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Influence of Rest Period on the Fatigue Response of Bituminous Mixture at Low Temperature

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Abstract

Laboratory fatigue characterization of bituminous mixtures is carried out by conducting four-point bending test at a given frequency and temperature for various strain/stress levels. In the current fatigue test methods, the material is tested at 20°C with continuous loading and the fatigue life is estimated based on the stiffness modulus and energy dissipation. Very little data exists on the influence of low temperature (0°C), and tests with a rest period.

In this study, the fatigue life of bituminous mixture is estimated at a lower temperature and the influence of rest period on lower temperature is quantified. For this purpose, a typical bituminous mixture used in Indian highways was fabricated. Experiments were conducted at 0 and 20°C with and without a rest period in strain-controlled mode (600 and 800 microstrain). For tests with a rest period, a 0.9 s rest period was provided after 0.1 s loading. The evolution of stiffness modulus (AASHTO T321, 2007) and normalized modulus (ASTM D7460, 2010) was used in fatigue life estimation. Also, the evolution of energy dissipation during testing was

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analyzed to characterize the response of material (elastic/viscoelastic) and the beneficial effect of the rest period, if any. The difference between without rest test protocol and with test result was found to be substantial. The influence of rest period was more pronounced when tested at 20 °C in comparison to testing at 0°C.

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Keywords: Four point beam bending test; low temperature; rest period; stiffness modulus; energy dissipation; damage; fatigue life

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1. Introduction

The fatigue damage in the bituminous mixture occurs as the tensile stress accumulates due to continuous loading. The accumulation of tensile stress in the material is also strongly dependent on the temperature. The fatigue test on the bituminous mixture in the laboratory is generally conducted at 20°C (AASHTO T321 (2017), ASTM D7460 (2010)). Bhattacharjee and Malick (2012) observed that the tensile strain in the hot mix asphalt mixture varies with the temperature and the rate at which the temperature changes. The damage in the material accumulates due to repeated loading and the fatigue life in term of the number of load cycle is determined by the quantum of tensile strain or stress in the material.

Different post-processing methods are available for determining the fatigue life. Such post-processing procedures compute the fatigue life by monitoring the reduction in the flexural modulus or the dissipated energy during loading/unloading cycles. The number of cycles to reach 50% of the flexural modulus (AASHTO T321 (2017)), normalized modulus (ASTM D7460 (2010)), energy ratio (Rowe and Bouldin (2000)) are some of the methods followed currently to estimate the fatigue life.

The stiffness modulus used for the fatigue life estimation depends on the temperature of testing. At low temperature, the initial stiffness before damage is expected to be high when compared to the stiffness modulus measured at a higher temperature. The stiffness modulus reduces as the damage accumulates in the material and the rate of reduction in the stiffness modulus controls the fatigue life of the bituminous mixture (Lundstrom et al. (2004)). Deacon et al. (1994) observed the slope of structural number (SN) curve to be sensitive to the temperature of testing and hence used the temperature equivalency factor in the estimation of fatigue life at a different temperature. Asadi et al. (2013) quantified the fatigue life of bituminous mixture at different temperatures and strain level using four-point beam bending test and it was observed that the influence of temperature on the fatigue life of bituminous mixture is more prominent at the higher strain level. While the influence of temperature on the fatigue life of bituminous mixture is well understood, the influence of rest period on the bituminous mixture, especially at a lower temperature is not precisely quantified.

The provision of the rest period between two loading cycles in the laboratory is expected to simulate the vehicle loading in the pavement. Bonnaure et al. (1982), Hsu and Tseng (1996) and Groenendijk et al. (1997) captured the improved fatigue life by introducing rest period between loading cycles. One can refer to Baburamani (1999) for a detailed review of the literature on the influence of rest period and healing on the fatigue life of bituminous mixture. Due to recovery of damage during rest period, 2 to 10 times increase in fatigue life were observed (Baburamani (1999)). However, the exact magnitude depends on the stiffness of the binder. To predict the fatigue life of bituminous mixture at different temperatures, it is necessary to understand the influence of rest period at different temperatures.

In the current practice, the fatigue test is conducted at 20°C, and the material behaves identically to a viscoelastic material. At 0°C, it is not clear whether the response of the material is elastic or viscoelastic. If the response of the material at such temperatures is indeed elastic, the beneficial effect of the rest period is expected to be minimal. On the other hand, if the response of the material is viscoelastic, one can expect to see increased energy dissipation after rest periods in strain-controlled testing. Such precise quantification linking rest periods on the energy dissipation at 0 ^{o}C has not been reported in the literature to the best of the knowledge of the authors. This study attempts to quantify the influence of rest period on the fatigue life of bituminous mixture at 20 and 0 ^{o}C.

2. Experimental Investigation

2.1. Materials and Sample Preparation

The bituminous mixture for this investigation was prepared using a VG40 grade of the binder as per IS73 (2013). The VG40 binder used in the test has a softening point of 53°C. The viscosity of the binder measured at 60 and 135°C and the penetration measured at 25°C was found to be 3640 Poise, 652 cSt, and 40 dmm. The bituminous mixture used in this investigation was fabricated with binder weighing 5% of total weight of the mixture. The binder content was selected as per minimum specification recommended by MoRTH, (2001) for Bituminous Concrete mix. The aggregate gradation corresponds to mid-gradation of Bituminous Concrete (BC) grade – II with a nominal maximum size aggregate of 13.2 mm (MoRTH (2001)).

For the preparation of BC mixture, the aggregate and the bitumen was heated to 165 ^{o}C, and the mixing of aggregate and the binder was carried out at the temperature of 165 °C (MoRTH (2001)). The mixture was then short-term aged for 4 hours at 135 °C and 30 minutes at 155 °C (AASHTO R30, (2006)). With 5% by weight of bitumen, the theoretical specific gravity of the mix was 2.591.

The short-term aged mixture was compacted using a shear box compactor to produce a beam sample of size 450 × 150 × 160 mm, and the beam sample was further sliced before testing. During compaction, the level of compaction was fixed to target 4±0.5% air voids in the sliced beam. For the target air voids of 4±0.5%, the bulk specific gravity of the beam sample varied from 2.483 to 2.486. From the compacted beam size of 450 × 150 × 165 mm, four beams of size 380 × 63 ×50 mm were sliced and further used for testing.

2.2. Experimental Method

In the testing process, the four-point beam bending test was conducted on the bituminous concrete beam sample. The test was conducted in the strain controlled mode, and the bituminous concrete beam was subjected to the repeated sinusoidal (tension-compression) loading. The deformation at the middle of the span was recorded using LVDT fixed on the beam specimen.

The repeated load was applied at the loading frequency of 10 Hz. Two different tests were conducted in this investigation. In the first test, the beam sample was subjected to continuous loading with the time period of each cycle as 0.1 seconds (10 Hz). This is the conventional method of four-point beam bending test recommended by AASHTO T321 (2017). In the second test, the rest period of 0.9 seconds was introduced between each cycle of loading. Hence in the second test method, each cycle of loading consist of 0.1 second loading followed by a 0.9 second rest period. The test was conducted for the strain amplitude of 600 and 800 microstrain. The data points were collected at an interval of 1/100th of a second. The sample strain and stress waveform with and without rest period corresponding to 600 microstrain are shown in figure 1. All the test were conducted at 20°C which is the standard recommended temperature (AASHTO T321 (2017)) and also at 0°C. In this repeated load test, the test termination criterion is fixed based on the flexural stiffness of the sample or time of testing. The continuous loading test was stopped when the flexural stiffness reduced to 80% of the initial value or 1×10^{6} cycles whichever occurred earlier. For 1×10^{6} cycles, the test running time corresponding to 10 Hz frequency is 27 hours 46 minutes 40 seconds. For the test with rest, the test was stopped after 1 × 10^5 cycles (testing time - 27 hours 46 minutes 40 seconds). All the samples were tested twice to ensure the repeatability of the results as per ASTM D 7460 (2010). The details of the testing condition are listed in table 1.

Table 1. Details of four-point beam bending test

Loading Condition	Temperature (°C)	Strain amplitude (microstrain)	Test termination cycle	Testing time
Without rest period	20	600	57293	1 h 35 min 29 s
		800	4123	0 h 6 min 52 s
	0	600	143140	3 h 58 min 34 s
		800	2310	0 h 3 min 51 s
With rest period	20	600	45197	27 h 46 min 40 s
		800	29125	8 h 5 min 25 s
	0	600	100000	27 h 46 min 40 s
		800	24622	6 h 50 min 22 s

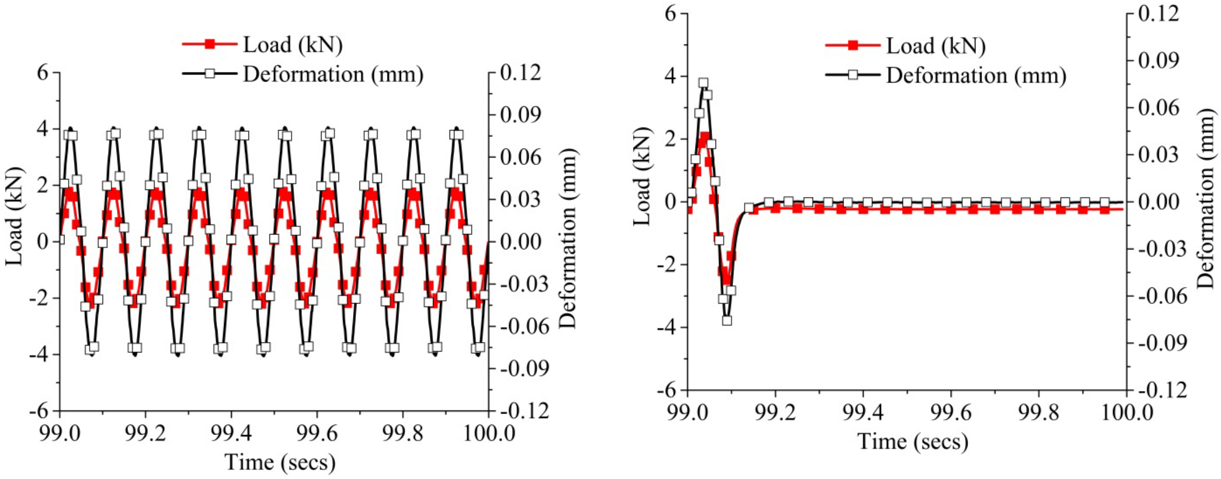

Fig. 1a. without rest period

Fig 1b. With rest period

Fig 1. Sample load and deformation waveform with and without a rest period

3. Results and Discussion

3.1. Stiffness modulus

From the load and the deformation waveform, the peak load and peak deformation were identified for each cycle. Following AASHTO T 321 (2017), the stress and the strain corresponding to peak load and deformation were calculated, and the stiffness modulus was determined. Figure 2 shows the variation of the stiffness modulus of the sample tested at 0 and 20°C. As expected, the initial stiffness modulus of the bituminous mixture at 0°C is higher than the stiffness modulus measured at 20°C. The stiffness modulus at 0 and 20 °C for the initial cycle of loading (50th cycle) is tabulated in table 2. On continuous loading, as the damage progresses, the stiffness modulus decreased at both 0 and 20 °C. In figure 2, it can be observed that the rate of reduction in the stiffness modulus of the sample when tested with and without rest period is different at both 0 and 20 °C.

Figure 3 shows the stiffness modulus normalized with respect to the maximum value. The difference in normalized stiffness modulus curve with and without a rest period at 20 and 0 °C indicates the influence of rest period at a given temperature and strain level. At both 0 and 20 °C for 600 and 800 microstrain, the reduction in stiffness modulus of the sample when tested with rest period is less when compared to the sample tested without a rest period. This indicates that there is a recovery during the rest period between each cycle. Comparing figure 3a and 3b, it can be concluded that the recovery during the rest period at 800 microstrain is higher when compared to the stiffness modulus at 600 microstrain. Further, to study the influence of temperature and rest period on the fatigue life of bituminous mixture, fatigue life was estimated from the stiffness modulus following AASHTO T321 (2017) and ASTM D 7460 (2010).

Table 2. Stiffness modulus at 50th cycle

Loading condition	Stiffness modulus (MPa)			
	At 20 °C		At 0 °C	
	600 με	800 με	600 με	800 με
Without rest period	7641	10643	16323	13519
With rest period	7293	8004	15027	14267

3.2. *Fatigue life as per AASHTO T3212(2017)*

Following AASHTO T321 (2017), the number of the cycle corresponding to 50% of initial stiffness is recorded as the fatigue life of bituminous mixture. In case of termination of the test before reaching 50% of initial stiffness, the stiffness modulus was fitted to an exponential function of the form given in equation 1 and used in the fatigue life estimation. S in the equation (1) represents the stiffness modulus, x represents cycle and a, b, c and d represents the constants. The sample exponential fit is shown in figure 4. The number of cycle (x) corresponding to 50% of initial stiffness modulus (S) was estimated using equation (1).

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

The fatigue life calculated as per AASHTO T321 (2017) for all the loading conditions and temperatures is listed in table 3. At 0°C, though the initial stiffness modulus at 0 °C is higher (table 2), the fatigue life is found to be less than the fatigue life at 20 °C. On comparing the fatigue life of the sample tested without and with a rest period, the sample tested with rest period resulted in higher fatigue life at both 0 and 20°C. The fatigue life at 20 °C and 600 microstrain for the sample tested with rest period are 4.32 times the fatigue life of the sample tested without a rest period. At 0°C, the fatigue life without rest period is 2.25 times of the fatigue life with a rest period. This shows that the influence of the rest period on the fatigue life of bituminous mixture is more at 20 °C when compared to 0 °C. This temperature dependency is due to the viscoelastic nature of the material.

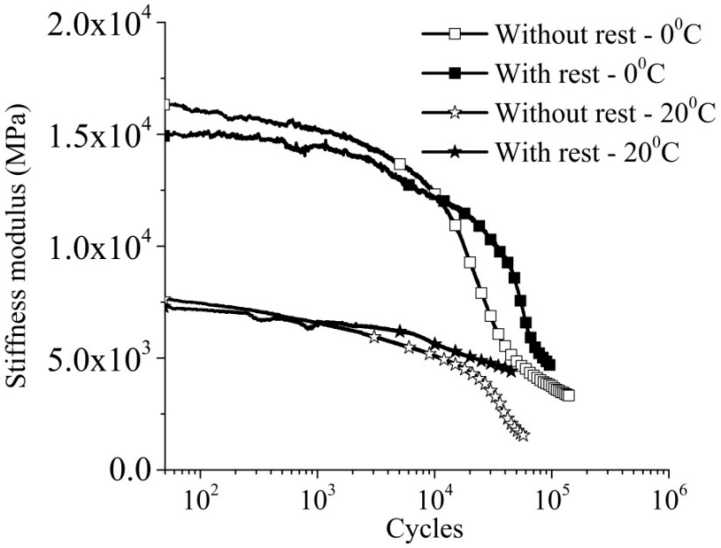

Fig. 2a. 600 microstrain

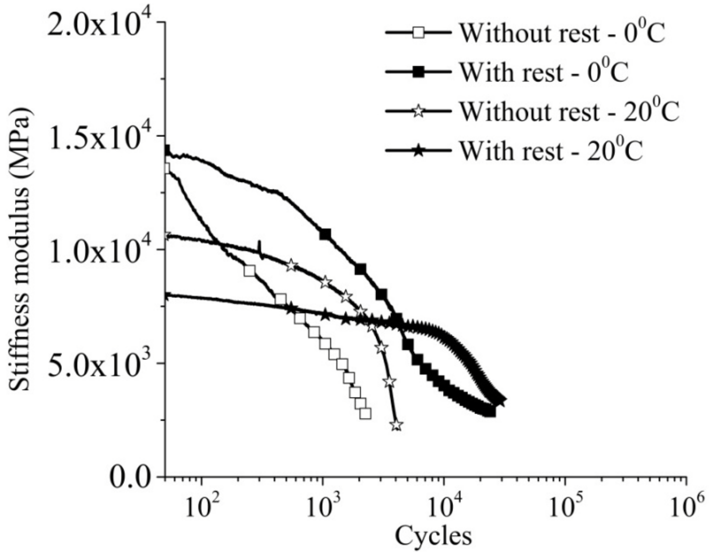

Fig. 2b. 800 microstrain

Fig. 2. Variation of stiffness modulus as a function of temperature and loading conditions

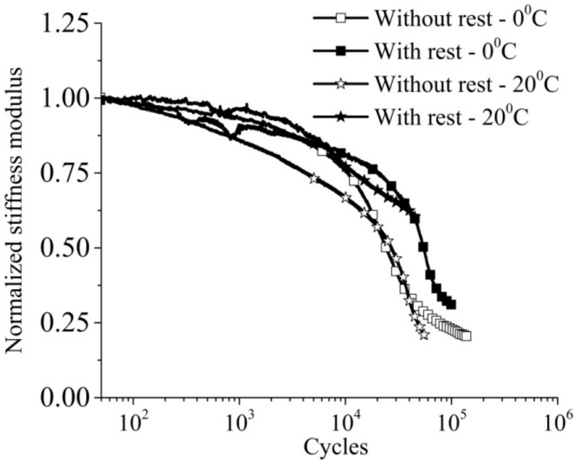

Fig. 3a. 600 microstrain

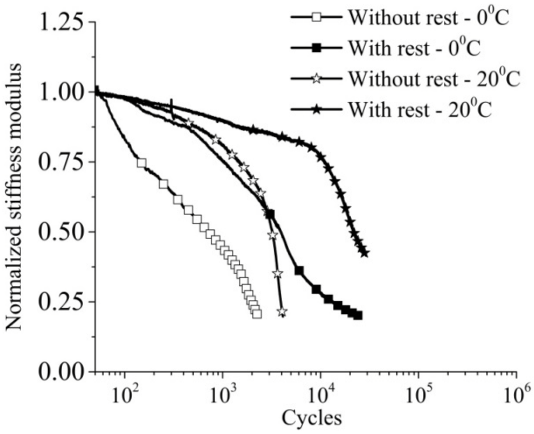

Fig. 3b. 800 microstrain

Fig. 3. Variation of stiffness modulus (normalized) as a function of temperature and loading conditions

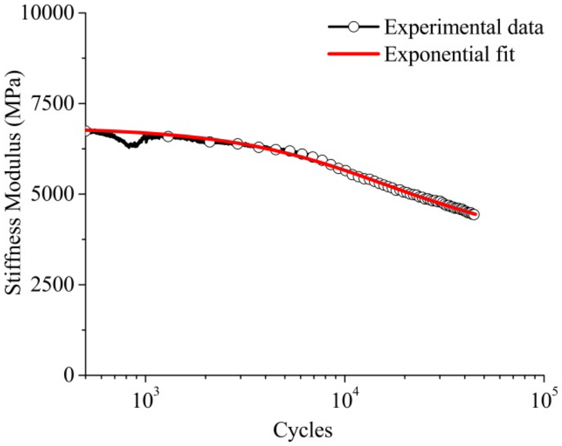

Fig. 4. Exponential fit for stiffness modulus (with rest period) at 20 °C and 600 microstrain.

Table 3. Fatigue life

Method of fatigue life estimation	Loading condition	20 °C		0 °C	
		600 με	800 με	600 με	800 με
AASHTO Method	Without rest period	27100	3212	24159	713
	With rest period	117000*	21772	54382	3934
ASTM Method	Without rest period	31281	3115	26896#	1654
	With rest period	87412#	20661	50593	3450#

* Fatigue life estimated using exponential fit

Fatigue life estimated using Weibull distribution

3.3. Fatigue life as per ASTM D 7460 (2010)

For the determination of fatigue life as per ASTM D 7460 (2010), the normalized modulus (NM) is calculated from the stiffness modulus using equation (2). S_0 and S_i in the equation represents stiffness the modulus at 50th and ith cycle and N_i and N_0 represents the corresponding number of cycle.

$$NM = \frac{S_i}{S_0} \times \frac{N_i}{N_0} \tag{2}$$

The normalized modulus of the bituminous concrete mixture, when tested at 600 microstrain, is shown in Figure 5a, 5b, 5c and 5d. Considering the low temperature as well as loading with a rest period, it is not clear whether the trend as depicted in ASTM D7460 (2010) can be useful to quantify the fatigue life. In this context, the investigation carried out by Verma et al. (2016) comes in handy. Varma et al. (2016) classified the normalized modulus curve into four types. The normalized modulus curve of the sample at 20 °C with a rest period as shown in figure 5a in which the peak value falls out of experimental limit is identified as type I. The normalized modulus curve of the sample at 20 °C without rest period can be categorized under type II curve. In this type II curve, the normalized modulus peak is well defined as seen in figure 5b. In type III and type IV curves the peak point of normalized modulus is not well defined. The normalized modulus curve at 0 °C with and without a rest period (figure 5c and 5d) in which the peak is not well defined is type IV curve. The number of the cycle corresponding to peak normalized modulus is identified as fatigue life of the material. In a conventional method of testing, it is recommended to conduct the test at 20 °C and the normalized modulus curve as used by ASTM D 7460 (2010) is type II curve. The standard also recommends to use Weibull function to extrapolate the failure point in type I curve. It can be observed that the normalized modulus plot at 0°C differs from the conventional normalized modulus plot (at 20 °C). The peak point of normalized modulus is not well defined at 0 °C.

For all the normalized modulus curve except type II, the number of the cycle corresponding to peak normalized modulus was identified using Weibull fit. The Weibull fit is carried out as per ASTM D 7460, 2010 using the expression given in equation 3. SR in the equation represents $\frac{S_i}{S_0}$, N represents the number of the cycle, γ and Λ are regression constants.

$$\ln(-\ln(SR)) = \gamma \times \ln(N) + \ln(\Lambda) \tag{3}$$

The fatigue life estimated as per ASTM D 7460 (2010) is tabulated in table 3. It can be seen that the provision of rest period increased the fatigue life of the bituminous mixture at both 0 and 20 °C. At both 0 and 20 °C, the fatigue life estimated using ASTM method is near the value of fatigue life estimated using the AASHTO method.

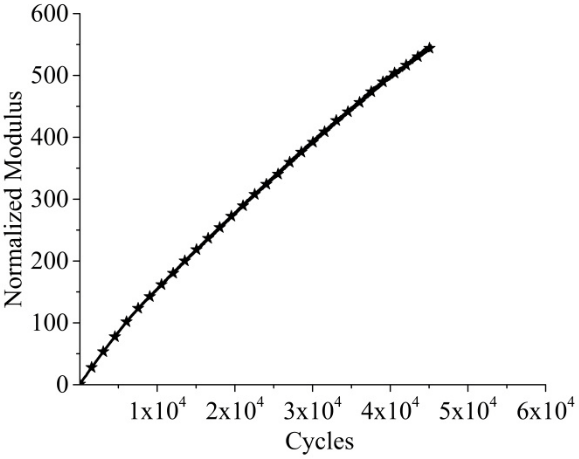

Fig. 5a. Normalized modulus at 20 °C – With rest period (Type I)

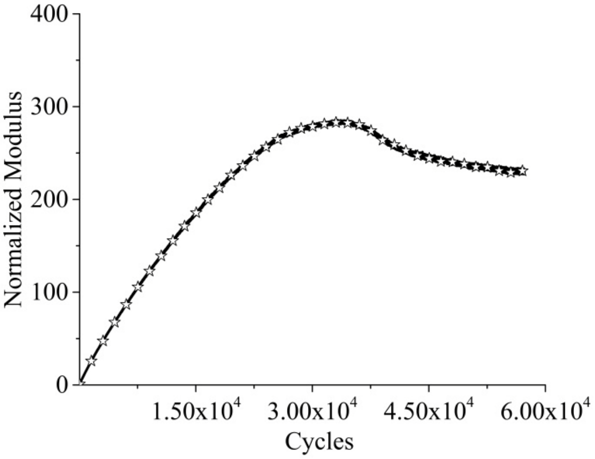

Fig. 5b. Normalized modulus at 20 °C – Without rest period (Type II)

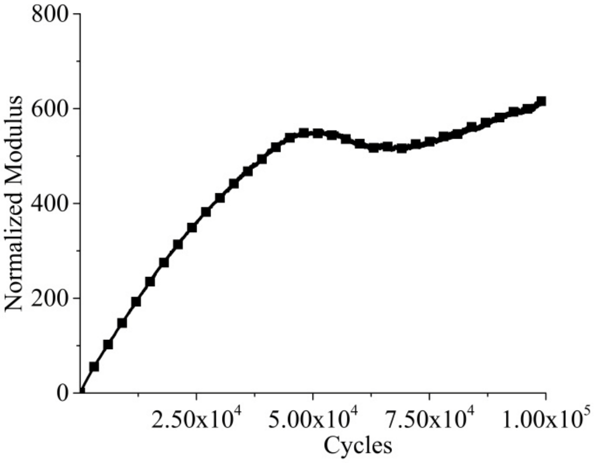

Fig. 5c. Normalized modulus at 0 °C – With rest period (Type IV)

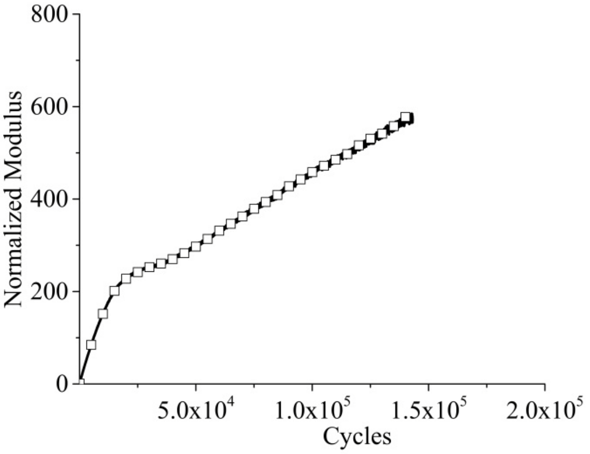

Fig. 5d. Normalized modulus at 0 °C – Without rest period (Type IV)

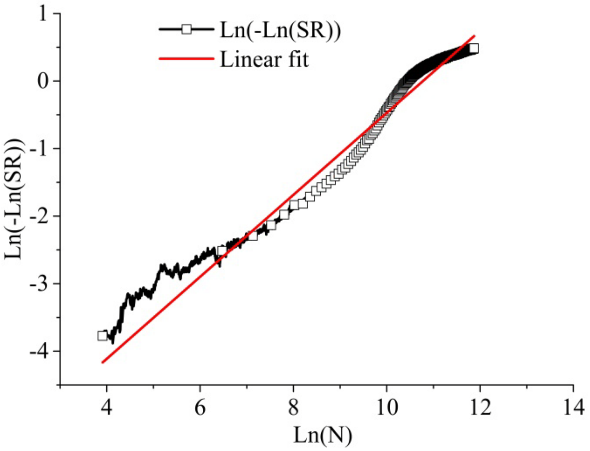

Fig. 5e. Weibull curve for 0 °C with rest period

Fig. 5. Normalized modulus and Weibull curve for 600 microstrain

3.4. Energy Dissipation and fatigue life based on energy dissipation

The total energy dissipation, which includes dissipation due to viscoelastic behavior of the bituminous mixture and dissipation due to damage for each cycle is calculated from the stress-strain plot. The stress-strain plot for a viscoelastic material due to sinusoidal loading is elliptical as shown in figure 6. The area inside the stress-strain plot signifies the total energy dissipated. The energy dissipated at the 50th cycle for all the strain levels and temperatures are listed in table 4. The energy dissipation in the material at initial loading cycles is more due to viscoelastic behavior of the material, and as the damage in the material progresses due to continuous loading, the dissipation due to damage accumulates to the viscoelastic dissipation. Hence, considering the energy dissipation at the 50th cycle as the viscoelastic dissipation, it can be seen that the energy dissipation due to viscoelastic behavior at 20°C is higher when compared to 0 °C.

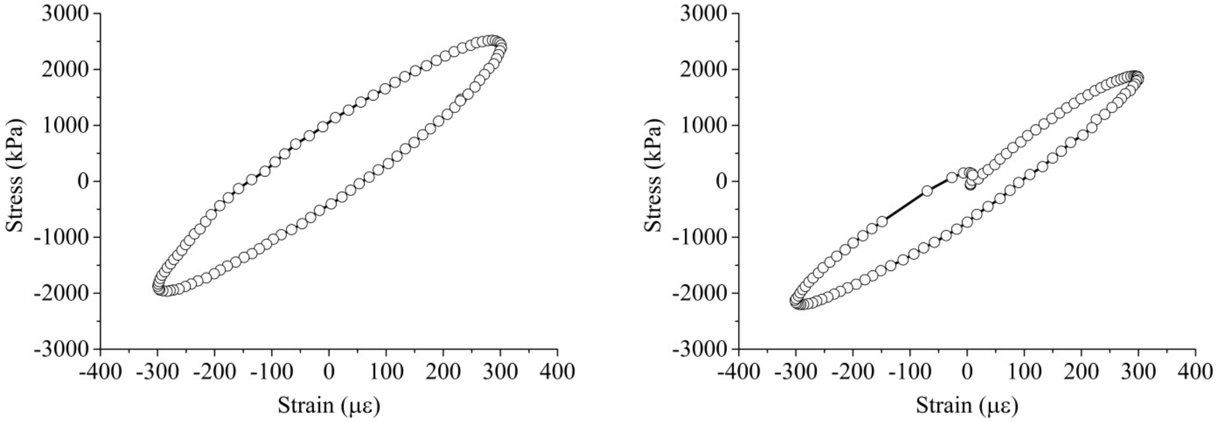

Fig. 6a. Loading without rest period – 50th cycle

Fig. 6b. Loading with rest period – 50th cycle

Fig. 6. Stress-strain plot of BC sample at 20 °C and 600 microstrain

Table 4. Energy dissipation measured in kJ/m^3 at 50th cycle

Loading condition	At 20 °C		At 0 °C	
	600 με	800 με	600 με	800 με
Without rest period	0.68	1.45	0.48	0.80
With rest period	0.52	0.89	0.34	0.58

In the strain-controlled test, as the damage in the material progress due to repeated loading, the energy dissipation decreases. The trend in total energy dissipation at 20 and 0°C for different loading conditions and strain amplitude are shown in figure 7. Comparing the energy dissipation of the sample tested with and without a rest period at 0 and 20 °C, the decrease in dissipation is more for the samples tested without a rest period. This indicates that during the rest period, the recovery of damage occurs at both 0 and 20 °C.

Further, energy ratio is calculated from the energy dissipation, and the fatigue life is estimated from the energy ratio. The energy ratio (ER) as defined by Rowe and Bouldin, 2000 is computed using the expression $ER = n\,W_0/W_n$, where n represents the number of cycle, W_0 and W_n represents energy dissipation at the initial and nth cycle.

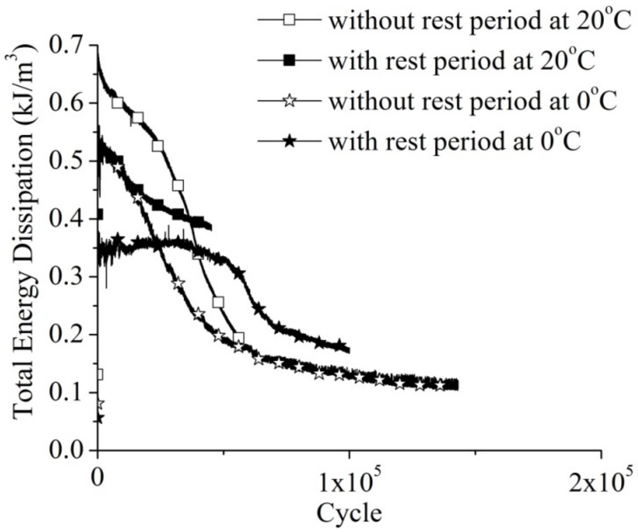

Fig. 7a. 600 microstrain

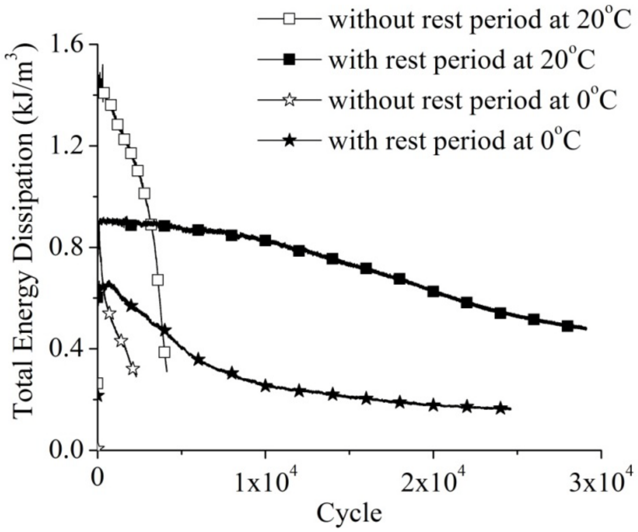

Fig. 7b. 800 microstrain

Fig. 7. Energy dissipation

The variation in energy ratio with the number of cycles for the sample tested without a rest period for 600 microstrain and 20 °C is shown in figure 8a. For all the samples except for the sample tested with rest period at 600 microstrain and at 20 °C, the energy ratio curve was observed to be a two-stage curve. The derivative of energy ratio was estimated, and the number of the cycle corresponding to the point of change in the derivative curve as indicated in figure 8b is calculated as the fatigue life, and the same is listed in table 5. It has to be noted that for the sample tested at 600 microstrain, 20 °C with rest period, energy ratio is a single stage curve and the fatigue life cannot be estimated based on the energy ratio. The fatigue life calculated from the energy dissipation is in the same order as that of fatigue life as per AASHTO T321, 2007 and ASTM D 7460, 2010.

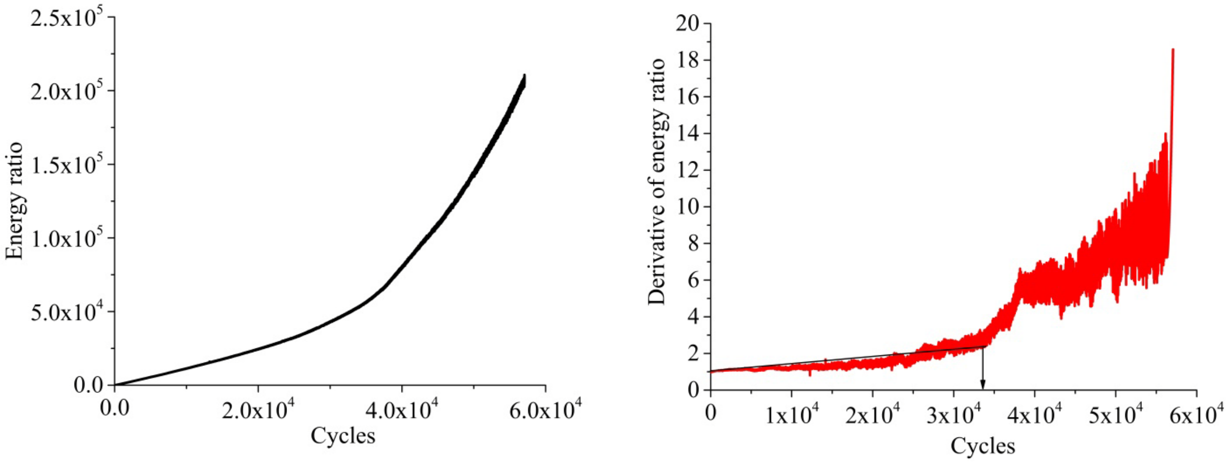

Fig. 8a. Energy ratio

Fig. 8b. Derivative of energy ratio

Fig. 8. Energy ratio and its derivative for 600 microstrain at 20 °C

Table 5. Fatigue life from energy ratio

Loading condition	At 20 °C		At 0 °C	
	600 με	800 με	600 με	800 με
Without rest period	33450	3200	23087	1628
With rest period	--	16162	48666	3200

4. Conclusion

The fatigue life of bituminous mixture is commonly measured at 20 °C and under continuous loading. The stiffness modulus and the energy dissipation is used to quantify the fatigue life. At lower temperature (0°C), the stiffness modulus of the bituminous mixture is higher when compared to 20 °C. However, the reduction in stiffness modulus due to continuous loading is higher at 0 °C. This indicates that the progress in damage at 0 °C is faster when compared to 20 °C. Due to the viscoelastic nature of the material, the energy dissipation at initial cycles of loading is more at a higher temperature. The fatigue life estimated from the energy dissipation is in the same order as that of fatigue life from the stiffness modulus. The influence of the rest period between the load cycle showed an improved fatigue life at both 20 and 0 °C. However, the influence of the rest period was more pronounced at 20 °C when compared to 0 °C.

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