On the use of Normalised Modulus for estimation of fatigue life of asphalt mixtures

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ABSTRACT: A parameter termed 'normalised modulus' (NM) is used as the basis for developing the ASTM: D7460 (2010) standard for determining the fatigue of compacted asphalt concrete subjected to repeated flexural bending. The parameter (NM) is calculated and the cycle corresponding to the peak of NM curve is referred as the fatigue life of the material. However, it is observed that the material response need not always follow the assumptions related to NM.
In the present investigation, four point beam bending tests were conducted on asphalt mixtures using unmodified and modified binder. The control binder and modified binder used for the study were Viscosity Grade 30 (VG30) and Polymer Modified Binder 40 (Elastomer) as per Indian standards. Experiments were carried out on beam samples of size 380 × 63 × 50 mm fabricated with 4 ± 0.5% air voids at 10Hz frequency for five strain levels (200, 400, 500, 600 and 800 micro-strain) at 20 and 0°C. While for some testing conditions, a clear peak value was seen when the data corresponding to normalised modulus was analysed, for different strains and materials, such peak was not seen. In fact, four different types of NM curve trends were observed and each such trend was quantified using the evolution of the stress-strain-time curve.

1 INTRODUCTION

Keywords: Miner's hypothesis, fatigue, normalised modulus, asphalt, stress-strain-time curve

1.1 *Background*

The concept of cumulative damage in fatigue was originally proposed by Miner (1945) for the uniaxial tests conducted on aluminum alloys. According to this concept, the damage could be expressed in terms of the ratio of number of cycles applied to the number of cycles to failure at a given stress level. Failure occurs when the summation of these increments of damage at several stress levels equals unity. The failure is considered as the inception of crack. Miner's hypothesis can be expressed as:

$$\sum \frac{n_i}{N_i} = 1 \tag{1}$$

where n_i is the number of load cycles applied at stress level i and N_i is the number of load cycles to failure at stress *i*. As per this hypothesis, each load contributes a certain amount of damage to the material. Such linear cumulative damage hypothesis assumes that the total life of the material can be estimated by adding the percentage of life consumed by the material at each stress level. An important assumption here is that the definition of failure at any strain/stress level is always identified by a "single process".

Miner's hypothesis has been used widely for the metals even though many deviations have been observed (Fatemi and Yang, 1998). It is expected that the validity or otherwise of the Miner's hypothesis be verified by detailed experimental investigations (See Barenberg (1972), Soussou and Moavenzadeh (1974) for early investigations on hot mix asphalt).

Asphalt pavements are subjected to different stress levels during the life as a result of varying traffic conditions. Miner's hypothesis related to cumulative fatigue damage needs a re-look within the context of increased understanding developed related to the evolution of material micro-structure, sophisticated equipment currently being used and of course, the use of modified binders. For instance, when the fatigue damage is quantified using four point bending, one sees three different stages of damage evolution. In the first stage, micro-cracks are initiated. In the second stage, the micro-crack coalesce to form macro-crack and in the third stage, the sample disintegrates. It should be noted that for the validity of the Miner's equation to hold, it is necessary that one needs to stay within one "single process" defining the failure point (cycles to failure: N_f) and not the three or more stages of damage evolution as is normally seen for asphalt mixtures.

Hopman et al., (1989) carried out investigations on asphalt mixes using four point bending tests to check the validity of Miner's hypothesis. Using the framework of the three stage fatigue damage process, Hopman et al., (1989) concluded that the concept of linear cumulative damage cannot be applied to all the three stages, but is limited to the first stage. It should be noted that Hopman et al., (1989) quantified damage using dissipated energy. Weise (2012) investigated the validity of Miner's hypothesis for the asphalt mixes using cyclic indirect tensile test with different loading configuration. It was observed that the Miner's hypothesis is dependent on the test temperature, loading frequency and also on the order of different stresses and strains. The validity or otherwise of such hypothesis was found to be dependent on the sequence of loading. The aim of this paper is to show that if one uses Miner's equation in a realm beyond its limit, one is likely to get erroneous results and it is illustrated using the concept of normalised modulus.

To use Miner's hypothesis for asphalt, the number of cycles to failure at each stress or stress level has to be determined using a common definition of failure. The peak of the normalised modulus has been used as the basis for developing the ASTM: D7460 (2010) standard for determining the fatigue failure of compacted asphalt concrete subjected to repeated flexural bending. The parameter 'normalised modulus' (NM) is calculated and the cycle corresponding to the peak of NM curve is referred as the fatigue life of the material. However, it is observed that the materials need not always follow the idealized NM curve. This investigation re-looks at the validity of Normalised Modulus for typical bituminous mixtures tested in four point bending at two different temperatures.

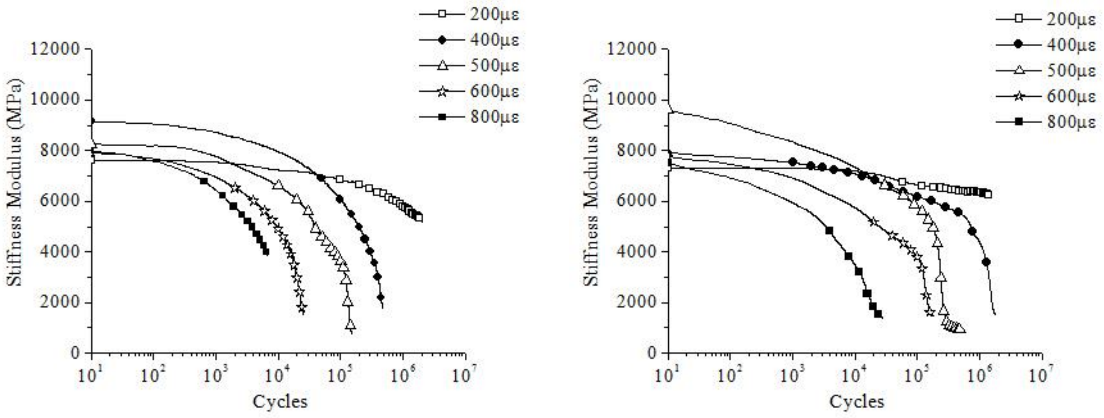
2 MATERIALS

The asphalt mixture selected for the study is bituminous concrete (BC) with unmodified and modified binders. The control binder and modified binder used for the study were Viscosity Grade 30 (VG30) and Polymer Modified Binder 40 (Elastomer) as per Indian standards IS: 73-2013 (2013) and IS: 15462-2004 (2004) respectively. The corresponding mixes are designated here as VG30 and PMB40 (E) in this study for ease of reference.

3 EXPERIMENTAL INVESTIGATION

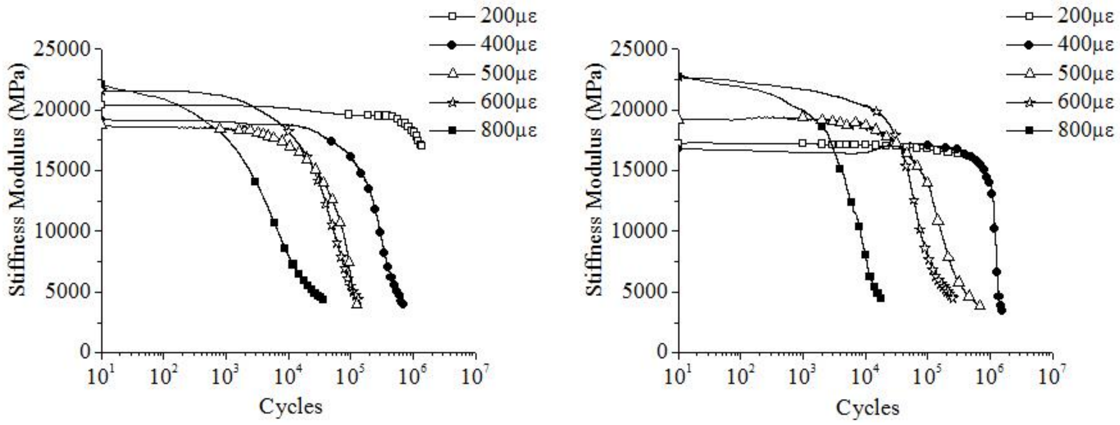
In the present investigation, four point beam bending tests were conducted on asphalt mixtures using VG30 and PMB40 (E). Beam samples were fabricated using PReSBOX shear compactor (ASTM: D7981 (2015)). Experiments were carried out on beam samples of size 380×63×50 mm with 4± 0.5% air void. Tests were performed in a controlled displacement mode using sinusoidal waveform at 10 Hz frequency for five different strain levels (200, 400, 500, 600 and 800 micro-strain) at 20 and 0°C test temperature. The load and displacement data were recorded at every 0.001 sec using which stiffness modulus and normalised modulus were calculated. Detailed analysis of the results is covered in the following section.

4 RESULTS AND DISCUSSION



a) VG30 b) PMB40 (E)

Figure 1. Stiffness modulus variation with the loading cycles at 20˚C and 10Hz



a) VG30 b) PMB40 (E)

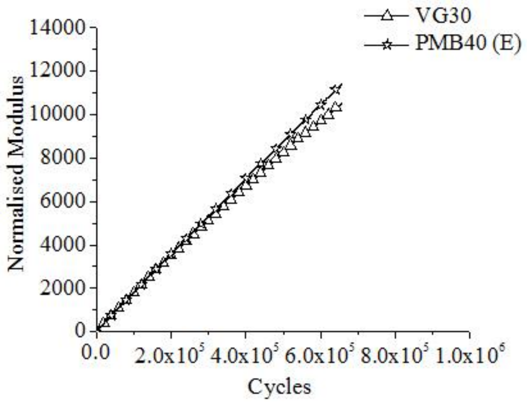
Figure 2. Stiffness modulus variation with the loading cycles at 0˚C and 10Hz

The stiffness modulus (SM) is calculated by solving the equations of simple bending theory assuming the beam as a linearised elastic material. Not withstanding the fact that such analysis has limitations since asphalt mixtures behave like viscoelastic material, considering the ease of computations such approximations are valid. The stiffness modulus values calculated for the asphalt mixture with modified and unmodified binder are shown in figures 1 and 2. The traditional criteria for determining the fatigue life of the material considers the cycle corresponding to 50% of the initial stiffness modulus as the fatigue life of the material.

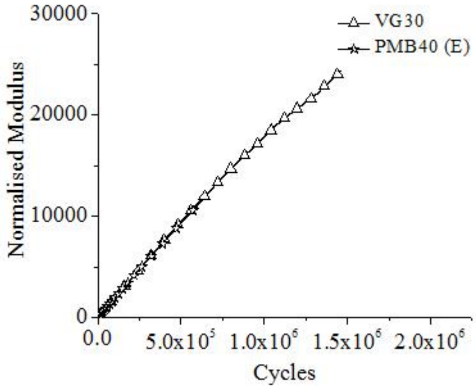
ASTM: D7460 (2010) suggests equation 2 to calculate the normalised modulus. As per this equation, the product of stiffness modulus and number of cycles are normalised with respect to the reference cycle and stiffness modulus at the reference cycle.

$$NM = \frac{S_i \times N_i}{S_0 \times N_0} \qquad (2)$$

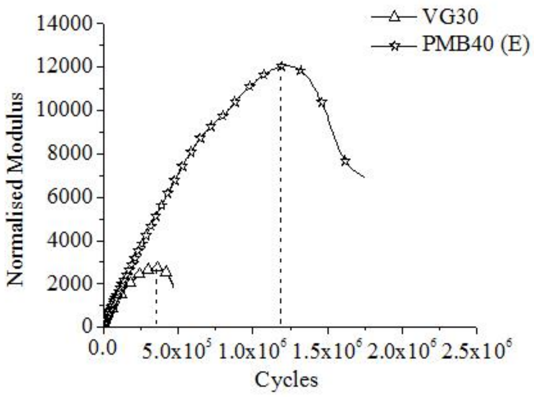
where, NM is the normalised modulus; S_i is the flexural beam stiffness at cycle i, N_i is the i^{th} cycle, S_0 is the flexural beam stiffness at reference cycle and N_0 is the reference cycle (generally, 50^{th} cycle). As per this approach, the fatigue life is considered as the number of cycles corresponding to the peak of the normalised curve. The main idea here is that the first deviation from the Miner's equation is considered as the onset of fatigue damage. Such assumption rules out the possibility of additional fatigue life present in the material after the onset of such peak value. It should be also pointed out that reduction in the beam stiffness modulus is taken as the parameter to quantify the damage.



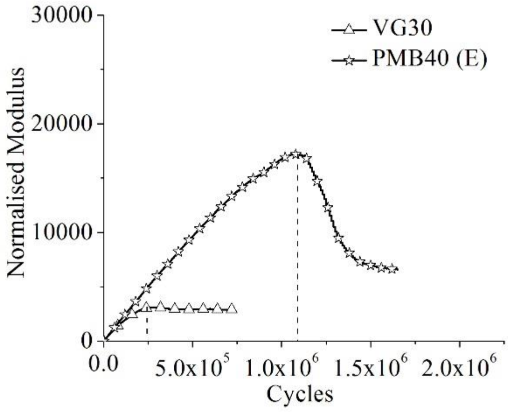
a) 200με and 20˚C



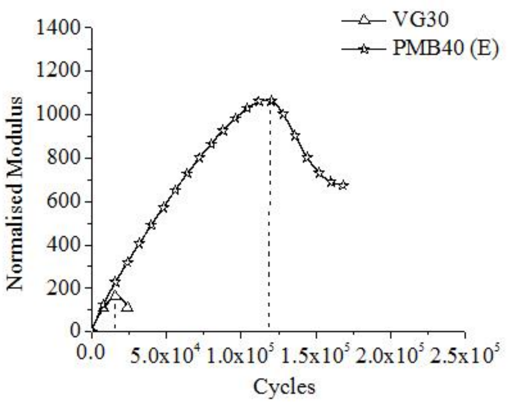
b) 200με and 0˚C



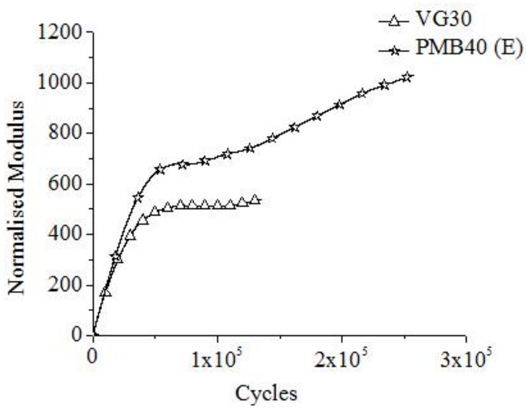
c) 400με and 20˚C



d) 400με and 0˚C



e) 600με and 20˚C



f) 600με and 0˚C

Figure 3. Normalised modulus curves[¥]

[¥] Normalised modulus curve mentioned in this paper is same as the Normalised Complex Modulus × Cycles versus Cycles as per the ASTM: D7460 (2010) standard. But for simplicity, it will be referred as Normalised modulus (NM) curve in this paper.

Figure 3 shows the normalised modulus curves for the samples at 200, 400 and 600 micro-strain tested at 20 and 0˚C and at 10Hz frequency. It is evident that the normalised modulus trend changes with the strain amplitude, temperature and material used. At lower strain levels, the normalised modulus value increases with the number of cycles and shows the linear trend. This is the clear case where the Miner's hypothesis of cumulative damage exhibits the linear trend. Every loading cycle adds identical amount of damage to the material quantified here in terms of reduction of stiffness modulus. From figure 3a and 3b, it is observed that at lower strain level, 200με, both BC with VG30 and BC with PMB40 (E) exhibited the same NM curve trend. At 400με (figures 3c and 3d), the temperature influences the NM curve of BC with VG30 whereas at 600με (figures 3e and 3f), NM curve of both BC with VG30 and BC with PMB40 (E) are identically influenced by the temperature. The asphalt mixture with modified binder shows better fatigue performance compared to the unmodified binder. Based on the various trends of the normalised modulus curves, the response were classified into four categories. To extract meaningful information of the trend, it will be interesting to look at the stress-strain behaviour of the material for each such category and such approach is followed here.

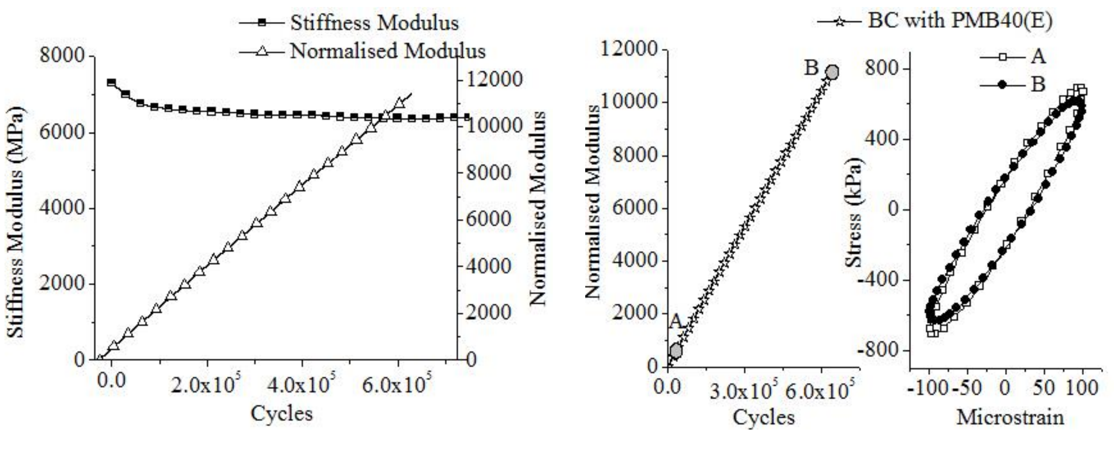
4.1 *Type I*

Type I response exhibit normalised modulus curve with a linear trend in which the material follows Miner's hypothesis of cumulative damage. The normalised modulus value increases with the cycles and the peak value is not attained within the testing cycles. This generally happens when the material is subjected to lower strain amplitude (200με in this case). To extrapolate type I trend, Weibull distribution is used. Equation 3 represents the Weibull function used for extrapolation of fatigue life (Tsai et al., 2002).

$$\ln(-\ln(\mathrm{SR})) = \gamma \times \ln(\mathrm{N}) + \ln(\lambda) \qquad (3)$$

where, SR represents the stiffness ratio given as the ratio of the stiffness modulus at any given cycle to the reference stiffness modulus; N is the cycle number; γ is the slope of the line, $\ln(-\ln(\mathrm{SR}))$ versus $\ln(\lambda)$ and $\ln(\lambda)$ is the intercept of the line, $\ln(-\ln(\mathrm{SR}))$ versus $\ln(\lambda)$. The fatigue life of the material can be estimated by solving equation for the value of N where value of SR is 0.5.

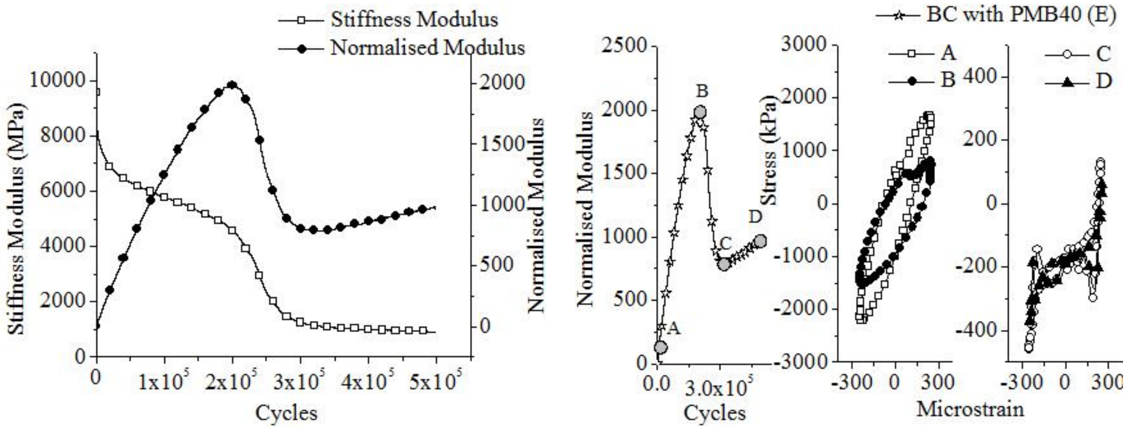
Figure 4 shows the stiffness modulus and normalised modulus curve for Type I response along with the stress-strain curve. The reduction in the stiffness modulus indicates the increment of material damage. From figure 4a, it is noted that the changes in the stiffness modulus value is small as the cycle proceeds. The stiffness is reducing at a lower rate indicating the reduced damage accumulation signifying higher fatigue life of the material. Figure 4b shows the normalised modulus curve of Type I response. Figure 4c shows the stress-strain curve for the points A and B in the normalised curve. From figure 4c, it is observed that the stress-strain behaviour hardly changes even when the material is subjected to 600,000 cycles. This indicates that the material is not damaged. It is also clear from the elliptical shape that the response of the material is viscoelastic in nature (Padmarekha et al., 2013).



a) SM and NM curves b) NM curve c) Stress-Strain curves

Figure 4: Type- I response – PMB40 (E) at 20˚C, 10Hz and 200 με

4.2 *Type II*



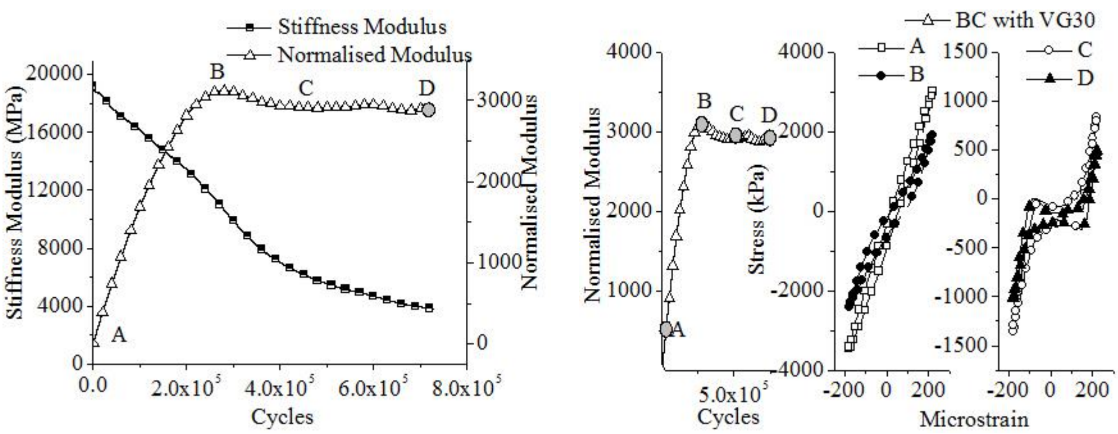
a) SM and NM curves   b) NM curve   c) and d) Stress-Strain curves

Figure 5. Type- II material – PMB40 (E) at 20˚C, 10Hz and 600 με

Type II response show the NM curve in which the NM value increases linearly, attains a peak and then decreases. However after attaining the peak of normalised modulus, the stiffness reduces at a higher rate compared to the increase in the number of cycles. This indicates the on-set of material damage and the number of cycles corresponding to the peak value is considered as the initiation of fatigue damage. In some cases, a secondary increase in NM value is also observed following this reduction stage. However, this secondary increase is not considered for the analysis since it represents the material in damaged condition (Rowe et al. (2012)).

Figure 5a shows the stiffness modulus and normalised modulus curve for Type II response. It clearly shows the connection between the cycles corresponding to the peak of the normalised modulus curve and the initiation of third stage of the stiffness modulus curve which occurs almost at the same number of cycles. Figure 5c and 5d show the stress-strain curves for the points A, B, C and D in the normalised curve. The shape of stress-strain curve at B still indicates that the material is in good condition. From the stress-strain curve at the points C and D, it is observed that the material is completely damaged, stiffness modulus is almost negligible and the material can crack at any time and hence the region is not considered for the analysis.

4.3 *Type III*



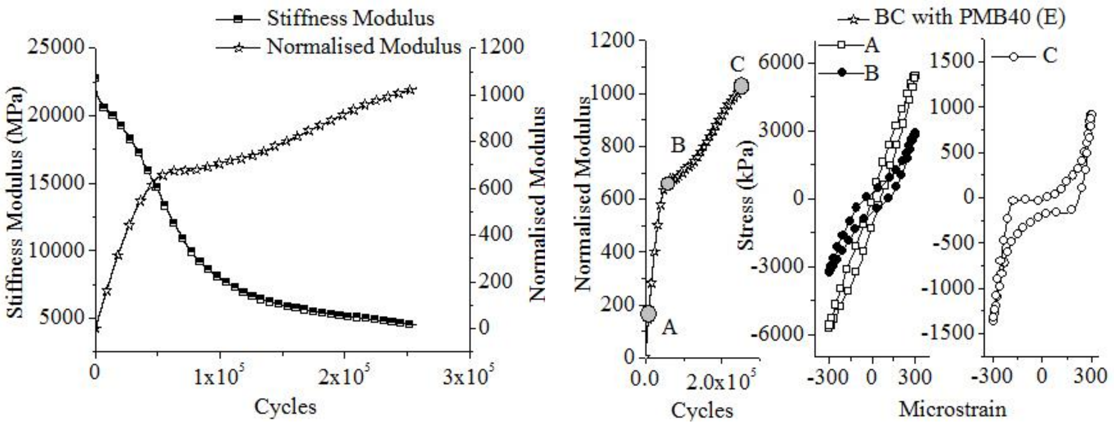
a) SM and NM curves   b) NM curve   c) and d) Stress-Strain curves

Figure 6. Type- III material – VG30 at 0˚C, 10Hz and 400 με

Figure 6a shows the stiffness modulus and normalised modulus curve for the Type III response. Type III response exhibit an increasing normalised modulus trend initially, attains a peak value and continue to be in that peak value range. This is shown in figure 6b. There is no drastic reduction stage following the peak value and also the normalised modulus does not increase further with the loading cycles. The stiffness modulus trend at this region shows the decrease at a much lower rate with a constant slope as the loading cycles increases. Figure 6c shows the stress-strain curves for the cycles A and B marked on the NM curve. It is noted that at A and B, stress-strain curve is a straight line which shows that the material is elastic in nature. The distortions of stress-strain curve shown in figure 6d at C and D indicates the material damage. Type III trend is generally observed at 0˚C. This shows that the failure mode is completely different for the material at 20 and 0 ˚C and the associated NM criterion of the peak value may not be valid for Type III response. From figure 5d and 6d, it is observed that the shape of the stress-strain graphs of BC with PMB40 (E) at 20˚C and BC with VG30 at 0˚C are found to be the same once the material is damaged irrespective of the temperature and the material response (elastic vs. viscoelastic).

4.4 *Type IV*

Type IV response shows linearly increasing trend initially, attains a peak and either maintain this peak for some cycles before starting a secondary increasing trend or increase with a different slope, lesser than the initial slope. This trend is mostly evinced at 0˚C when the material response is elastic.



a) SM and NM curves b) NM curve c) and d) Stress-Strain curves

Figure 7. Type- IV material – PMB40 (E) at 0˚C, 10Hz and 600 με

Figure 7a shows the sample stiffness modulus and normalised modulus curve for Type IV response. The deviation of stress-strain graph is used to quantify the onset of damage. Figure 7b shows the normalised modulus curve. In case of materials where the secondary increasing trend is observed, the slope of the second stage increase is generally lower compared to the first stage. This indicates that most of the damage that happens to the material is at the first stage and the rate of stiffness reduction is more during this stage. The stress-strain curve deviation increases with the increase in the number of cycles even when there is an increasing trend for the NM curve after the first peak as shown in figure 7c and 7d. It has been noted that the stress-strain graph forms a straight line as in the case of Type III response indicating the elastic nature of the material. It is not clear whether one can ascribe onset of damage at cycle C. From figure 5 and 7, it can be concluded that the same material can have different mode of damage at different temperature. This is attributed to the changes in the material from viscoelastic nature at 20˚C to elastic at 0˚C.

It is interesting to note that substantial changes take place to Type- III and IV trends after the primary NM increasing stage. These issues are not addressed in the ASTM: D7460 (2010). It is observed that the stress-strain response of the material is different at different temperatures and strain levels and the usage of NM is seen to be ineffective for quantifying the fatigue damage of the asphalt mixtures.

Table 1 shows the classification of materials based on the NM curve trends. From Table 1, it is clear that at 20˚C, asphalt mixtures with unmodified and modified binders follow the trend which can be analysed using the NM. It should be pointed out here that even ASTM D7460 (2010) stipulates 20˚C though an effective test temperature for equivalent fatigue damage is also defined. However the same materials follow different trends at 0˚C depending on the strain amplitude. The trends are scattered and this makes the analysis of the material using NM inconsistent. The damage accumulation of asphalt mixture with modified binder is completely different when compared to that of unmodified binder at 0˚C. Except at 200με, NM curves of modified and unmodified binders did not match in the trend of any higher strain levels. This also raises issues related to quantifying the advantages of modified binders with unmodified binder. The asphalt mixture with modified binder exhibits better fatigue performance compared to unmodified binders at all strain levels as evident from the stiffness modulus. However it is not clear whether one can use the NM approach to differentiate the same 0˚C since one sees different trends of damage accumulation for the same applied strain level.

Table 1.Classification based on the NM curve trend.

Material	Temperature (˚C)	Strain (με)				
		200	400	500	600	800
VG30	20	I	II	II	II	I*
	0	I	III	II	III	IV
PMB40 (E)	20	I	II	II	II	II
	0	I	II	IV	IV	II

*Test was run only till 50% of the stiffness value and within the testing conditions NM did not show any peak.

Table 2 shows the fatigue life of the asphalt mixtures with unmodified and modified binders at various strain levels and test temperatures. From table 2, it is clear that the asphalt mixture with modified binder shows better fatigue performance compared to unmodified binders and the order of performance varies depending on the temperature and strain levels. As the strain level increases, the difference in the fatigue life of asphalt mixtures with unmodified and modified binders becomes less. This may be because at higher strain levels, the influence of damage due to the coalescence of micro-cracks to form macro-cracks is more prevalent than the viscoelastic nature of the material.

In case of the material where NM curve peak value is not attained, Weibull function is used to calculate the fatigue life as explained under the section 4.1 of Type I response. However such assumption of Weibull damage process needs to be verified and it has always been non-unique (Prowell et al., 2010)). Also one needs to have proper understanding on how to select the cycle corresponding to the peak value depending on the various NM curve trend.

Table 2. Fatigue life of the materials tested.

Strain (με)	BC with VG30		BC with PMB40 (E)	
	20˚C	0˚C	20˚C	0˚C
200	7.57 E+07[&]	1.25 E+06[&]	8.31 E+10[&]	1.45 E+09[&]
400	3.63 E+05[#]	2.45 E+05[#]	1.23 E+06[#]	1.09 E+06[#]
500	1.13 E+05[#]	7.92 E+04[#]	1.97 E+05[#]	1.88 E+05[#]
600	1.72 E+04[#]	5.94 E+04[#]	1.17 E+05[#]	6.72 E+04[#]
800	5.65 E+03[&]	8.12 E+03[#]	1.36 E+04[#]	8.28 E+03[#]

[&] Using Weibull fit

[#] Using NM curve peak (cycle corresponds to point B of the NM curve)

5 CONCLUSION

Fatigue of engineering materials is normally interpreted using Miner's hypothesis. Such hypothesis states that every loading cycle with a given magnitude of stress/strain adds identical amount of damage to the material. Such assumptions have been used widely in the literature for quantifying fatigue damage for a range of materials. However, it is not clear whether one could use similar ideas for asphalt concrete mixtures since quantification of fatigue damage has always been a challenge due to its complex response characteristics. Not only the material dissipates energy during every cycle of loading due to propagation of damage, the material dissipates energy due to its viscoelastic nature also. Attempts are being currently made to decompose the total dissipation into dissipation due to the mechanical response and dissipation due to damage.

In this investigation, four point beam bending tests on asphalt mixtures were carried out on unmodified and modified binder mixtures at two different temperatures. The concept of 'normalised modulus' was used to define the cycles to failure at a given stress level as required in the Miner's hypothesis. It was observed that the mixtures tested exhibited different NM curve trends based on the temperature and strain levels. At 20˚C and at strain levels of 400με and more, the trend expected was seen for unmodified and modified binders. However, at 0˚C, one could not see any clear cut trend as expected.

The important consideration here is the change in the material response at 0˚C when compared to 20˚C. While at 0˚C, the material response was elastic in nature, at 20˚C, the material exhibited viscoelastic nature and this could be clearly gleaned from the Lissajous plots. It was also seen that at 0˚C, the mechanism and the accumulation of damage was different between the modified and unmodified binders. Since the mechanical response of the material plays a critical role in the accumulation of fatigue damage, one should be looking at developing constitutive models for the material at the appropriate testing temperature and tracking the changes in the material parameters as the material is subjected to loading cycles. While this is computationally a challenging effort, such an approach can help to precisely identify the mechanism leading to fatigue damage.

ACKNOWLEDGEMENT

The first and second authors thank the Department of Science and Technology, Govt. of India for funding this investigation. The grant number is DST/TSG/STS/2011/46. The authors acknowledge the technical assistance provided by M/s IPC Controls, Australia during the conduct of the experiments.

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