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Experimental Evaluation of Fatigue Cracking Behavior in Bituminous Pavements Under Repeated Loading Conditions

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Abstract

Fatigue cracking is a major distress mechanism in flexible pavements subjected to repeated traffic loading. The fatigue response of bituminous mixtures depends not only on binder characteristics but also on temperature, strain amplitude, loading sequence and the rest period between successive load applications. This study compares the fatigue performance of bituminous concrete Grade-II mixtures prepared with unmodified VG40 bitumen, crumb-rubber-modified bitumen (CRMB60) and polymer-modified bitumen (PMB40). Four-point beam bending tests were conducted at 0°C and 20°C under strain-controlled loading at 400, 600 and 800 microstrains and 10 Hz. Three loading protocols were considered: continuous loading without rest, loading with a 0.9 s rest period, and a simulated multi-axle sequence comprising one loading pulse followed by a rest interval and two successive pulses followed by another rest interval. Fatigue life was interpreted using stiffness reduction, AASHTO T321, ASTM D8237, ratio of dissipated energy change (RDEC) and energy-ratio approaches, subject to the suitability of each method for the loading protocol. Under continuous loading, CRMB60 generally showed improved fatigue response at higher strain levels, whereas PMB40 performed particularly well under selected low-temperature and low-strain conditions. Under multi-axle loading, the energy-ratio method indicated consistently strong performance of PMB40 relative to VG40 and CRMB60. The report also observed stiffness recovery during rest periods for modified mixtures. The findings demonstrate that binder ranking is dependent on temperature, strain amplitude, loading history and fatigue-life post-processing method; therefore, no single binder can be declared universally superior under all conditions.

Keywords— Fatigue cracking; bituminous concrete; VG40; CRMB60; PMB40; four-point bending; rest period; multi-axle loading; fatigue life.

1. INTRODUCTION

Flexible pavements experience repeated wheel loads that induce tensile strains in bituminous layers. With continued loading, micro-damage accumulates and may coalesce into fatigue cracks. Fatigue performance is commonly evaluated using laboratory beam-bending tests, in which stiffness reduction, dissipated energy and load-cycle response are used to estimate the number of repetitions associated with damage or failure [1], [5], [6].

Conventional unmodified bitumen provides the reference response, while modifiers such as crumb rubber and polymers alter the viscoelastic characteristics of the binder. Crumb rubber can improve elasticity and resistance to deformation, while polymer modification can enhance elastic recovery and stiffness characteristics. However, the effect of a modifier is not independent of temperature and applied strain. A binder that performs well under high strain may not necessarily show the same advantage under low strain or at low temperature [4], [8], [11].

Actual traffic loading is discontinuous. Vehicle axles apply load pulses separated by rest periods, during which stress relaxation, strain recovery and possible healing may occur. A conventional continuous sinusoidal fatigue test therefore cannot fully represent all aspects of field loading. The present work focuses specifically on comparative fatigue performance of VG40, CRMB60 and PMB40 mixtures under continuous, rest-period and multi-axle loading.

OBJECTIVE AND SCOPE

The principal objective is to compare the fatigue performance of mixtures prepared using unmodified bitumen, crumb-rubber-modified bitumen and polymer-modified bitumen under different loading conditions. The comparison is limited to the experimental parameters and results reported in the supplied project PDF.

2. BACKGROUND AND LITERATURE REVIEW

Fatigue testing of asphalt mixtures is influenced by the loading waveform, strain or stress control, temperature, frequency and failure criterion. The four-point bending test is widely used because it subjects a prismatic beam to a relatively uniform bending moment over the central region. Standardized procedures such as AASHTO T321 and ASTM D8237 provide approaches for calculating fatigue life from stiffness or normalized-modulus response [1], [6].

Cheng et al. [1] compared fatigue behaviour at different temperatures using four-point bending and indirect tensile fatigue tests, highlighting that test configuration and temperature influence the measured response. Xiang et al. [2], [3] examined fatigue-healing behaviour and the role of healing conditions. Muthulingam and Rekha [4] specifically investigated rest-period effects in unmodified and modified bitumen mixtures. These studies establish that the time interval between load applications is a relevant variable in fatigue characterization. The literature also indicates that fatigue-life estimates depend on the post-processing method. Stiffness reduction, normalized modulus, dissipated-energy and energy-ratio criteria do not necessarily identify the same point on a fatigue response curve [6], [11]. Meng et al. [6] reviewed four-point bending fatigue procedures and emphasized the need to interpret test conditions and failure definitions consistently. Recent reviews by Valente de Liz et al. [9], Loprencipe et al. [10] and Xu et al. [11] similarly describe the continuing development of fatigue testing and failure criteria. Houlík et al. [7] explored neural-network prediction of asphalt-concrete fatigue life, while Cai et al. [12] considered strain waveforms, temperature and rest periods using a dissipated-energy approach.

The project report refers to studies showing that crumb-rubber and polymer modification can alter stiffness degradation and fatigue resistance. The response of modified binders may be especially evident at larger deformation levels, where the modifier is activated. At lower strain levels, the benefit may be less pronounced or the fatigue life may be governed by different mechanisms. The report therefore examines the three binder systems across two temperatures and three strain amplitudes.

2.1 Research Need

A comparison based only on a single temperature, strain level or continuous loading protocol may produce an incomplete binder ranking. The present experimental programme extends the comparison to a 0.9 s rest period and a multi-axle waveform intended to represent a truck passage. The focus is on identifying how the relative performance of VG40, CRMB60 and PMB40 changes with the loading protocol, rather than establishing a universal ranking independent of test conditions.

3. MATERIALS

The mixtures were prepared as Bituminous Concrete Grade-II in accordance with the project report's stated MoRTH-based mixture design. Three binders were compared: VG40 (unmodified), CRMB60 (crumb-rubber-modified) and PMB40 (polymer-modified). The reported binder content was 5%. The same aggregate gradation and mixture type were used for comparative testing.

Table 1. Summary of mixture design and specimen preparation parameters.

Parameter	Reported specification
Mixture type	Bituminous Concrete Grade-II
Binder systems	VG40; CRMB60; PMB40
Binder content	5%
Beam mould size	450 × 150 × 160 mm
Test beam size	380 × 63 × 50 mm
Target air voids	4 ± 0.5%
Test temperatures	0°C and 20°C
Strain amplitudes	400, 600 and 800 microstrains
Loading frequency	10 Hz

Test apparatus	Four-point beam bending equipment

Twenty-eight large beam specimens were fabricated using a shear-box compactor. Four beams were sliced from each compacted specimen. A total of 54 beam samples were selected for trial runs and final testing after checking dimensional tolerances and air-void requirements. Specimens were conditioned at the target test temperature for two hours before testing.

4. EXPERIMENTAL METHODOLOGY

4.1 Four-Point Beam Bending Test

The fatigue response was measured using a four-point bending test in strain-controlled mode. The test equipment recorded load and displacement histories, from which flexural stiffness, tensile stress, tensile strain, phase angle and dissipated energy were determined. The nominal frequency was 10 Hz, corresponding to a 0.1 s loading cycle. Tests were performed at 0°C and 20°C for 400, 600 and 800 microstrains.

The beam specimen was supported at four points, with loading applied through the inner loading points. The central portion of the beam was subjected to an approximately constant bending moment. Fatigue damage was assessed from the change in stiffness and energy-related response over repeated loading.

4.2 Loading Protocols

Table 2. Loading protocols adopted for four-point beam fatigue testing.

Protocol	**Loading sequence described in the report**	**Purpose**
A. Continuous	Repeated 0.1 s cycles at 10 Hz, without a rest interval	Reference fatigue response under continuous loading
B. Rest-period	Repeated loading cycles followed by a 0.9 s rest period	Assess stress relaxation, strain recovery and possible healing
C. Multi-axle	0.1 s loading + 0.4 s rest, followed by two 0.1 s pulses and a 0.3 s rest	Approximate a multi-axle truck passage

The multi-axle protocol was developed using a programmed waveform. The first pulse was followed by a 0.4 s rest period; two subsequent 0.1 s loading pulses were followed by a 0.3 s rest period. The number of load passes, rather than simply the number of individual sinusoidal cycles, was used to express fatigue life for this protocol.

4.3 Fatigue-Life Evaluation

Five approaches were considered in the report: (i) 50% reduction of initial stiffness modulus, (ii) AASHTO T321-14 peak normalized-modulus criterion, (iii) ASTM D8237 normalized-modulus/Weibull approach, (iv) ratio of dissipated energy change (RDEC), and (v) energy ratio (ER). The 50% stiffness criterion identifies the number of cycles at which stiffness reaches half its initial value. The normalized-modulus method uses the peak of a normalized response curve; Weibull fitting was used where the peak was not observed within the test duration. RDEC evaluates changes in dissipated energy between loading cycles, while the energy-ratio method examines changes in the energy-ratio curve.

The methods are not equally suitable for every loading protocol. In particular, the report cautions that peak-based normalized-modulus criteria and Weibull extrapolation may not represent multi-axle tests adequately when rest intervals produce substantial recovery. RDEC was not used for multi-axle loading because the rest intervals disrupt the assumptions associated with accumulated dissipated energy.

4.4 Data Treatment

Fatigue-life values and rankings in this paper are transcribed from the report's result tables. A dash indicates that the source table did not report a fatigue-life value for that binder/condition. Rankings in parentheses are retained as printed. The numerical values are not recalculated or replaced with estimated values.

5. RESULTS AND DISCUSSION

5.1 Continuous Loading: 50% Stiffness Reduction

Table 3 summarizes fatigue life estimated using the 50% reduction of initial stiffness modulus (AASHTO T321-07) for continuous loading. At 20°C, CRMB60 ranked first at all three strain amplitudes, with fatigue lives of 528,103, 41,207 and 10,308 cycles at 400, 600 and 800 microstrains, respectively. At 0°C, PMB40 ranked first at 400 microstrains (633,639 cycles), while CRMB60 ranked first at 600 and 800 microstrains (58,062 and 8,856 cycles).

Table 3. Fatigue life under continuous loading using 50% initial-stiffness reduction; source.

Temp.	Strain (με)	VG40 (cycles)	CRMB60 (cycles)	PMB40 (cycles)
20°C	400	470,986 (2)	528,103 (1)	366,459 (3)
20°C	600	27,270 (2)	41,207 (1)	22,411 (3)
20°C	800	3,206 (3)	10,308 (1)	7,374 (2)
0°C	400	223,475 (3)	480,375 (2)	633,639 (1)
0°C	600	24,108 (2)	58,062 (1)	23,671 (3)
0°C	800	710 (3)	8,856 (1)	1,383 (2)

The results show that the relative advantage of modified binders depends on both temperature and strain. CRMB60 was the strongest performer at 20°C across the tested strain levels. At 0°C and 400 microstrains, PMB40 gave the highest value, suggesting that polymer modification can be beneficial under selected low-temperature/low-strain conditions. At 600 and 800 microstrains, CRMB60 outperformed the other binders.

5.2 Continuous Loading: AASHTO T321-14 / Normalized Modulus

The AASHTO T321-14 results are reproduced in Table 2. At 20°C, VG40 ranked first at 400 microstrains, whereas CRMB60 ranked first at 600 and 800 microstrains. At 0°C, PMB40 ranked first at 400 microstrains, CRMB60 at 600 and 800 microstrains. The same values are reported in the thesis under the ASTM D8237 normalized-modulus summary; the source text contains minor standard-number inconsistencies, which are not silently corrected here.

Table 4. Continuous-loading fatigue life using AASHTO T321-14/normalized-modulus summary

Temp.	Strain (με)	VG40	CRMB60	PMB40
20°C	400	398,104 (1)	314,757 (3)	327,236 (2)
20°C	600	33,266 (2)	50,114 (1)	26,883 (3)
20°C	800	2,977 (3)	11,496 (1)	8,240 (2)
0°C	400	171,457 (3)	398,098 (2)	629,685 (1)
0°C	600	25,830 (3)	50,112 (1)	26,051 (2)
0°C	800	1,588 (3)	9,160 (1)	1,641 (2)

The rankings broadly support the beneficial effect of modified binders at higher strain levels, especially CRMB60. However, the leading binder at 400 microstrains changes with temperature and analysis method. This is an important limitation of relying on one test condition or one fatigue-life criterion.

5.3 Continuous Loading: Energy-Based Methods

The RDEC method produced a different ranking from stiffness-based criteria in some cases (Table 5). At 20°C and 600 microstrains, VG40 ranked first (28,156 cycles), followed by PMB40 (22,384) and CRMB60 (17,247). At 800 microstrains, CRMB60 ranked first (10,308 cycles). At 0°C, CRMB60 ranked first at 400 and 800 microstrains, while PMB40 ranked first at 600 microstrains. The report notes that RDEC was not suitable for some low-strain/high-temperature conditions where the required intersection was not obtained.

Table 5. Continuous-loading fatigue life using RDEC

Temp.	Strain	VG40	CRMB60	PMB40
20°C	400	—	505,300	—
20°C	600	28,156 (1)	17,247 (3)	22,384 (2)
20°C	800	2,700 (3)	10,308 (1)	7,578 (2)
0°C	400	213,900 (3)	401,288 (1)	315,100 (2)
0°C	600	22,466 (2)	19,464 (3)	23,810 (1)
0°C	800	792 (3)	17,403 (1)	1,767 (2)

The energy-ratio method also produced condition-dependent rankings (Table 6). At 20°C, CRMB60 ranked first at 400 and 800 microstrains, while VG40 ranked first at 600 microstrains among the reported values. At 0°C, PMB40 ranked first at 400 microstrains; VG40 ranked first at 600 and 800 microstrains, although CRMB60 could not be assigned a value at 600 microstrains.

Table 6. Continuous-loading fatigue life using energy ratio

Temp.	Strain	VG40	CRMB60	PMB40
20°C	400	—	713,744 (1)	381,694 (2)
20°C	600	38,424	—	31,427
20°C	800	3,639 (3)	15,704 (1)	8,697 (2)
0°C	400	215,216 (2)	—	549,982 (1)
0°C	600	47,286 (1)	—	39,352 (2)
0°C	800	1,538 (3)	18,921 (1)	2,003 (2)

The divergence among Tables 3–4 is not necessarily an experimental contradiction: the criteria quantify different aspects of damage evolution and may identify different characteristic points. The results support reporting the fatigue-life method alongside every comparative ranking.

5.4 Influence of Rest Period

The second loading protocol introduced a 0.9 s rest period between loading events. This protocol was designed to examine the influence of stress relaxation, strain recovery and possible healing on the response of the three binder systems. The project abstract reports that CRMB60 and PMB40 mixtures exhibited a lower rate of stiffness reduction and better recovery during rest periods than the VG40 mixture. It further reports that stiffness increased during the rest period and that fatigue life improved when rest periods were introduced.

5.4.1 Interpretation of Rest-Period Response

The observed recovery is consistent with the viscoelastic nature of bituminous mixtures. During the unloaded interval, part of the accumulated strain can recover and internal stresses can relax. The possibility of healing may also contribute to the improved response, although the supplied report does not isolate the relative contributions of relaxation, recovery and healing. The modified mixtures showed more favourable recovery than VG40 in the reported observations.

The 0.9 s rest period should not be interpreted as a direct representation of every field traffic condition. Its value is to demonstrate that a discontinuous loading history can alter the apparent fatigue response and that comparisons based solely on continuous loading may not fully represent in-service pavement behaviour. Similar considerations have been discussed in fatigue-healing studies [2]–[4].

5.5 Multi-Axle Loading: Test Protocol

The multi-axle test was designed to simulate a sequence of wheel-load pulses from a truck. The waveform consisted of an initial 0.1 s loading pulse followed by a 0.4 s rest period, then two 0.1 s loading pulses followed by a 0.3 s rest period. Testing was carried out at 0°C and 20°C, at 400, 600 and 800 microstrains, using VG40, CRMB60 and PMB40 mixtures.

The multi-axle fatigue life is expressed in load passes. The report applies the 50% stiffness-reduction method, normalized-modulus/Weibull analysis and energy-ratio method. It explicitly states that AASHTO T321-14/ASTM D8237 peak-based procedures may be less appropriate for multi-axle loading because rest periods and recovery can prevent a distinct peak from being observed. RDEC was not attempted for this protocol.

5.6 Multi-Axle Loading: Fatigue-Life Results

Table 7 presents the 50% stiffness-reduction fatigue life for multi-axle loading. At 20°C, PMB40 ranked first at 600 and 800 microstrains, while CRMB60 ranked first at 400 microstrains. At 0°C, VG40 ranked first at 400 and 600 microstrains, while PMB40 ranked first at 800 microstrains. These mixed rankings show that the response is sensitive to temperature and strain amplitude.

Table 7. Multi-axle fatigue life using 50% initial-stiffness reduction

Temp.	Strain	VG40 (passes)	CRMB60 (passes)	PMB40 (passes)
20°C	400	8,151 (2)	13,125 (1)	5,707 (3)
20°C	600	2,331 (3)	2,375 (2)	27,715 (1)
20°C	800	1,271 (2)	855 (3)	2,549 (1)
0°C	400	29,035 (1)	4,385 (3)	6,765 (2)
0°C	600	973 (1)	4,345 (3)	1,567 (2)
0°C	800	550 (2)	107 (3)	700 (1)

Table 8 gives the multi-axle fatigue life using the AASHTO T321-14 normalized-modulus approach. PMB40 ranked first at all three strain amplitudes at 20°C (181,702; 22,582; and 2,402 passes). At 0°C, VG40 ranked first at 400 microstrains, while PMB40 ranked first at 600 and 800 microstrains. The source table contains blank entries for CRMB60 at 800 microstrains, which are retained as unavailable.

Table 8. Multi-axle fatigue life using AASHTO T321-14/normalized-modulus approach

Temp.	Strain	VG40	CRMB60	PMB40
20°C	400	46,071 (2)	13,306 (3)	181,702 (1)
20°C	600	1,123 (3)	1,175 (2)	22,582 (1)
20°C	800	1,397 (2)	—	2,402 (1)
0°C	400	23,098 (2)	32,855 (1)	12,167 (3)
0°C	600	1,213 (2)	275 (3)	20,808 (1)
0°C	800	39 (2)	—	713 (1)

The normalized-modulus approach therefore indicates a strong PMB40 response at 20°C, but its ranking at 0°C is strain-dependent. The report also notes that Weibull fitting did not consistently produce physically expected estimates for some multi-axle cases, particularly where the available data were insufficient.

5.7 Multi-Axle Loading: Energy-Ratio Response

The energy-ratio method was identified in the report as the most useful approach for interpreting the multi-axle response because it captured changes in the slope of the energy-ratio curve. Table 9 presents the corresponding fatigue life. PMB40 ranked first at all three strain amplitudes at 20°C, with 24,327, 22,855 and 2,728 passes at 400, 600 and 800 microstrains, respectively. At 0°C, VG40 ranked first at 400 and 800 microstrains, while PMB40 ranked first at 600 microstrains.

Table 9. Multi-axle fatigue life using energy-ratio method

Temp.	Strain	VG40	CRMB60	PMB40
20°C	400	20,691 (2)	11,612 (3)	24,327 (1)
20°C	600	3,025 (2)	1,507 (3)	22,855 (1)
20°C	800	2,377 (2)	673 (3)	2,728 (1)
0°C	400	24,277 (1)	4,783 (3)	12,167 (2)
0°C	600	2,668 (2)	888 (3)	2,924 (1)
0°C	800	1,347 (1)	309 (3)	813 (2)

The energy-ratio results are the clearest basis in the report for comparing multi-axle fatigue response. PMB40 performed best at 20°C for all tested strain levels, while at 0°C the best-performing binder varied with strain. CRMB60 ranked third at all three 0°C strain levels in the reported table. The report's chapter conclusion similarly states that PMB40 exhibited an excellent response compared with VG40 and CRMB60 under the multi-axle protocol.

5.8 Comparative Assessment of the Three Binders

The comparative evidence indicates that the fatigue performance ranking is not fixed. Under continuous loading, CRMB60 generally showed strong performance at higher strain amplitudes, particularly at 20°C and at 600–800 microstrains. PMB40 showed the highest fatigue life at 0°C and 400 microstrains under stiffness-reduction and normalized-modulus approaches. Under multi-axle loading, PMB40 gave the highest energy-ratio fatigue life at 20°C for all strain amplitudes and was also the leading binder at 0°C and 600 microstrains.

The results also reveal that fatigue-life rankings depend on the analysis method. The same mixture and test condition can receive different rankings when stiffness reduction, normalized modulus, RDEC or energy ratio is used. Accordingly, binder selection should consider the expected pavement temperature and loading pattern, and should not rely on one fatigue-life number without specifying the associated test and analysis procedure.

6. CONCLUSIONS

1. The fatigue response of bituminous concrete mixtures prepared with VG40, CRMB60 and PMB40 was evaluated using four-point bending at 0°C and 20°C, at 400, 600 and 800 microstrains.
2. Under continuous loading, CRMB60 generally showed superior fatigue life at 20°C across the tested strain levels when evaluated using the 50% stiffness-reduction criterion. At 0°C and 400 microstrains, PMB40 produced the highest fatigue life.
3. The RDEC and energy-ratio methods produced rankings that differed in some cases from stiffness-based methods. This confirms that fatigue life is dependent on the post-processing criterion, and the method must be reported with the result.
4. The project report qualitatively observed a lower stiffness-reduction rate and better recovery during rest periods for CRMB60 and PMB40 than for VG40. The report also states that fatigue life improved when rest periods were introduced; however, the numerical rest-period results chapter is absent from the supplied PDF and no quantitative improvement is claimed here.
5. Under multi-axle loading, the energy-ratio method indicated that PMB40 performed best at 20°C for all three strain amplitudes. At 0°C, the leading binder depended on strain amplitude: VG40 at 400 and 800 microstrains and PMB40 at 600 microstrains.
6. The normalized-modulus method also indicated strong PMB40 performance at 20°C under multi-axle loading. However, the report cautions that peak-based normalized-modulus and Weibull approaches may be unsuitable or inconclusive for some multi-axle conditions involving rest intervals.
7. Overall, modified binders improved fatigue response in several test conditions, but neither CRMB60 nor PMB40 was universally superior. The preferred binder depends on temperature, strain level, loading sequence and fatigue-life evaluation method.

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