product of stiffness modulus and the number of cycles in fatigue life estimation. The number of cycles corresponding to the peak point in the product of stiffness modulus and the number of cycles is considered fatigue life. *ASTM D8237-21* recommends using the product of normalised stiffness modulus and normalised cycle in determining fatigue life. The fatigue life based on *AASHTO T 321* and *ASTM D8237-21* is expected to be identical.

Ghuzlan, & Carpenter (2000), Kim et al. (2003), Carpenter & Shen (2006), and Shen et al. (2006) used the evolution of energy dissipation to estimate fatigue life. As the damage accumulates in the material on repeated loading, it dissipates energy. The evolution of energy dissipation determines the fatigue life of a bituminous mixture. The material dissipates energy due to the viscous effect and damage. Assuming the viscous effect of the material to be constant on repeated loading, the change in dissipation is only due to damage. One considers total dissipation to estimate fatigue life (Varma et al., 2016, 2019). The ratio of dissipated energy change (Shen & Carpenter, 2005), energy ratio (Rowe & Bouldin, 2000), and cumulative energy dissipation (Ghuzlan & Carpenter, 2000) are some of the standard methods that use total dissipation in the fatigue life estimation.

Cheng et al. (2021) reported the fatigue life of bituminous mixture measured at different temperatures within the 15 °C to 40 °C range using four-point beam bending and Indirect tension tests. In a strain-controlled test (four-point beam bending test), the fatigue life of the bituminous mixture was observed to increase as the temperature increased. Whereas in the stress-controlled test (IDT), the fatigue life of the bituminous mixture was observed to decrease with an increase in temperature. Saboo et al. (2016) determined the fatigue life of bituminous mixture produced using different unmodified and modified bitumen. A bituminous mixture with a plastomeric modified binder exhibited higher strain susceptibility. De Mello et al. (2018) measured the fatigue life of different bituminous mixtures with and without crumb rubber using a four-point beam bending test. The bituminous mixture with crumb rubber exhibited lower temperature susceptibility when compared to the conventional mixtures. Most post-processing methods (modulus/energy dissipation) are applied to standard testing (20 °C conducted without any rest period). It is unclear how these post-processing methods work when non-standard testing is attempted, such as testing at 20 °C and with a rest period. Also, it is unclear how the modified binders such as crumb rubber modified binder (CRMB) and polymer modified binder (PMB) behave at lower temperatures and with a rest period. This study captures the influence of temperature and rest periods on the different estimation methods of fatigue life. This experimental investigation was conducted on the bituminous mixture with one unmodified binder and two modified binders (CRMB and elastomer modified binder). The fatigue damage in the bituminous mixture is conducted using four-point beam bending tests. The fatigue life was estimated using 50% initial stiffness, normalised modulus curve and energy ratio method, material performance at different test conditions were ranked, and the influence of temperature and rest period on different post-processing methods was analysed.

1. Experimental investigation

1.1. Materials and sample preparation

The laboratory investigation was conducted on a bituminous mixture of bituminous concrete (BC) grade – II (Ministry of Road Transport…, 2001). Three different bituminous mixtures were prepared using three different types of binders. One is of VG40 grade of binder graded as per *IS 73:2018 Paving Bitumen – Specification (Fourth Revision)*. The second binder is the crumb rubber modified binder graded as CRMB60 as per inactive standard *IS 15462:2004 Indian Standard for Polymer and Rubber Modified Bitumen.* The third binder is an elastomer modified binder graded as PMB40 as per inactive standard *IS 15462:2004*.

Further, the respective bituminous mixtures in this study were termed VG40, CRMB60 and PMB40. For the preparation of a bituminous mixture, 5% of the total weight of bitumen is used. The aggregate with a nominal maximum size of 13 mm and the gradation corresponding to the mid-gradation of Bituminous Concrete grade – II (BC-II) as per Ministry of Road Transport… (2001) specificationwas used. For the production of the VG40 mixture, bitumen and aggregate were heated to 165 °C and 175 °C, respectively and mixed at 165 °C using a temperature-controlled mixture machine. For the CRMB60 and PMB40 mixture production, bitumen and aggregate were heated to 185 °C and 195 °C and mixed at 185 °C.

Further, the loose mixture was short-term aged before compaction. For the short-term ageing of VG40, the mixture was kept at 135 °C for 4 hours and 155 °C for 30 minutes. CRMB60 and PMB40 mixtures were short-term aged at 155 °C for 4 hours and at 175 °C for 30 min. The mixture was compacted to the size of 450×150×160 mm using a shear box compactor following *ASTM D7981-20 Standard Practice for Compaction of Prismatic Asphalt Specimens by Means of the Shear Box Compactor*. The compacted beam was further sliced to the size of 380×63×50 mm. Four such sliced beams were obtained from the single compacted beam. During compaction, the degree of compaction was controlled to achieve target air voids of 4 ± 0.5% in the sliced beam.

1.2. Fatigue testing

The prismatic beam is subjected to a strain-controlled repeated tension-compression mode. The deflection was measured using LVDT placed on the beam middle length.

The test was conducted for two different loading conditions. The first test set is the conventional four-point beam bending test as per *AASHTO T 321* or *ASTM D8237-21,* where the loading is applied without providing any rest period for two cycles, as shown in Figure 1a. The beam sample was subjected to repeated sinusoidal loading with the period of each cycle as 0.1 s (second) (10 Hz). In the second test, the rest period of 0.9 s was introduced between each loading cycle. Hence, each loading cycle consistsof 0.1 s loading followed by a 0.9 s rest period, as shown in Figure 1b. The tests were carried out with three strain amplitudes of 400 μm/m, 600 μm/m and 800 μm/m. The test conducted without a rest period was terminated when the stiffness modulus reduced to 80% of the initial stiffness modulus or 1×10^6 cycles, whichever occurred earlier. For the test protocol with the rest period, the test was terminated at the end of 1×10^5 cycles (test time duration – 27 h 46 min 40 s). Both tests were conducted at 20 °C and 0 °C. For a sample to reach the test temperature, the beam sample was kept in the temperature-controlled environmental chamber maintained at the test temperature for a minimum of 2 h before testing. The load and the deformation data were collected at 1/100th of a second interval. Table 1 presents the details of each test. All the tests were repeated twice, and the repeatability among the samples was ensured as per *ASTM D8237-21* standard.

Table 1. Details of the four-point beam bending test

Material	Loading condition	Temperature	Strain amplitude, μm/m	Test termination cycle	Testing time
VG40	without rest period	20 °C	400	501 187	13 h 5 min 18.7 s
			600	57 293	1 h 35 min 29.3 s
			800	4123	6 min 52.3 s
		0 °C	400	584 304	16 h 13 min 50.4 s
			600	143 140	3 h 58 min 34 s
			800	2310	3 min 51 s
	with a rest period	20 °C	400	100 000	27 h 46 min 40 s
			600	45 197	12 h 33 min 17 s
			800	29 125	8 h 5 min 25 s
		0 °C	400	98 962	27 h 29 min 22 s
			600	100 000	27 h 46 min 40 s
			800	24 622	6 h 50 min 22 s
CRMB60	without rest period	20 °C	400	901 832	25 h 3 min 3.2 s
			600	63 095	1 h 45 min 9.5 s
			800	21 795	36 min 19.5 s
		0 °C	400	1 000 000	27 h 46 min 40 s
			600	125 893	3 h 29 min 49.3 s
			800	51 536	1 h 25 min 53.6 s
	with a rest period	20 °C	400	100 000	27 h 46 min 40 s
			600	100 000	27 h 46 min 40 s
			800	42 552	11 h 49 min 12 s
		0 °C	400	100 000	27 h 46 min 40 s
			600	76 806	21 h 20 min 6 s
			800	64 106	17 h 48 min 26 s
PMB40	without rest period	20 °C	400	699 351	19 h 25 min 35.1 s
			600	46 398	1 h 17 min 19.8 s
			800	16 663	27 min 46.3 s
		0 °C	400	942 133	26 h 10 min 13.3 s
			600	112 762	3 h 7 min 56.2 s
			800	2347	3 min 54.7 s
	with a rest period	20 °C	400	100 000	27 h 46 min 40 s
			600	100 000	27 h 46 min 40 s
			800	100 000	27 h 46 min 40 s
		0 °C	400	100 000	27 h 46 min 40 s
			600	100 000	27 h 46 min 40 s
			800	5962	1 h 39 min 22 s

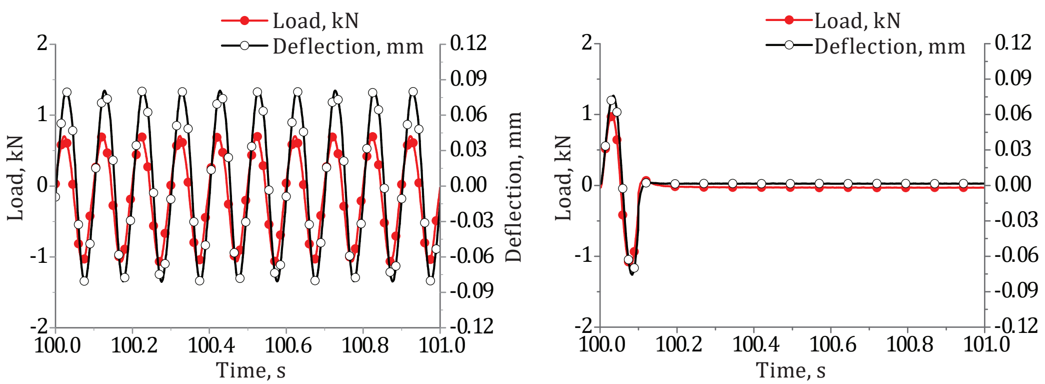
2. Results and discussion

2.1. Fatigue life based on *AASHTO T 321* of 2010 (inactive)

2.1.1. Stiffness modulus

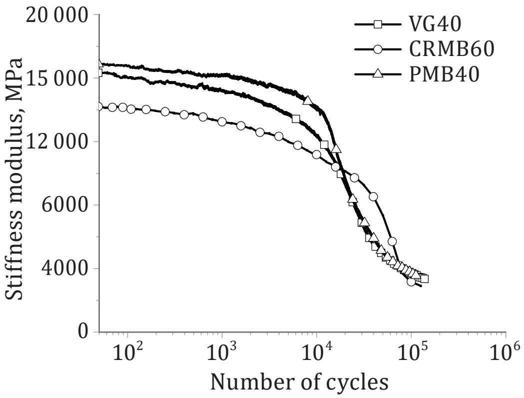
The peaks of load and deflection for the waveforms shown in Figure 1 were identified and was carried out for all the loading cycle tested with and without a rest period. The stiffness modulus was computed following *AASHTO T 321* of 2010 (inactive). Figure 2 shows the stiffness modulus at 20 °C and 0 °C when measured at 600 μm/m with and without a rest period. The initial stiffness modulus at 0 °C is higher than 20 °C. Here, the 50th cycle is considered an initial cycle. Figure 2 also shows that the initial stiffness modulus of VG40, CRMB60 and PMB40 are in the same order of magnitude. However, on continuous loading, the modulus of VG40, CRMB60 and PMB40 decreased at a different rate.

Further, to study the influence of temperature and rest period on the reduction in stiffness modulus, the modulus is normalised to the initial modulus. The normalised plot is shown in Figures 3–5. Figures 3 and 4 show the normalised stiffness modulus of VG40 and CRMB60 at different temperature and loading conditions. For both the VG40 and CRMB60 mixture, the reduction in modulus at 0 °C occurred faster than at 20 °C. Likewise, the reduction in modulus at both 0 °C and 20 °C is slower when tested with a rest period. On repeated loading, the stiffness modulus reduced as the damage accumulated in the material. Hence for both VG40 and CRMB60 mixture, the damage at 0 °C accumulates at

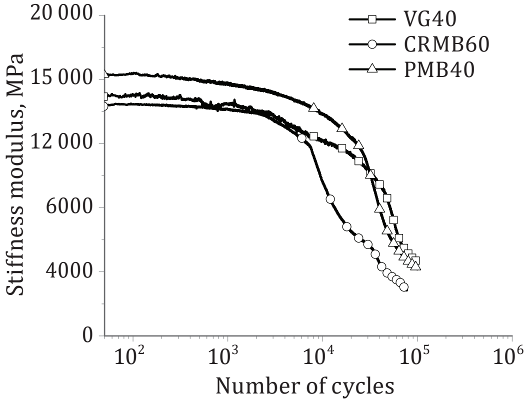


a) without rest **b)** with a rest period

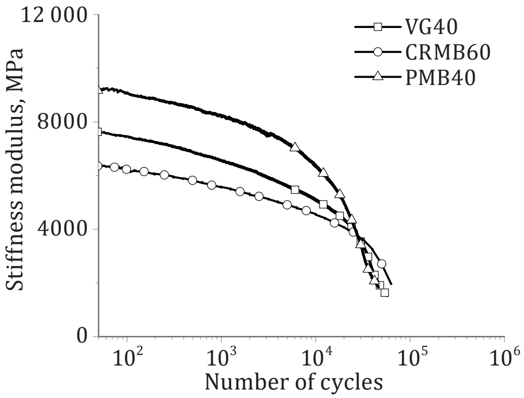
Figure 1. Load and deformation waveform of PMB40(E) at 600 μm/m and 20 °C



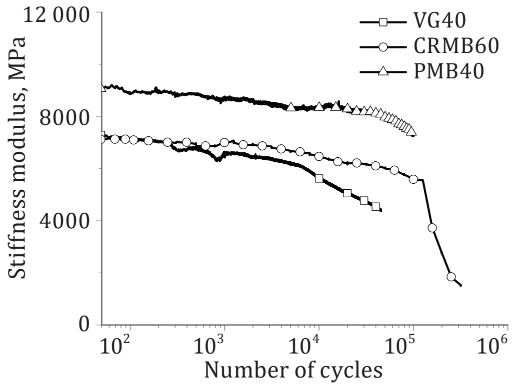
a) without a rest period at 0 °C



b) with a rest period at 0 °C

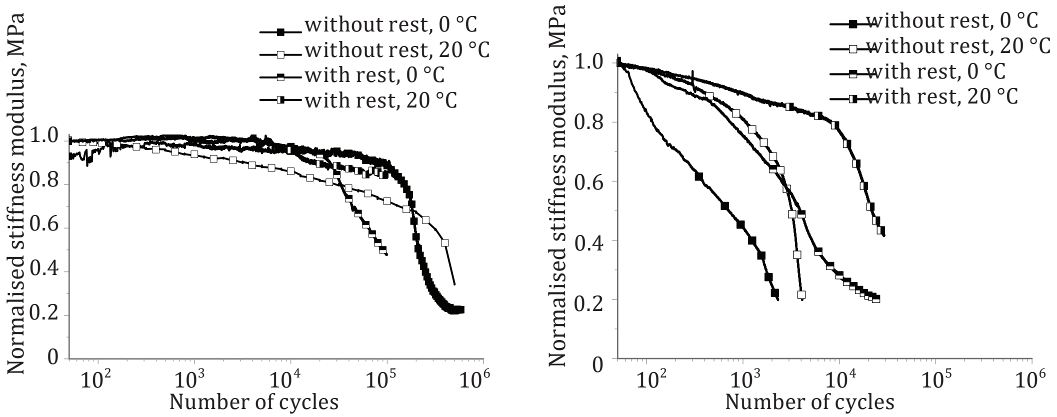


c) without a rest period at 20 °C



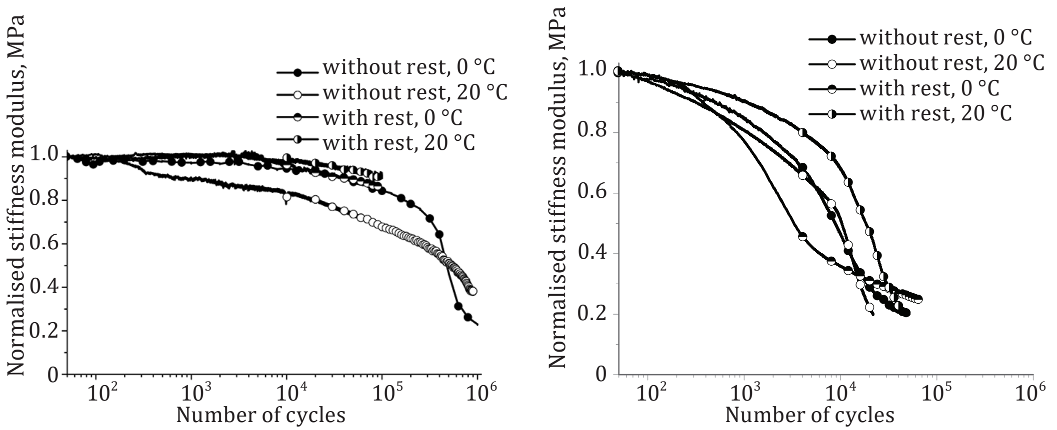
d) with a rest period at 20 °C

Figure 2. Evolution of stiffness modulus at 600 μm/m



a) 400 μm/m **b)** 800 μm/m

Figure 3. Evolution of normalised stiffness modulus of VG40



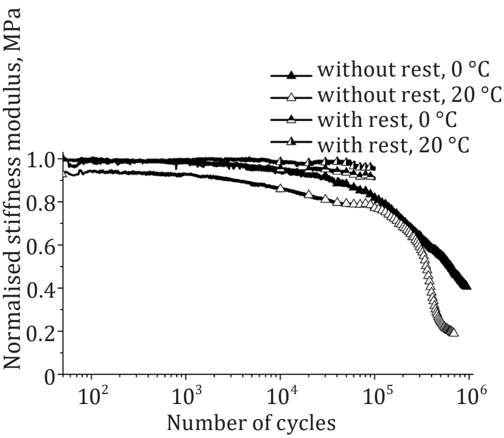
a) 400 μm/m **b)** 800 μm/m

Figure 4. Evolution of normalised stiffness modulus of CRMB60

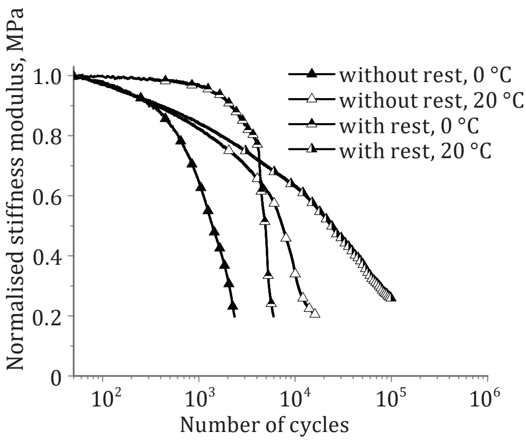
a faster rate when compared to 20 °C. Also, a rest period between two loading cycles had reduced the damage rate in both VG30 and CRMB60 mixture at 20 °C and 0 °C. Figure 5 shows the normalised stiffness modulus of PMB40 at different temperature and loading conditions. Comparing the normalised stiffness modulus at 20 °C and 0 °C, when measured without a rest period, at 400 μm/m (Figure 5a), the reduction in stiffness at 20 °C is faster than 0 °C. The bituminous material is stiffer at 0 °C. One expects the damage to occur faster in the condition where the material is more stiffer. As expected, the evolution of damage in the VG40 and CRMB60 mixture occurred faster at 0 °C when compared to 20 °C. In the PMB40 mixture, though the material is stiffer at 0 °C, the damage at 0 °C progressed at a slower rate when compared to 20 °C. The dominance of elastomer in the binder probably reduced the rate of change in stiffness at 0 °C. A study by Lu et al. (2003) also reported improved low-temperature properties of elastomeric bituminous material through different test methods. Figure 5a also shows that on the provision of a rest period, the stiffness modulus at 20 °C reduced at a slower rate when compared to 0 °C. The slower reduction in modulus at 20 °C also indicates that the provision of a rest period for PMB40 was more beneficial at 20 °C than at 0 °C.

2.1.2. Fatigue life based on stiffness modulus

The fatigue life of the bituminous mixture was estimated following *AASHTO T 321* of 2010 (inactive). The number of cycles corresponding to 50% of initial stiffness represents the fatigue life of the bituminous



a) 400 μm/m



b) 800 μm/m

Figure 5. Evolution of normalised stiffness modulus of PMB40

mixture. *EN* standard *BS EN 12697-24* also recommends using 50% of initial stiffness to calculate fatigue life. For the test that was terminated before reaching 50% of initial stiffness, the stiffness modulus was extrapolated using an exponential function of the form given in Equation (1), where S in Equation (1) represents the stiffness modulus, x represents anumber of cycles, and a, b, c and d represents the constants. The sample exponential fit and the experimental data for VG40 material at 400 μm/m, when tested with a rest period at 20 °C, are shown in Figure 6. The number of cycles (x) corresponding to 50% of the initial stiffness modulus (S) was estimated using Equation (1):

$$S = ae^{bx} + ce^{dx}, \tag{1}$$

where a, b, c, and d are model constants.

AASHTO T 321 of 2010 (inactive) recommends using the Equation of the form $S = ae^{bx}$ instead of Equation (1). The exponential Equation (1) with four constants resulted in a better prediction of the experimental results. Hence, in this study, the prediction was made using four exponential constants a, b, c and d. For instance, the exponential fitting for some samples, PMB40 at 400 μm/m, with a rest period and at 20 °C (Figure 5a), as the stiffness modulus remained almost constant within the test duration. The fatigue life based on 50% of initial stiffness and the ranking of the material based on the fatigue life is given in Table 2. The material is ranked as (1), (2) and (3) based on its fatigue life. The material with higher fatigue life is ranked as (1). At 20 °C, when tested without a rest period, CRMB60 was observed to exhibit better fatigue resistance, followed by VG40 and PMB40. At 0 °C, PMB40 exhibited

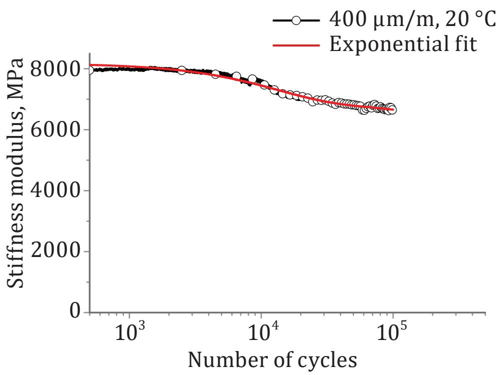


Figure 6. Stiffness modulus and exponential fit for VG40 at 400 μm/m and 20 °C when tested with a rest period

better fatigue performance than VG40. The provision of rest periods between load cycles changed the ranking of the material. The rest period was found to be more beneficial for PMB40. PMB40 exhibited better fatigue resistance, followed by CRMB60 and VG40.

2.2. Fatigue life based on ASTM D8237-21

2.2.1. Normalized modulus

ASTM D8237-21 recommends the use of the product of normalized stiffness $(\hat{S})$ and normalised cycles $(\hat{N})$ to determine the fatigue life of the bituminous mixture. The product of normalised stiffness and normalised modulus is determined using Equation (2):

$$\hat{S} \cdot \hat{N} = \frac{S_i \cdot N_i}{S_o \cdot N_o}, \tag{2}$$

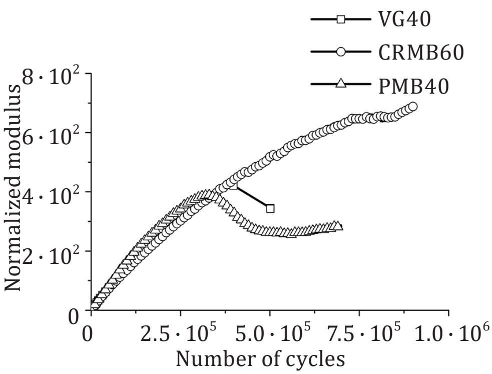
where S_i is stiffness modulus at i^{th} cycle; N_i is a cycle I; S_o is stiffness modulus at the 50^{th} cycle; N_o is the initial cycle (here is taken as 50).

Table 2. Fatigue life ranking based on 50% initial stiffness

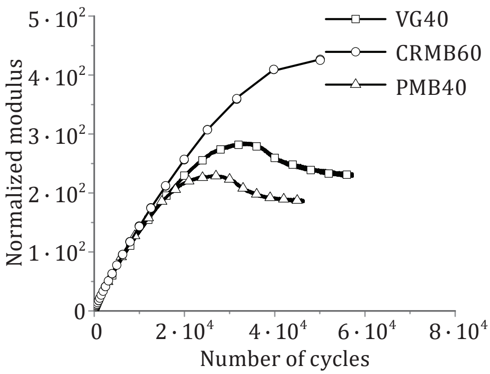
Temperature	Loading condition	Strain, µm/m	Number of cycles and ranking		
			VG40	CRMB60	PMB40
20 °C	with a rest	400	1 778 722	2 175 193	–
		600	116 741(3)	174 143(2)	301 046(1)
		800	21 713(3)	18 296(2)	23 723(1)
	without rest	400	470 986(2)	528 103(1)	366 459(3)
		600	27 270(2)	49 382(1)	22 411(3)
		800	3206(3)	10 308(1)	7374(2)
20 °C	with a rest	400	85 089(3)	1 002 372(2)	1 185 188(1)
		600	24 108(2)	16 552(3)	38 978(1)
		800	3934(2)	3299(3)	4904(1)
	without rest	400	223 475(3)	480 375(2)	633 639(1)
		600	23 417(3)	49 013(1)	23 671(2)
		800	710(3)	8856(1)	1383(2)

Further, in this paper, the normalised stiffness and normalised cycles product is represented as the normalised modulus. Figure 7 shows the normalised modulus of all the material at 20 °C when tested without a rest period. When the normalised stiffness modulus is plotted versus the number of cycles, a well-defined peak, as observed in the case of VG40 and PMB40 at 400 μm/m and 600 μm/m in Figures7a and 7b, is expected to occur; this point is considered the failure point. For some cases, as in the case of CRMB60 in Figures 7a and 7b, the peak point has not occurred within the test duration. The standard recommends using the sixth-order polynomial function, logit equation, or Weibull function to extrapolate the failure point.

Figure 8 shows the normalised modulus of all the material at 20 °C when tested with the rest period. There is no well-defined peak in these normalised modulus curves. Figure 9 and 10 shows the normalised modulus curve at 0 °C when tested with and without a rest period. There is no well-defined peak at 0 °C. American Society for Testing and Materials recommends conducting the test at 20 °C without a rest period. Figure 7 presents a well-defined peak for the testing conditions prescribed in the standard. No well-defined peak was observed when tested with a rest period between loading cycles or at 0 °C. Hence, when the beam is loaded by providing a rest period or when tested at low temperature, the normalised modulus trend differs from *ASTM D8237-21* depicted trend.

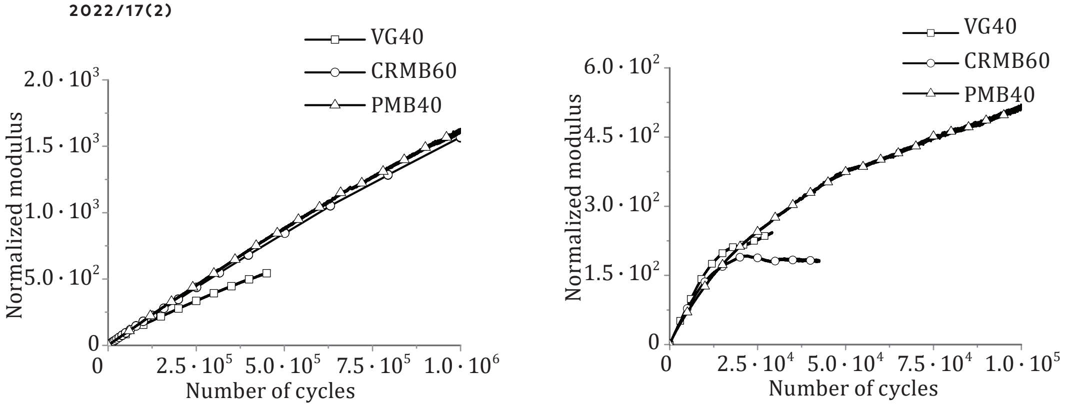


a) at 400 μm/m



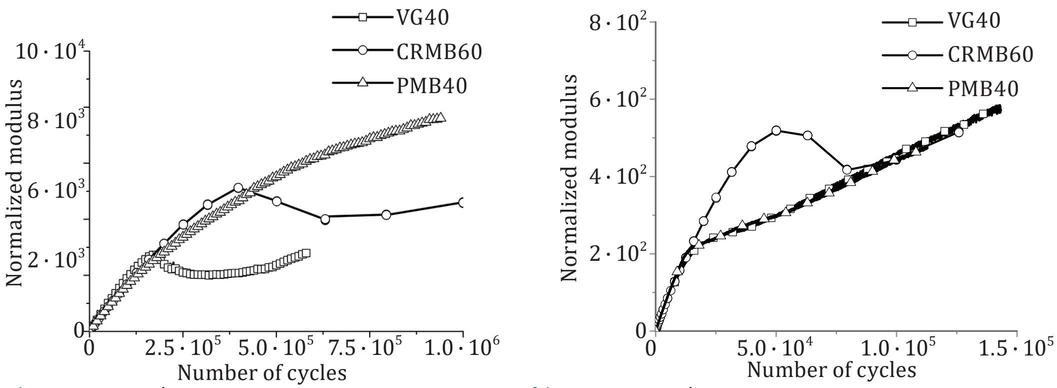
b) at 600 μm/m

Figure 7. Normalised modulus at 20 °C when tested without a rest period



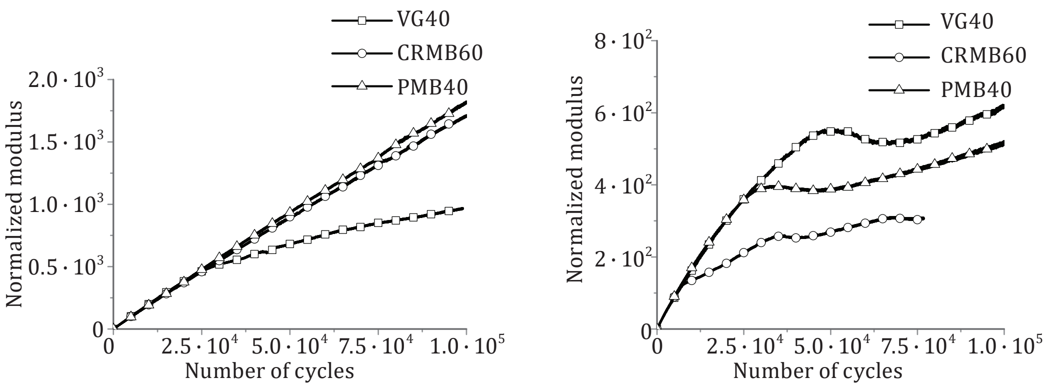
a) at 600 μm/m **b)** at 800 μm/m

Figure 8. Normalised modulus at 20 °C when tested with a rest period



a) at 400 μm/m **b)** at 600 μm/m

Figure 9. Normalised modulus at 0 °C when tested without a rest period



a) at 400 μm/m **b)** at 600 μm/m

Figure 10. Normalised modulus at 0 °C when tested with a rest period

2.2.2. Fatigue life based on the normalised modulus

The number of cycles to failure was identified using the Weibull function following Equation (3). SR in the Equation (3) represents S_i / S_0, N represents the number of the cycle, γ and Λ are regression constants.

$$\ln\left(-\ln\left(SR\right)\right) = \gamma \cdot \ln\left(N\right) + \ln\left(\Lambda\right). \tag{3}$$

The sample Weibull fit is shown in Figure 11, and the estimated fatigue life and the ranking of a bituminous mixture based on fatigue life are presented in Table 3. The material is ranked as (1), (2) and (3) based

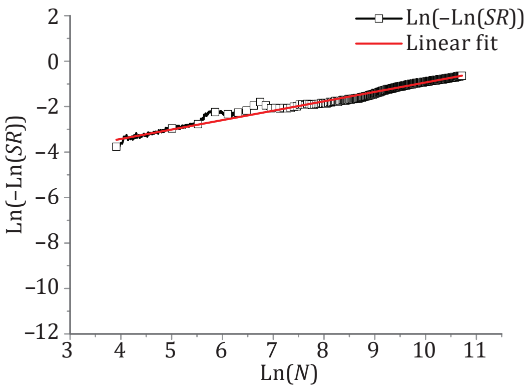
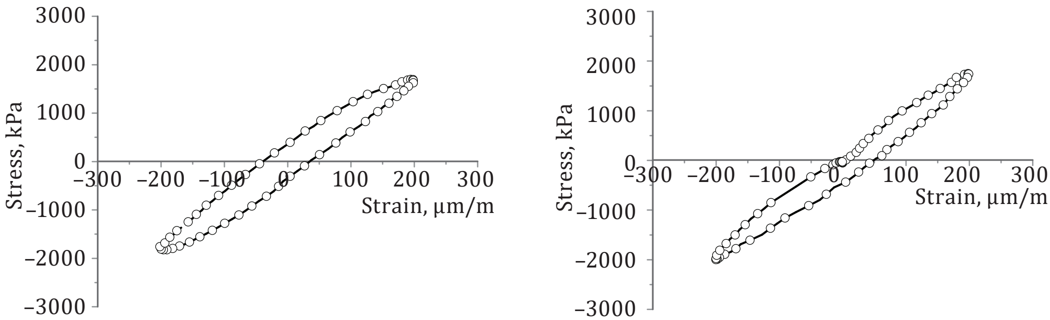


Figure 11. Weibull fit corresponding to VG40 with rest period test for 600 µm/m and 20 °C

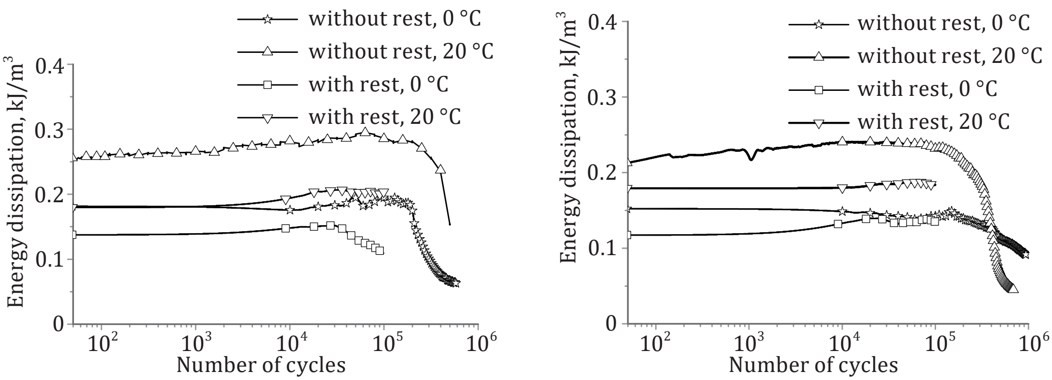
Table 3. Fatigue life ranking based on *ASTM D8237-21*

Temperature	Loading condition	Strain, µm/m	Number of cycles and ranking		
			VG40	CRMB60	PMB40
20 °C	with a rest	400	928 375	1 968 632	–
		600	87 448(3)	7 181 746(2)	11 947 317(1)
		800	27 602(1)	16349(3)	22 462(2)
	without rest	400	398 104(2)	403 421(1)	327 236(3)
		600	18 652(2)	35 377(1)	16 676(3)
		800	6217(2)	7792(1)	5482(3)
0 °C	with a rest	400	91 002(3)	993 305(2)	51 869 073(1)
		600	52 164(1)	22 693(3)	41 574(2)
		800	29 120(1)	3601(3)	12 608(2)
	without rest	400	171 457(3)	398 098(2)	629 685(1)
		600	25 830(3)	53 380(1)	26 051(2)
		800	2977(2)	51 261(1)	1269(3)

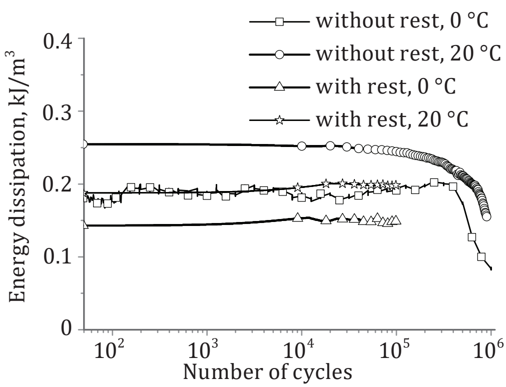


a) without a rest period **b)** with a rest period

Figure 12. 50th cycle Lissajous plot of PMB40 at 20 °C and 400 μm/m



a) VG40 **b)** PMB40



c) CRMB60

Figure 13. Evolution of energy dissipation in a different bituminous mixture at 20 °C and 0 °C, with and without a rest period at 400 μm/m

on its fatigue life. The material with higher fatigue life is ranked as (1). When tested without a rest period, the order of the fatigue life ranking at 20 °C when tested without a rest period is the same when compared to the ranking based on 50% of initial stiffness. However, the material ranking differed when the test was conducted with a rest period or at 0 °C.

2.3. Energy dissipation and fatigue life using energy ratio

It is well known that the bituminous mixture behaves as a viscoelastic material, and it dissipates energy. The magnitude of dissipation depends on the extent of viscoelastic behaviour. In addition, to the viscoelastic dissipation, the material also dissipates energy as the damage progress due to repeated loading. At the initial loading cycles, the energy dissipation was the minimal damage that could be considered the dissipation due to viscoelastic behaviour. The dissipation after applying a few loading cycles can be due to viscoelastic behaviour and damage.

The energy dissipation at each loading cycle is calculated using a stress-strain plot (Lissajous plot). The 50^{th} cycle Lissajous plot for PMB40 at 20 °C and 400 µm/m with and without rest period are shown in Figure 12. The area of the stress-strain plot indicates the energy dissipation in the material. Further, the energy dissipation is calculated for all cycles to loading using the Lissajous plot and the damage in the material is predicted using energy dissipation.

Figure 13 shows the evolution of energy dissipation on repeated loading for all the materials at 400 µm/m. This test being strain-controlled, the energy dissipation decreased on continuous loading. The following observations were made from the evolution of the energy dissipation curve. Provision of the rest period between two loading cycles has reduced the decrease in energy dissipation at both 20 °C and 0 °C. The rate of reduction in energy dissipation is higher at 0 °C.

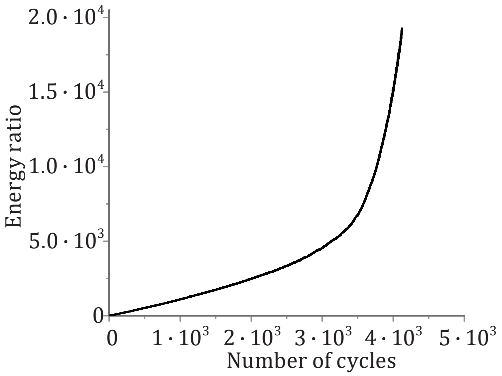
Further, fatigue life based on energy dissipation is estimated based on the energy ratio approach. The energy ratio is calculated from energy dissipation following Rowe& Bouldin (2000) using the expression (Equation (4)):

$$ER = n\frac{W_0}{W_n}, \tag{4}$$

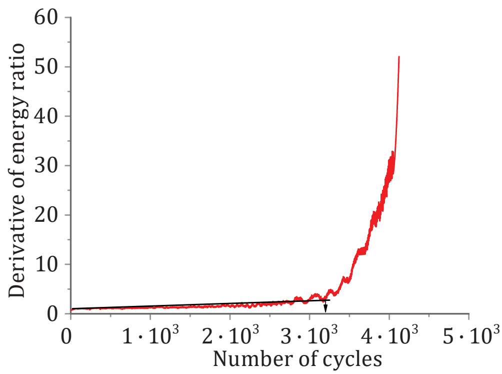
where ER is the energy ratio; n represents the number of cycles; W_0 and W_n represents the energy dissipation (kJ/m^3) at the initial and n^{th} cycle.

The sample energy ratio curve of the VG40 sample is shown in Figure 14a. The increase in energy ratio indicates the fatigue damage accumulation. All the energy ratio curves were observed to be two slope curves, with a gradual change in the slope. The fatigue life is identified as the number of cycles corresponding to the point of change in the slope. The derivative curve is used to identify the fatigue life. The sample derivative curve is shown in Figure 14b. The point of steep change in the energy ratio derivative is considered the fatigue life of the bituminous mixture. Table 4 presents the fatigue life obtained based on the energy ratio method and ranking.

The fatigue life and ranking obtained from the energy ratio method were in the same order as ranking based on 50% of initial stiffness. For instance, considering the testing carried out at 20 °C, without a



a) energy ratio



b) derivative of energy ratio

Figure 14. The energy ratio and derivative curve of VG40 at 800 μm/m and 20 °C when tested without a rest period

Table 4. Fatigue life based on the energy ratio approach

Temperature	Loading condition	Strain, μm/m	Number of cycles and ranking		
			VG40	CRMB60	PMB40
20 °C	with a rest	400	–	–	–
		600	–	–	–
		800	11 739(3)	19 560(2)	52 159(1)
	without rest	400	421 785(2)	596 140(1)	335 743(3)
		600	33 352(2)	50 174(1)	18 010(3)
		800	3181(3)	8370(1)	6265(2)
0 °C	with a rest	400	–	–	–
		600	16 430(2)	7720(3)	26 157(1)
		800	3026(2)	2581(3)	4180(1)
	without rest	400	391 231(3)	429 573(2)	573 858(1)
		600	23 552(3)	41 954(1)	28 391(2)
		800	834(3)	22 401(1)	1081(2)

rest period and 400 μm/m, from the fatigue life obtained from 50% modulus (Table 2), CRMB60 ranked 1 with a fatigue life of 528 103 cycles, and VG40 ranked 2 with the fatigue life of 470 986 cycles, and PMB40 ranked three with the fatigue life of 366 459 cycles. For the exact testing condition, from the fatigue life estimated from the energy ratio approach, the ranking is in the same order as CRMB60 rank 1, VG40 rank 2, and PMB40 rank 3. In comparing the magnitude of fatigue life and ranking in Table 2 and Table 4, though the fatigue life varied between these two post-processing methods, the ranking was the same for all the test conditions.

Conclusions

Various post-processing methods exist in determining the fatigue life of the bituminous mixture. On repeated loading, damage occurs in the material, and the damage is identified based on the evolution of stiffness modulus or energy dissipation. In the conventional testing method, fatigue testing is conducted at 20 °C and on continuous loading without providing a rest period between two loading cycles. This experimental investigation was conducted to check the influence of temperature and rest period on different post-processing methods, and the following observations were made.

1. Fatigue performance ranking of VG40, CRMB60 and PMB40 varied with temperature and loading conditions. In addition, the ranking also varied with different post-processing methods adopted.
2. When the fatigue life was estimated based on the 50% of the initial value of stiffness modulus, at the conventional test temperature of 20 °C when tested without a rest period, CRMB60 exhibited higher fatigue life, followed by VG40 and PMB40. The influence of the rest period on PMB40 was observed to be more prominent at 0 °C. PMB40 exhibited more fatigue resistance when tested with a rest period and at 0 °C.
3. From the normalised modulus curve at different temperatures and different loading conditions, the sharp peak in the normalised stiffness modulus curve, as recommended by *ASTM D8237-21 Standard Test Method for Determining Fatigue Failure of Asphalt-Aggregate Mixtures with the Four-Point Beam Fatigue Device* was only observed when tested at 20 °C without a rest period. On testing, at 0 °C and provision of rest period between loading cycle altered the trend in normalised stiffness modulus curve and no sharp peaks were observed in such cases.

4. The fatigue life ranking of VG40, PMB40 and CRMB60 based on normalised stiffness modulus and 50% initial value of stiffness modulus coincided only at 20 °C when tested without a rest period between two load cycles. In this test condition, the normalised modulus curve exhibited a sharp peak. The ranking for other test conditions is different from the ranking based on *AASHTO T 321 Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending*.
5. Fatigue performance ranking using the energy dissipation approach for all test conditions coincided with a 50% initial value of stiffness modulus.

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