PROJECT REPORT

P10: Cost Effective Design of Asphalt Pavements at Queensland Pavement Temperatures – Year 6 (2019/2020)

ARRB Project No.: 014919

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SUMMARY

Full depth asphalt pavements are the preferred pavement type for heavily trafficked urban roads throughout Queensland. The structural design of these pavements is sensitive to the road's operating environment, particularly pavement temperature and heavy vehicle speeds. Current asphalt pavement design models in Australia predict increased fatigue damage with an increase in temperature (or decrease in the speed of loading). This has resulted in asphalt thicknesses in excess of 400 mm on some roads in Queensland, which is not considered to be sustainable.

The National Asset Centre of Excellence (NACOE) has embarked on a multi-year study (P10 – *Cost effective design of asphalt pavements and Queensland temperatures*) to optimise the design and construction of asphalt pavements for the Queensland environment, particularly at elevated pavement temperatures. To date, the study has facilitated the introduction of Enrobés à Module Elevé Class 2 (EME2) asphalt on the Queensland Department of Transport and Main Road's road network, as well as published Technical Note 167 *A new approach to asphalt pavement design*.

TN167 introduced a methodology to develop mix-specific modulus and fatigue relationships that can be used for the design of asphalt pavements. This methodology was used in this project to characterise five locally manufactured EME2 asphalt mixes in the laboratory to develop 'typical' flexural modulus and fatigue relationships that will more accurately capture the performance of these mixes compared to using the presumptive relationships that were previously developed for more conventional asphalt mixes.

A case study showed that the use of the 'typical' relationships developed as part of this project resulted in similar EME2 thicknesses compared to the current presumptive relationships adopted by TMR. It is recommended that the presumptive moduli and fatigue relationships currently being used by TMR be replaced by the 'typical' relationships developed in this project.

ACKNOWLEDGEMENTS

The project team would like to acknowledge the contributions from the Transport and Main Roads and ARRB laboratories. NACOE would also like to thank the contractors who participated in this study.

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1 INTRODUCTION

1.1 BACKGROUND

Full depth asphalt thicknesses in excess of 400 mm have previously been design and constructed on heavily trafficked urban roads in Queensland. These thick pavement structures are not considered to be cost-effective; however, the current pavement design models predict increased fatigue damage accumulation at high pavement temperatures commonly experienced throughout Queensland.

Enrobés à Module Elevé Class 2 (EME2) is a high-modulus asphalt originally developed in France during the 1970s. These mixes have exceptionally good fatigue resistance and, together with their high modulus, EME2 is an ideal material for use as a basecourse in heavy duty pavements (Austroads 2014). The combination of high modulus and good fatigue resistance of EME2 can result in reduced pavement thicknesses compared to more conventional dense-graded asphalt mixes. The benefits of using EME2 were demonstrated in a previous phase of this project as part of a demonstration trial on the Gateway Upgrade North (GUN) project (Grobler 2018).

The current approach adopted by Queensland Department of Transport and Main Roads (TMR) is to design EME2 layers based on the presumptive fatigue relationship for asphalt mixes recommended by Austroads (2019). This presumptive relationship was originally developed based on laboratory fatigue testing of conventional asphalt mixes in Europe and the USA and may not necessarily fully capture the fatigue performance of locally manufactured EME2 mixes (Denneman 2016).

NACOE project P10 *Cost effective design of asphalt pavements at Queensland temperatures* is a multi-year research project aimed at optimising the design and construction of asphalt pavements for the Queensland environment, especially at elevated pavement temperatures. Earlier stages of this ongoing NACoE project developed a methodology that allows mix-specific asphalt modulus and fatigue relationships to be used as input into the Austroads design procedure. This methodology was published as Technical Note 167 *A new approach to asphalt pavement design* (TN167) (TMR 2017a). It has subsequently been implemented.

The past two years (2018-2020) of project P10 focussed on developing new 'typical' EME2-specific modulus and fatigue relationships that can be used for the design of asphalt pavements on TMR's road network.

1.2 OBJECTIVE AND APPROACH

The purpose of Year 5 (2018-2019) and Year 6 (2019-2020) of NACOE project P10 was to develop a new 'typical' fatigue relationship for TMR-registered EME2 mixes manufactured in South-east Queensland. This 'typical' relationship can then be used for the structural design of full depth asphalt pavements in Queensland that incorporate EME2 asphalt. The project objective was achieved through the following activities:

- Conduct laboratory testing to characterise the modulus and fatigue performance of three locally manufactured EME2 mixes. The fatigue results of two EME2 mixes previously tested as part of the GUN project were also included in the study.
- Develop a 'typical' EME2 flexural modulus and fatigue relationship for locally manufactured mixes based on the methodology recommended in TN167 (TMR 2017a).
- Assess the impact of adopting the 'typical' modulus and fatigue relationships on asphalt pavement designs in Queensland.
- Document the findings and recommendations in a project report.

1.3 REPORT STRUCTURE

Section 2 of the report presents the findings from the testing program undertaken for the study. The mix-specific modulus and fatigue relationships (including ‘typical’ relationships) are summarised in Section 3, followed by a case study in Section 4 to assess the impact of the newly developed relationships on the design of asphalt pavements in Queensland. Finally, the study conclusions and recommendations are provided in Section 5. The detailed test results are provided in Appendices to the report.

2 LABORATORY ASSESSMENT

2.1 LABORATORY TESTING PROGRAM

The purpose of the laboratory testing program was to characterise the flexural modulus and fatigue performance of EME2 mixes manufactured in South-east Queensland. An expression of interest to participate in the study was sent to asphalt suppliers that already had TMR-registered EME2 mix designs in place. An additional two EME2 mixes previously tested in Year 4 were also included in the study.

2.2 MIX DESIGN INFORMATION

The asphalt samples were prepared in the laboratory in accordance with the mix design information provided by the contractors. Binder content and grading information has been omitted from this report due to its commercial-in-confidence nature. It is important to note that the design of EME2 asphalt is performance based, and there are no specific PSD requirements in MRTS32 *High modulus asphalt (EME2)* (TMR 2017b).

2.3 BINDER TESTING

The EME2 mixes tested were all manufactured using 15/25 penetration grade binder. The properties of the binder used in the asphalt mixes tested in the study are summarised in Table 2.1. Many of the results have been omitted from this report as they are considered to be commercial-in-confidence. The results indicate that the binders used in the study complied with the requirements in MRTS32 (TMR 2017b).

Table 2.1: EME2 binder properties

Property	Test method	Test result (Mix A, B & C)	Test result (Mix D & E)	Specification limit
Softening Point (°C)	AS 2341.18:2020	69	67	56–72
Softening Point – post-RTFO (°C)	AS/NZS 2341.10:2015 AS 2341.18:2020	Tested	Tested	–
Increase in Softening Point (°C)		Conforming	Conforming	8 max.
Penetration at 25 °C, 5 s/100 g (pu)	AS 2341.12:2020	16	17	15–25
Penetration at 25 °C (post RTFO), 5 s/100 g (pu)	AS/NZS 2341.10:2015 AS 2341.12:2020	Tested	Tested	–
Retained Penetration (%)		Conforming	Conforming	55 min.
Viscosity at 60 °C (Pa.s)	AS/NZS 2341.2:2015	Conforming	Conforming	900 min.
Viscosity at 135 °C (Pa.s)	AS/NZS 2341.2:2015	Conforming	Conforming	0.6 min.
Matter insoluble in Toluene (% mass)	AS/NZS 2314.8:2016	Conforming	not tested	1.0 max.
Mass change (%)	AS/NZS 2341.10:2015	Conforming	Conforming	0.5 max.

2.4 FLEXURAL MODULUS TESTING

The flexural modulus of the beam specimens that were prepared from asphalt samples manufactured in the laboratory was measured in accordance with Austroads test method AGPT/T274 *Characterisation of flexural* *stiffness and fatigue performance of bituminous mixes* (Austroads 2016). The flexural modulus was determined at different loading frequencies (0.1 Hz, 0.5 Hz, 1 Hz, 3 Hz, 5 Hz, 10 Hz, 15 Hz, 20 Hz and 30 Hz) and temperatures (5 °C, 15 °C, 25 °C, 30 °C and 40 °C) to develop flexural modulus master curves (refer Section 3.2). The modulus results of the mixes tested have been omitted from this report.

2.5 FATIGUE RESISTANCE TESTING

Flexural fatigue testing of the beam specimens was also performed in accordance with AGPT/T274 (Austroads 2016). This included testing a minimum of 27 specimens per mix, comprising nine specimens at each test temperature (10 °C, 20 °C and 30 °C) in accordance with TN167. It should be noted that the upper temperature for the fatigue testing was limited to 30 °C, which means that extrapolation of the fatigue results was required to assess the fatigue resistance of EME2 mixes at pavement temperatures greater than 30 °C commonly experienced in Queensland. A limited study by Denneman (2016) found that testing asphalt specimens in four-point bending at a temperature of 40 °C yielded unreliable results due to specimen creep occurring. It is, however, proposed that future studies investigate the suitability of testing asphalt specimens at temperatures greater than 30 °C.

The testing was equally conducted at three different strain levels (i.e. low, medium, and high). The strain levels were selected to ensure that the fatigue lives of all the specimens exceeded 10,000 cycles, and that at least 22% of the specimens had a fatigue life greater than 1 million cycles. Fatigue failure (for the purposes of this study) was defined as the number of cycles until a 50% reduction in the modulus of the specimen occurred. The fatigue results of the five mixes tested have been omitted from this report.

The strain level required to achieve 1 million load cycles is often used to assess the fatigue resistance of an asphalt mix in the laboratory. The estimated strain levels after 1 million cycles for each of the testing temperatures are summarised in Table 2.2.

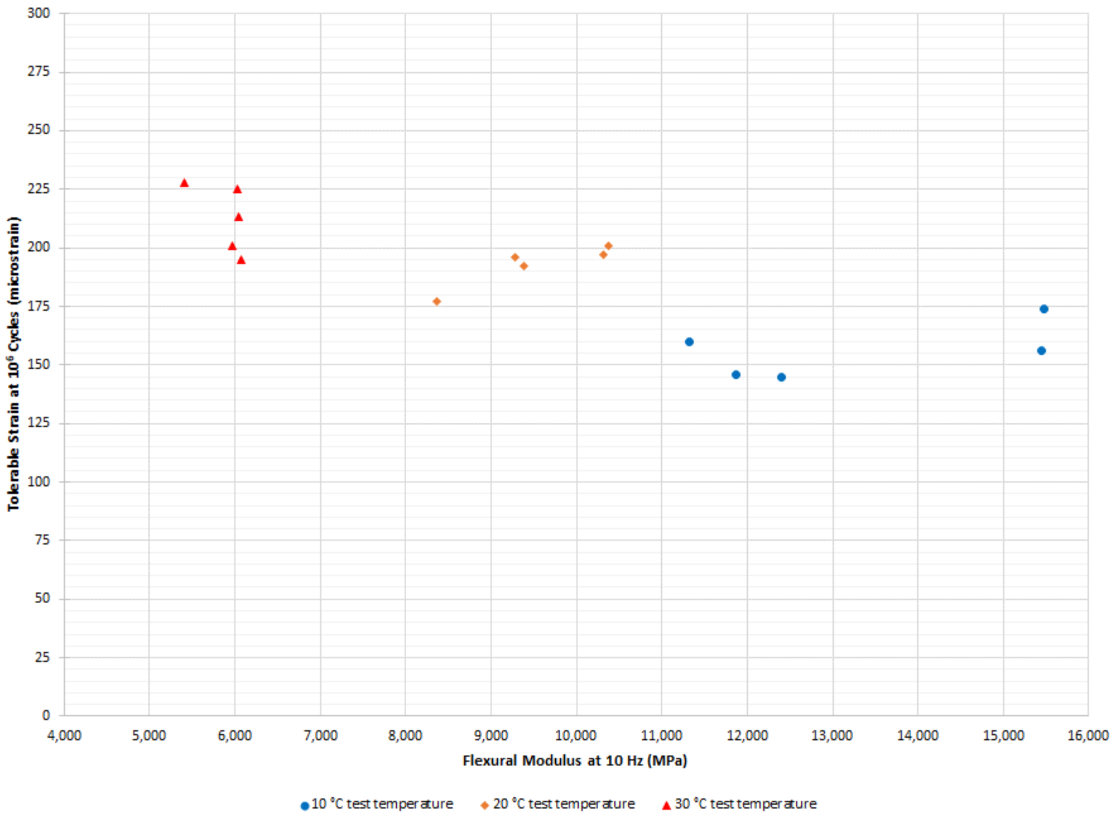
Table 2.2: Summary of fatigue resistance results

Temperature (°C)	Tolerable strain at 1 million cycles (με)				
	Mix A	Mix B	Mix C	Mix D	Mix E
10	145	146	160	174	156
20	196	192	177	201	197
30	201	195	228	225	213

The results indicate that the fatigue resistance of the EME2 mixes improved with an increase in temperature. Furthermore, at 20 °C, all the mixes tested achieved 1 million cycles prior to failure at a strain level greater than 150 µϵ, which is the minimum limit specified in MRTS32 (TMR 2017b).

Figure 2.1 shows the relationship between the tolerable strain level (at 1 million cycles) and flexural modulus at different test temperatures. Based on the testing undertaken for this project, it appears that there is not necessarily a strong correlation between tolerable strain and modulus, and that temperature may be a better predictor of tolerable strain.

Figure 2.1 Tolerable strain for different modulus values and test temperatures



2.6 INDIRECT TENSILE STRENGTH TESTING

Indirect Tensile Strength (ITS) testing was undertaken on EME2 specimens compacted in the laboratory to determine the resilient modulus of the various mixes included in the study. The testing was conducted at 25 °C in accordance with AS/NZS 2891.13.1 *Methods of sampling and testing asphalt: Method 13.1: Determination of the resilient modulus of asphalt – indirect tensile method*. The resilient modulus values obtained from the ITS testing are summarised in Table 2.3.

Table 2.3: Resilient modulus test results

Mix	Specimen no.	Air voids (%)	Resilient modulus (MPa)	Resilient modulus adjusted to 4.5% air voids (MPa)[1]
Mix A	2	4.9	8 989	9212
	3	5.2	8 968	9365
	4	4.8	8 963	9129
	6	4.7	8 919	8028
	7	5.3	9 407	9886
Average value			**9049**	**9324**
Mix B	1	4.7	8 316	8418
	3	5.0	7 761	8004
	5	5.0	9 501	9798
	6	4.9	9 394	9627
	8	4.7	10 233	10359
Average value			**9041**	**9241**
Mix C	2	5.3	8 449	8880
	3	5.2	8 207	8571
	4	5.4	8 280	8758

Mix	Specimen no.	Air voids (%)	Resilient modulus (MPa)	Resilient modulus adjusted to 4.5% air voids (MPa)[1]
	5	5.5	8 111	8634
	6	5.1	8 360	8675
Average value			**8281**	**8704**
Mix D	1	4.6	7 943	7991
	3	5.5	8 180	8708
	4	5.9	7 630	8337
	5	5.6	7 053	7557
	7	6.0	7 456	8202
Average value			**7652**	**8159**
Mix E	1	5.4	7 978	8438
	2	4.9	8 235	8440
	3	4.7	8 478	8582
	4	5.2	8 255	8621
	5	4.9	8 044	8244
Average value			**8198**	**8465**

Note: 1. The resilient modulus values were normalised to 4.5% air voids using Equation 22 in AGPT02.

TMR currently adopts an in-service air voids content of 4.5% for EME2 for pavement design purposes, which is 1% less than the maximum characteristic air voids specified in MRTS32 (TMR 2017b). The average resilient modulus of the EME2 mixes tested varied between 8159 MPa and 9241 MPa at an air voids content of 4.5%.

3 MIX-SPECIFIC RELATIONSHIPS

TMR published TN167 to facilitate the implementation of new procedures for the cost-effective design of asphalt pavements in Queensland (TMR 2017a). TN167 provides procedures for developing mix-specific modulus and fatigue relationships that can be used for pavement design instead of presumptive relationships. These procedures are compatible with the pavement design system adopted by Austroads in Part 2 of the *Guide to pavement technology* (AGPT02) (Austroads 2019).

3.1 MIX-SPECIFIC FLEXURAL MODULUS MASTER CURVES

Mix-specific flexural modulus master curves were developed for the five EME2 mixes included in the study. In addition, a 'typical' master curve was developed by combining the flexural modulus data from the five different mixes tested. These master curves were developed based on the procedure specified in TN167 (TMR 2017a). They can be used to determine the asphalt modulus for pavement design purposes at any given temperature and load frequency.

Equation 1, Equation 2 and Equation 3 provide the relationships between dynamic modulus, load frequency and temperature.

$$log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log f_r}} \quad (1)$$

$$f_r = a(T) \times f \quad (2)$$

$$\log a(T) = a(T - Tref)^2 + b(T - Tref) \quad (3)$$

where

E^*		Dynamic Modulus (MPa)
$\delta, \alpha, \beta, \gamma$	=	model fitting parameters
f	=	frequency (Hz)
f_r	=	reduced frequency (Hz)
$a(T)$	=	shift factor as a function of temperature (°C)
T	=	temperature (°C)
$Tref$	=	25 °C
a, b, c	=	model fitting parameters.

The master curve is developed by shifting the mean modulus test results obtained at the different load frequencies for each temperature to form a continuous function at a reference temperature (e.g. 25 °C for this study). The model fitting parameters obtained for each of the mixes tested are excluded from this report. The model fitting parameters for the combined ('typical') data are summarised in Table 3.1. It should be noted that these results are presented at the test air voids and have not been adjusted to the design in-service air voids.

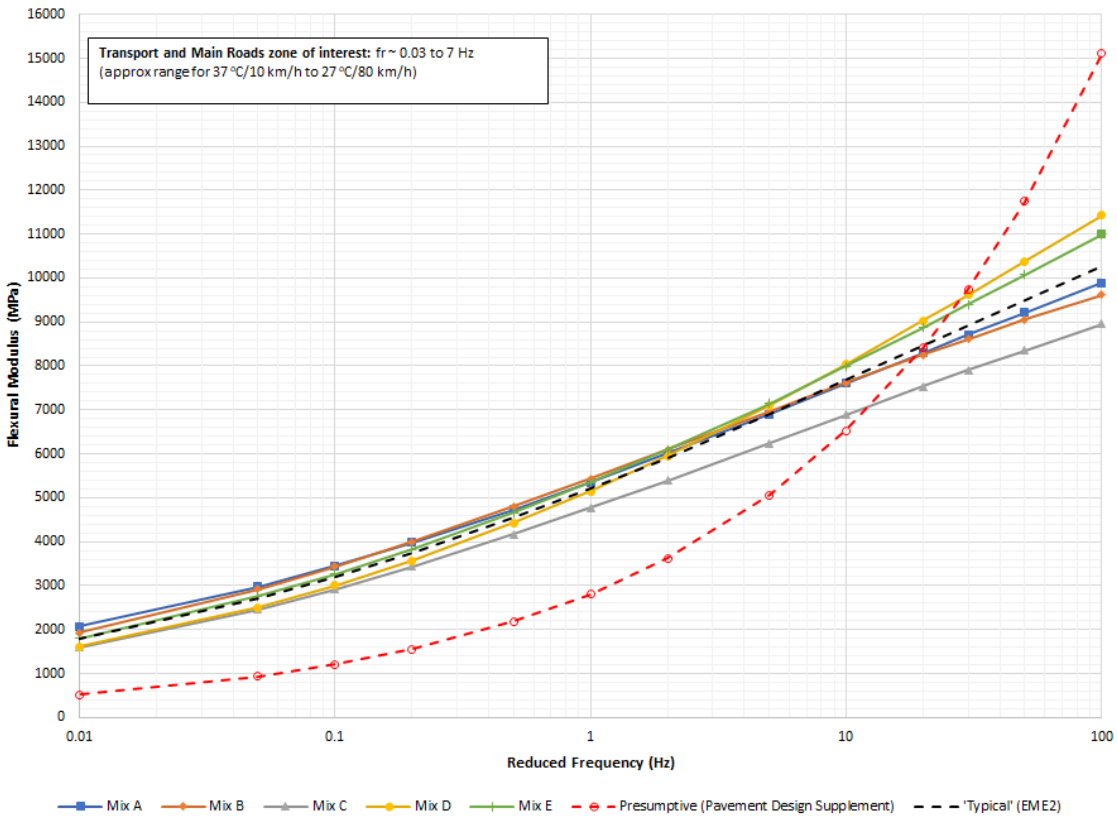
Table 3.1: Flexural modulus master curve fitting parameters

Mix	Master curve fitting parameters							
	T_{ref} (°C)	α	β	γ	δ	a	b	R^2
Presumptive[1]	25	15.3	0.0	-0.0958	-4.188	1.191×10^{-5}	-0.0951	–
'Typical'	25	2.759	-1.295	-0.409	1.550	7.049×10^{-4}	-0.143	0.999

Note: 1. Based on presumptive values in TN167.

Figure 3.1 compares the five mix-specific master curves, the 'typical' master curve (based on the combined results of the mixes tested), and a presumptive master curve for EME2 asphalt at a reference temperature of 25 °C and 5% air voids. The presumptive master curve was derived from the presumptive modulus values in the 2018 version of TMR's *Supplement to 'Part 2: Pavement structural design' of the Austroads guide to pavement technology* (TMR 2018).

Figure 3.1 Comparison of flexural modulus master curves



The flexural modulus testing to develop the master curves was undertaken over a wide range of load frequencies and temperatures. However, the zone of interest to TMR was for heavy vehicle speeds between 10 km/h and 80 km/h, and pavement temperatures between 27 °C and 37 °C, which corresponds to a reduced frequency of between 0.03 Hz and 7 Hz in Figure 3.6. All the mixes tested had a flexural modulus greater than the presumptive modulus over this range.

It should be noted that the minimum design modulus for pavement design purposes is 1000 MPa (irrespective of the value obtained from the master curve) which is the minimum stiffness that had previously been observed for in-service pavements.

The shape of the presumptive master curve is also different to the master curve of the mixes tested. However, this is likely due to presumptive relationship being developed based on the temperature and speed correction factors in AGPT02 (Austroads 2017).

3.2 MIX-SPECIFIC FATIGUE RELATIONSHIPS

Mix-specific fatigue relationships were developed in accordance with the procedure provided in TN167 (TMR 2017a), which can be summarised as follows:

- Undertake four-point bending fatigue testing on beam specimens over a range of strain levels and temperatures (as described in Section 2.6).
- Develop a mix-specific laboratory fatigue relationship by fitting the laboratory fatigue results to the model in Equation 4.

$$N_{lab} = EXP[c_1 * \ln^3(E) + c_2 * \ln^2(E) + c_3 * \ln(E) + c_4 + c_5 * \ln(\mu\varepsilon_{\mathrm{lab}})] \quad (4)$$

where

N_{lab}	=	number of cycles to failure in the laboratory flexural fatigue test
E	=	flexural modulus (MPa) at the test frequency and test temperature, determined from the master curve
$\mu\varepsilon_{\mathrm{lab}}$	=	strain in laboratory flexural fatigue test (microstrain)
$c_1 - c_5$	=	fitting parameters.

- The mix-specific in-service fatigue relationship in Equation 4 is then multiplied by a reliability and laboratory-to-field shift factor to relate laboratory performance to in-service performance for pavement design purposes (Equation 5).

$$N = SF/RF * EXP[c_1 * \ln^3(E_d) + c_2 * \ln^2(E_d) + c_3 * \ln(E_d) + c_4 + c_5 * \ln(\mu\varepsilon)] \quad (5)$$

where

N	=	number of cycles to failure in the laboratory flexural fatigue test
E_d	=	flexural modulus (MPa) at the test frequency and test temperature, determined from the master curve
$\mu\varepsilon$	=	strain in laboratory flexural fatigue test (microstrain)
$c_1 - c_5$	=	fitting parameters
SF	=	shift factor between mean laboratory and in-service fatigue lives
RF	=	reliability factor for asphalt fatigue.

It is important to note that TN167 uses the same reliability and shift factors that have been developed by Austroads for use with the Shell laboratory fatigue relationship. Ideally, the appropriateness of these factors should be verified in future when longer-term in-service performance data becomes available for EME2 mixes in Queensland.

The laboratory fatigue results of each of the individual five mixes tested were fitted to the model in Equation 4. A ‘typical’ EME2 fatigue relationship was also developed by combining the fatigue results from the different mixes tested and fitting the combined data to the model in Equation 4. The individual fatigue relationships, the ‘typical’ fatigue relationship (based on the combined data) and the Austroads presumptive fatigue relationship (based on the Shell fatigue relationship) are shown in Figure 3.2, Figure 3.3 and Figure 3.4 for temperatures of 10 °C, 20 °C and 30 °C respectively. The model fitting parameters are summarised in Table 3.2.

Figure 3.2 Fatigue relationships at 10 °C

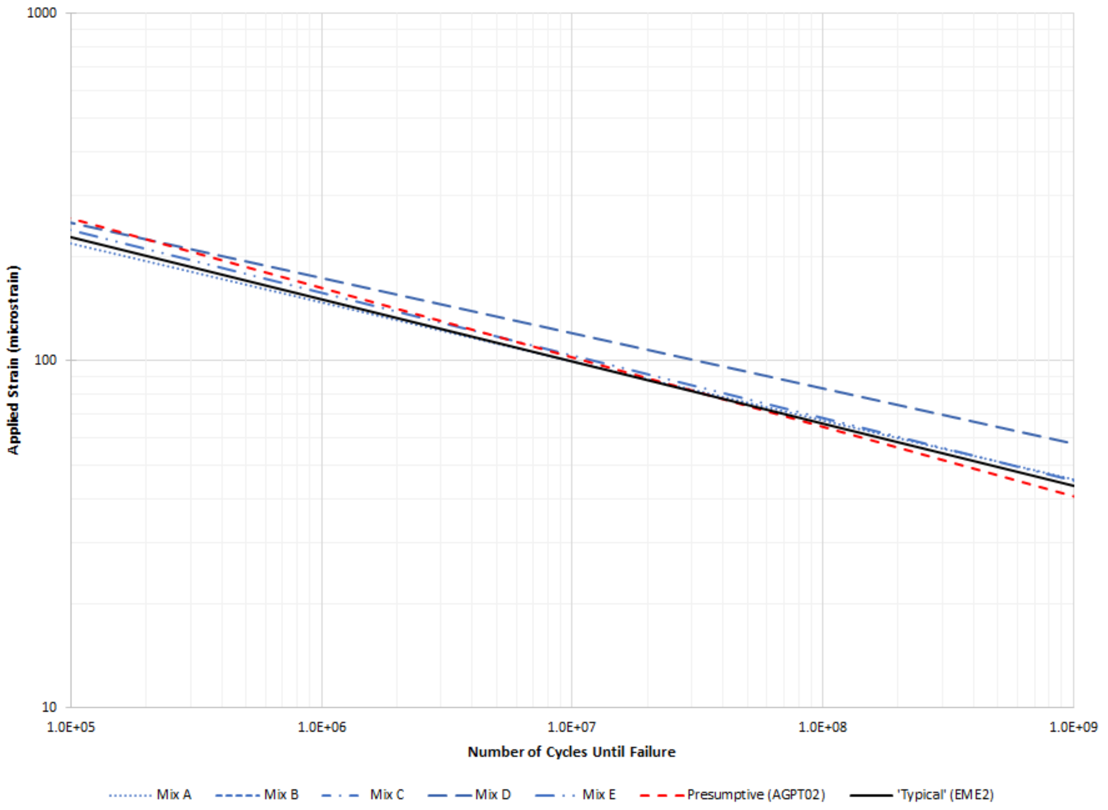


Figure 3.3 Fatigue relationships at 20 °C

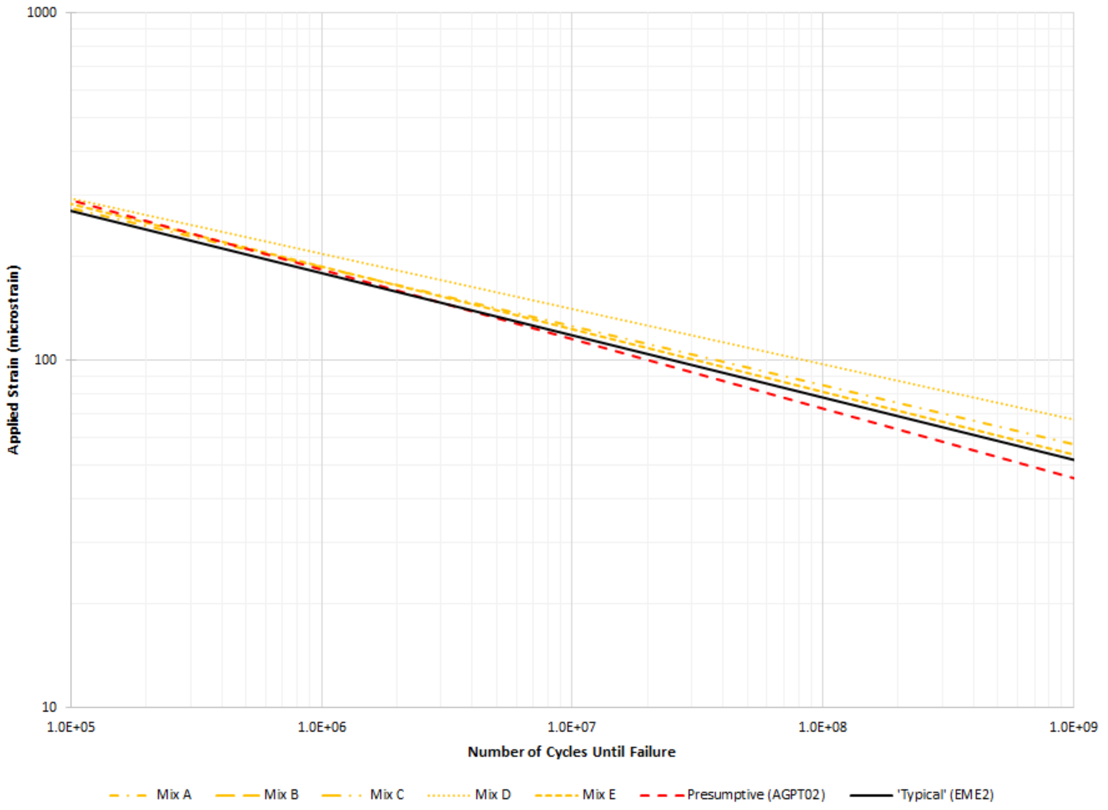


Figure 3.4 Fatigue relationships at 30 °C

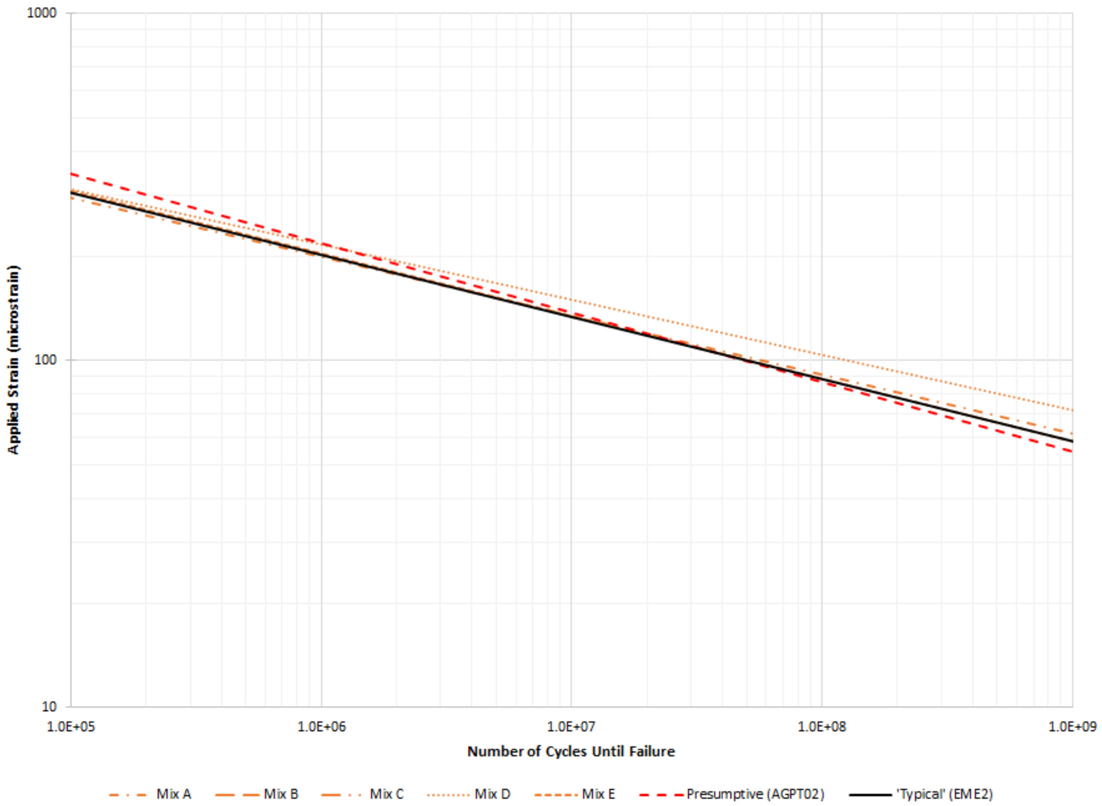


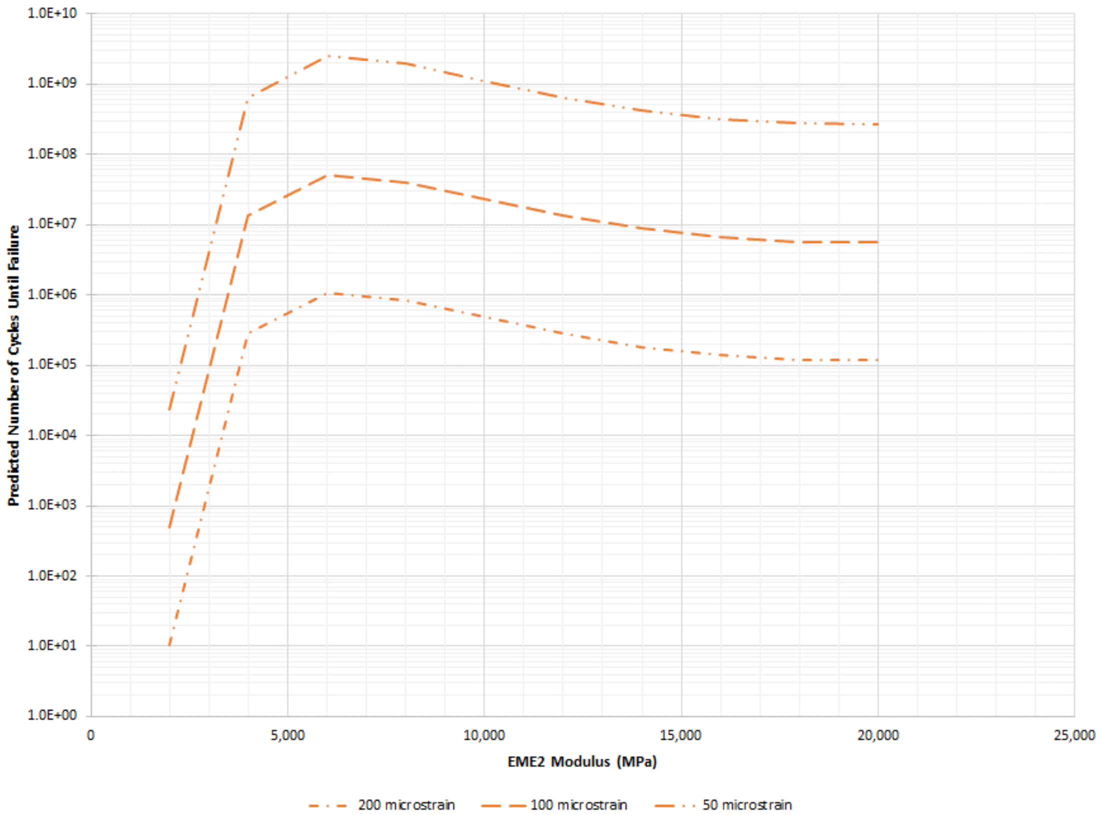
Table 3.2: Flexural fatigue relationship fitting parameters

Mix	Fatigue curve fitting parameters							
	c_1	c_2	c_3	c_4	c_5	Number of specimens	Standard deviation of residuals	R^2
'Typical'	3.1094	-86.850	805.647	-2439.499	-5.588	143	0.587	0.856

At lower strain levels, the 'typical' fatigue relationship predicts a higher number of cycles to failure at 10 °C, 20 °C and 30 °C compared to the presumptive Austroads relationship. However, the opposite is true for higher strain levels. Furthermore, the 'typical' fatigue relationships have a flatter slope compared to the Austroads relationships, suggesting that the EME2 mixes tested are likely to be more sensitive to changes in strain levels compared to what is suggested by the presumptive relationship in Austroads.

The relationships shown in Figure 3.2 to Figure 3.4 and Table 3.2 are only applicable to the three different test temperatures and single load rate included in the study. It is therefore also important to consider how the mix-specific relationships behave over a range of modulus values that are applicable to the structural design of asphalt pavements. As such, the 'typical' fatigue relationship developed using Equation 4 for a range of modulus values are shown in Figure 3.5.

Figure 3.5 Fatigue model behaviour over a range of modulus and strain levels



It can be seen from Figure 3.5 that, at high modulus values, the predicted number of load repetitions until failure gradually increases with a decrease in modulus for different strain levels. This behaviour is consistent with expectations, whereby fatigue damage accumulates more rapidly when the asphalt modulus increases at colder temperatures (or higher load frequencies).

However, the predicted fatigue life peaks at a modulus of approximately 6000 MPa and decreases rapidly as the modulus further decreases. This would suggest that fatigue damage accumulates more rapidly at higher pavement temperatures (compared to lower temperatures), which is not representative of the expected in-service performance of EME2. The model behaviour observed is therefore more likely a result of the form of Equation 4, rather than actual material behaviour.

This inconsistency in model behaviour is also evident when comparing the k-values of both the 'typical' and presumptive relationship with pavement temperature (Figure 3.6). The k-values are material constants (as defined in Equation 6 and Equation 7) used in the Austroads mechanistic-empirical pavement design procedure:

$$k = \frac{87{,}416}{E^{0.36}} \quad (6)$$

where

k	=	material constant from the presumptive Austroads relationship (refer Equation 9) based on 13.5% volume binder
E	=	asphalt modulus (MPa).

$$k = EXP\left(\frac{c_1 \times \ln(E)^3 + c_2 \times \ln(E)^2 + c_3 \times lm(E) + c_4}{c_5}\right) \quad (7)$$

where

k	=	material constant from Equation 4
E	=	asphalt modulus

$c_1 - c_5$ = fitting parameters (refer Table 3.1).

Figure 3.6 K-value vs WMAPT

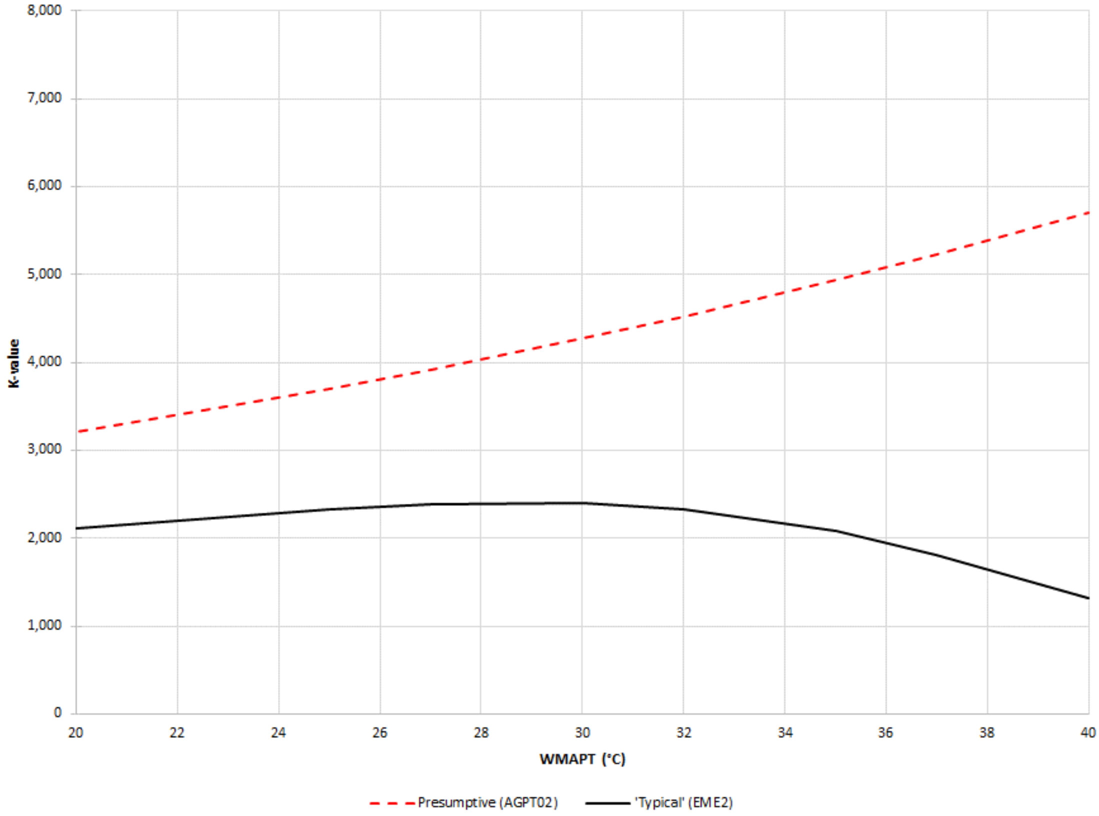


Figure 3.6 shows that the k-value of the 'typical' fatigue relationship increases as the WMAPT increases up to 30 °C, after which it decreases with an increase in pavement temperature. This suggests that the fatigue performance of the EME2 mixes decreases at elevated temperatures (i.e. greater than 30 °C) which again is inconsistent with field performance. There is no apparent reason for this behaviour other than that the model shown in Equation 4 does not appropriately extrapolate the fatigue performance of the EME2 mixes tested at temperatures greater than 30 °C. Contrary to this, the k-value of the Austroads presumptive model behaves consistent with expectations, whereby the predicted fatigue performance increases with an increase in pavement temperature.

Considering this, the fatigue model recommended in TN167 does not appear to be an adequate representation of the fatigue behaviour of the EME2 mixes tested as part of the study, particularly when extrapolating beyond the test conditions (i.e. at temperatures greater than 30 °C).

As such, a similar model to the proposed model in AGPT02 (Austroads 2017) for mix-specific fatigue data was further investigated as part of the study (refer Equation 8).

$$\ln(N_{lab}) = a + b\ln(\mu\varepsilon) \quad (8)$$

where

N_{lab} = number of cycles to failure in the flexural fatigue test

$\mu\varepsilon_{lab}$ = strain in laboratory flexural fatigue test (microstrain)

a and b = fitting parameters.

AGPT02 (Austroads 2017) also provides a presumptive fatigue relationship that can be used where no mix-specific fatigue data is available. This relationship, shown in Equation 9, was originally developed by Shell in the 1970s. It has been subsequently adjusted to predict the fatigue life of in-service pavements for local conditions (Austroads 2017).

$$N = \frac{SF}{RF}\left[\frac{6918(0.856V_b + 1.08)}{E^{0.36}\mu\varepsilon}\right]^5 \quad 9$$

where

N	=	allowable number of load repetitions in-service
$\mu\varepsilon$	=	load induced tensile strain at the base of the asphalt (microstrain)
V_b		volume of bitumen in the asphalt (%)
E	=	asphalt modulus (MPa)
SF		shift factor between mean laboratory and in-service fatigue lives
RF		reliability factor for asphalt fatigue.

Equation 9 can be rewritten (without the shift and reliability factors) in a similar form to Equation 8 as follows:

$$\ln(N_{lab}) = \left[5ln\left(\frac{6918(0.856V_b + 1.08)}{E^{0.36}}\right)\right] + (-5)\ln(\mu\varepsilon_{lab}) \quad 10$$

where

N_{lab}	=	number of cycles to failure in the flexural fatigue test
$\mu\varepsilon_{lab}$	=	strain in laboratory flexural fatigue test (microstrain)
V_b		volume of bitumen in the asphalt (%)
E	=	asphalt modulus.

The numerical values in Equation 10 are curve-fitting parameters determined for the mixes tested in the original Shell study and can therefore also be considered as material constants. A similar approach can be adopted for mix-specific fatigue data, whereby Equation 10 is rewritten as follows:

$$\ln(N_{lab}) = ln\left(\frac{a_1}{E^{a_2}}\right)^{-b} + b\ln(\mu\varepsilon_{lab}) \quad 11$$

where

N_{lab}	=	number of cycles to failure in the flexural fatigue test
$\mu\varepsilon_{lab}$	=	strain in laboratory flexural fatigue test (microstrain)
a_1, a_2 and b	=	curve fitting parameters (i.e. mix specific material constants)
E	=	asphalt modulus.

Equation 11 can then be simplified to:

$$\ln(N_{lab}) = ln\left(\frac{a_1}{E^{a_2}\mu\varepsilon_{lab}}\right)^{-b} \quad 12$$

where

N_{lab}	=	number of cycles to failure in the flexural fatigue test
$\mu\varepsilon_{lab}$	=	strain in laboratory flexural fatigue test (microstrain)
a_1, a_2 and b		curve fitting parameters (i.e. mix specific material constants)
E	=	asphalt modulus.

It is important to note that the simplified model in Equation 12 retains the asphalt's modulus dependency, similar to the presumptive Shell model.

The combined mix-specific fatigue results of the five mixes tested as part of the study were fitted to the model in Equation 12 to develop a 'typical' fatigue relationship. The 'typical' fatigue relationship and the

Austroads presumptive fatigue relationship are shown in Figure 3.7 for test temperatures of 10 °C, 20 °C and 30 °C. The model fitting parameters for the 'typical' fatigue relationship are also summarised in Table 3.3.

Figure 3.7 Comparison of pavement design fatigue relationships

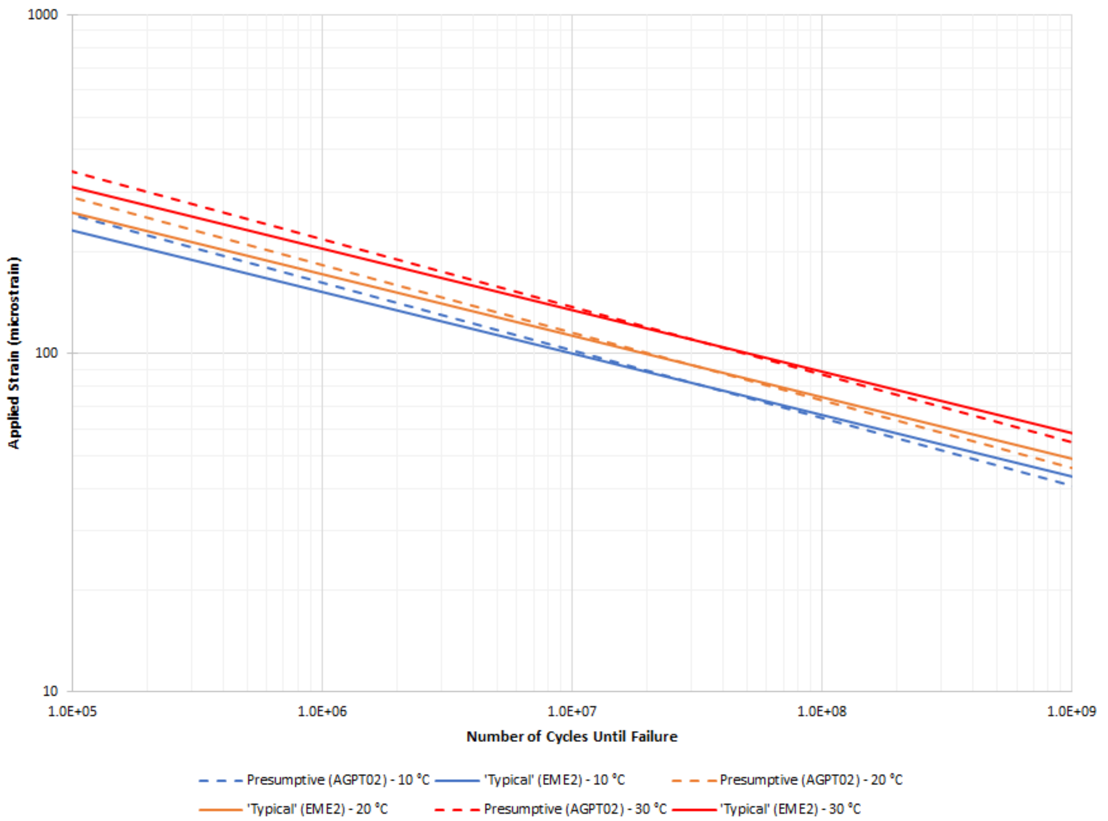


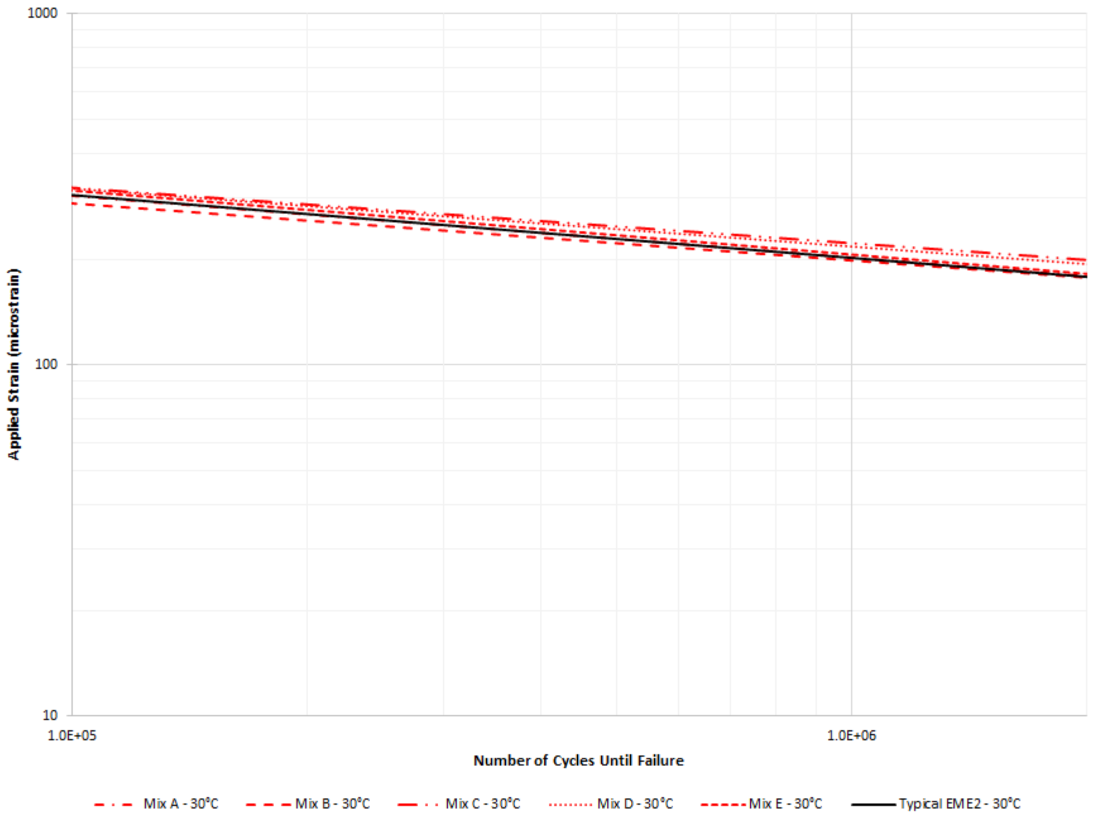
Table 3.3: Fatigue model fitting parameters

Mix	Modulus (MPa)	Fatigue model fitting parameters					
		a_1	a_2	b	Number of specimens	Standard deviation of residuals	R^2
'Typical'	13,400 at 10 °C 9600 at 20 °C 5900 at 30 °C	57,500	0.36	-5.5	143	0.601	0.848

Figure 3.7 shows that the 'typical' fatigue relationship based on the mixes tested are more sensitive to changes in strain levels compared to the presumptive relationship in AGPT02. The 'typical' relationship also predicts improved fatigue performance at low strain levels for EME2 asphalt compared to the presumptive Austroads relationship.

The individual mix-specific fatigue relationships for a 30 °C test temperature was also compared against the 'typical' fatigue relationship in Figure 3.8 across the range of cycles measured in the laboratory. The mix-specific fatigue relationships outperformed the 'typical' relationship at strain levels below approximately 150 microstrains.

Figure 3.8 Mix-specific and typical fatigue relationships at 30 °C



The behaviour of the model shown in Equation 12 was further investigated to determine if this model better predicts the fatigue behaviour of the EME2 mixes tested as part of the study (Figure 3.9 and Figure 3.10).

Figure 3.9 Fatigue model behaviour over a range of modulus and strain levels

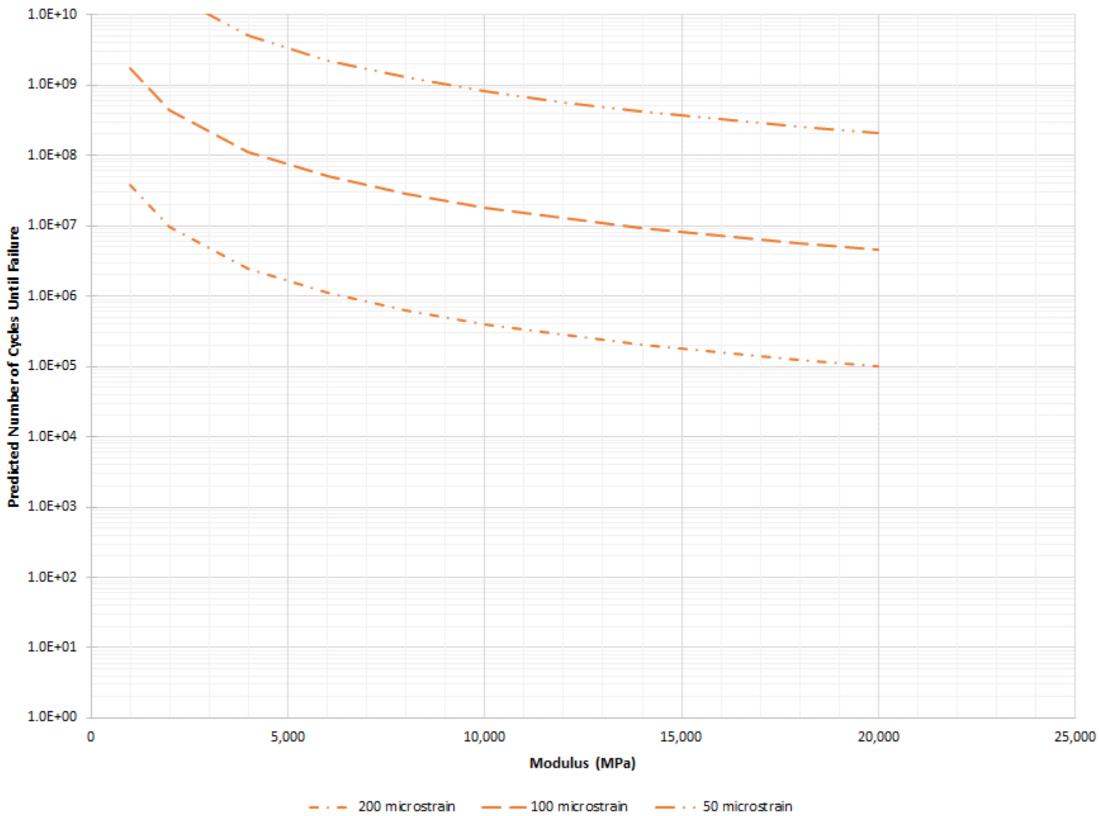


Figure 3.10 K-value vs WMAPT

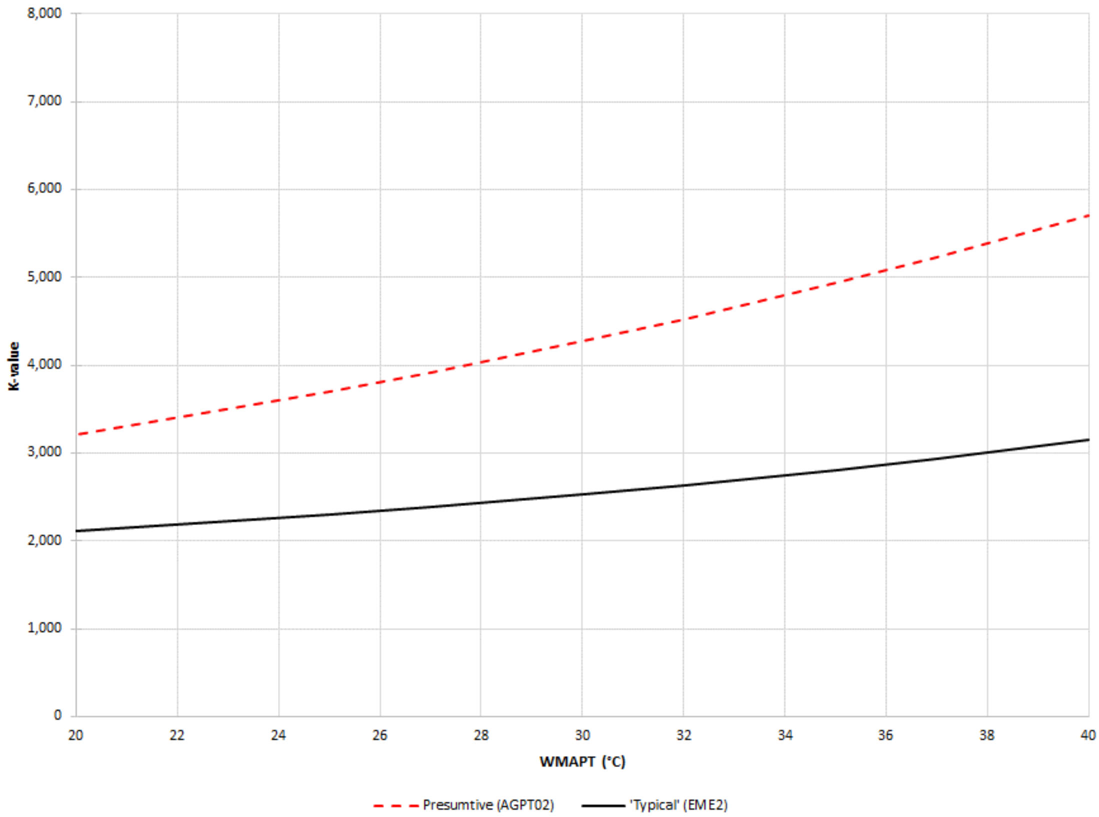


Figure 3.9 shows a gradual increase in predicted fatigue performance as the modulus of the asphalt decreases. This behaviour is consistent with expected field performance, whereby fatigue damage accumulates less at higher pavement temperatures.

Figure 3.10 also shows that the behaviour of the 'typical' EME2 fatigue relationship is similar to the presumptive relationship in AGPT02. This behaviour is more consistent with field conditions. It is therefore recommended that the 3-parameter model is used to develop a 'typical' fatigue relationship for the EME2 mixes tested as part of the study.

3.3 RESILIENT MODULUS

TMR typically do not use mix specific modulus values for pavement design purposes. However, their *Pavement Design Supplement* (TMR 2018) does provide presumptive design modulus values that can be used in pavement designs where no mix-specific information is available (Figure 3.11). These presumptive values were derived from indirect tensile testing of several TMR registered mix designs which have been converted to flexural modulus values using the procedure detail in Austroads (2017). It is worth noting that the presumptive design modulus values for EME2 included in the supplement are based on a limited number of test results from a single asphalt mix.

Figure 3.11 Presumptive design moduli

Asphalt Mix Type	Binder Type	Volume of Binder (%)	Asphalt Modulus at Heavy Vehicle Operating Speed (MPa)			
			10 km/h	30 km/h	50 km/h	80 km/h
OG10	A15E	9.5	800	800	800	800
OG14	A15E	8.5	800	800	800	800
SMA10	A15E	14.0	1000* (600)	1000* (900)	1100	1300
SMA14	A15E	13.0	1000* (600)	1000* (900)	1100	1300
AC10M	C320	11.5	1000* (900)	1300	1600	1900
AC10M AC10H	A15E	11.5	1000* (600)	1000* (800)	1000	1200
AC14M	C320	11.0	1100	1700	2000	2400
AC14M AC14H	C600	11.0	1400	2000	2400	2900
AC14M AC14H	A15E	11.0	1000* (700)	1000	1300	1500
AC20M	C320	10.5	1200	1800	2200	2600
AC20M AC20H	C600	10.5	1500	2200	2600	3100
EME2	EME2 binder	13.5	2000	3000	3600	4200

Notes:

1. Indicated values (*) have been limited to a value of 1000 MPa. When adjusting these moduli to another WMAPT using Equation 6.5.7, E32ºC should be taken as the value in brackets.

Source: TMR (2018).

The resilient modulus results of the five mixes tested as part of the study were combined and converted to design (flexural) modulus values so they could be compared with the current design modulus values in TMR's *Pavement Design Supplement*. The presumptive design modulus was determined as the 10th percentile value of the modulus results to provide a 90% confidence level (consistent with historic departmental practice). The 10th percentile resilient modulus and design modulus values of the five mixes tested are summarised in Table 3.4.

Table 3.4: Mix specific resilient modulus and design (flexural) values

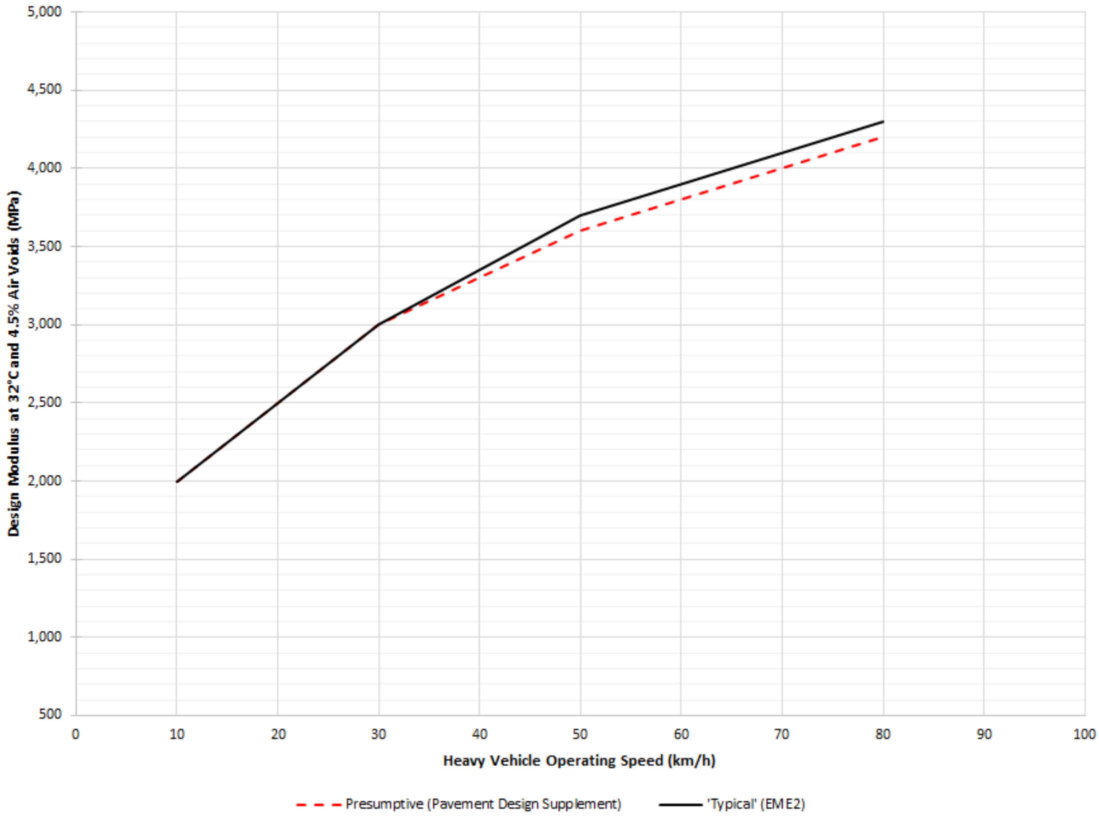
Mix	Resilient Modulus at 25 °C (MPa)	Resilient Modulus at 32 °C (MPa)	Design Modulus at 32 °C (MPa)			
			10 km/h	30 km/h	50 km/h	80 km/h
Mix A	9069	5180	2281	3406	4104	4872
Mix B	8169	4666	2055	3068	3697	4389
Mix C	8596	4910	2162	3228	3890	4618
Mix D	7731	4416	1944	2903	3499	4153
Mix E	8322	4753	2093	3125	3766	4471

Mix	Resilient Modulus at 25 °C (MPa)	Resilient Modulus at 32 °C (MPa)	Design Modulus at 32 °C (MPa)			
			10 km/h	30 km/h	50 km/h	80 km/h
Presumptive[1]	8083	4617	2033 (2000)	3036 (3000)	3658 (3700)	4342 (4300)

Note: 1. Values in brackets are rounded to the nearest 100 MPa.

A comparison between the previous and new presumptive design modulus values are shown in Figure 3.12.

Figure 3.12 Presumptive vs 'typical' EME2 resilient modulus



The new presumptive design modulus (based on the indirect tensile test results converted to flexural modulus) is only marginally higher (i.e. 100 MPa) for the five combined mixes at heavy vehicle operating speeds of 50 km/h and 80 km/h compared to the values included in the 2018 version of the *Pavement Design Supplement*.

The results show the design (flexural) modulus values estimated from the resilient modulus results are similar to the values currently used. However, the approach to convert resilient modulus to design values results in lower design values than what the actual flexural modulus test results indicate. Given that flexural modulus test results are now available, it is recommended that the current design values be replaced with values derived from the flexural modulus master curve.

4 IMPACT ON PAVEMENT DESIGN

The implications of using the ‘typical’ flexural modulus and fatigue relationship developed for locally manufactured EME2 mixes were assessed by comparing pavement thickness designs using both the ‘typical’ and Austroads presumptive relationships.

4.1 FLEXURAL MODULUS AND FATIGUE RELATIONSHIPS FOR PAVEMENT DESIGN

The flexural modulus master curve shown in Figure 3.6 was developed based on an air voids content of 5% (i.e. air voids of the beam specimens used for the laboratory testing). The flexural modulus values should therefore be adjusted to the design air voids content of 4.5%, which is the in-service air voids content used by TMR for pavement design purposes.

The master curve can be adjusted for different air void contents by replacing the ‘δ’ model parameter in Equation 1 with $\delta + \log\left(\frac{21-desing\ air\ voids}{21-test\ air\ voids}\right)$ to form a design flexural modulus master curve, as follows:

$$log\left|E^*{}_{design}\right| = \left(\delta + \log\left(\frac{21 - design\ air\ voids}{21 - test\ air\ voids}\right) + \frac{\alpha}{1 + e^{\beta+\gamma\log f_r}} \qquad 13$$

where

$E^*{}_{design}$		Dynamic Modulus for pavement design purposes (MPa)
$\delta, \alpha, \beta, \gamma$	=	model fitting parameters
f_r	=	reduced frequency (Hz) – Equation 2
$a(T)$	=	shift factor as a function of temperature (°C) – Equation 3.

The derivation of the adjusted master curve (Equation 13) is detailed in Appendix A.

The fatigue relationship shown in Equation 12 is a laboratory model that should be converted to a design model for pavement design purposes by applying shift and reliability factors in accordance with the approach recommended in AGPT02 (Austroads 2017).

CIRCLY is the preferred mechanistic-empirical design software in Australia. It requires fatigue relationships to be in the following form (Equation 14):

$$N_{field} = \frac{SF}{RF} \text{x} \left(\frac{k}{\mu\varepsilon}\right)^x \qquad 14$$

where

N_{field}	=	number of cycles to failure in-service
SF	=	shift factor between mean laboratory fatigue and the mean in-service fatigue life
RF	=	reliability factor for asphalt fatigue
k		material constant (refer Equation 14)
με	=	predicted load-induced strain at bottom of asphalt layer (microstrain)
x	=	damage exponent of EME2 (refer Equation 15).

The k -parameter and damage exponent (x) in Equation 13 are defined in Equation 15 and Equation 16.

$$k = \frac{a_1}{E^{a2}} \qquad 15$$

where

$a_1 - a_2$ = model fitting parameters (refer Table 3.3)

E = modulus of asphalt layer (refer modulus master curve).

$$x = -b \qquad 16$$

where

b = model fitting parameter (refer Table 3.3).

4.2 CASE STUDY

The implications of using the 'typical' fatigue relationship developed for locally manufactured EME2 mixes were assessed using three common pavement design environments. The pavement designs were prepared using the following technical documents and software:

- The strain based multiple-axle method in AGPT02 (2017), together with CIRCLY 7.
- TMR's *Pavement Design Supplement* (TMR 2018).

The design traffic assumed for the case studies was based on a presumptive traffic load distribution that was determined by combining all the available TMR weigh-in-motion data between 2013 and 2016 (refer Appendix B).

The case study included a range of WMAPTs found throughout Queensland, including 27 °C, 32 °C and 37 °C. Heavy vehicle operating speeds of 30 km/h, 50 km/h and 80 km/h were also considered in the study. The design modulus values adopted for the various pavement layers, except for the EME2 asphalt, were in accordance with the presumptive values provided in TMR's *Pavement Design Supplement*. The design moduli for the EME2 asphalt at various temperatures and loading speeds were obtained from the 'typical' master curve developed for the five EME2 mixes included in the study (refer Section 3.1). An in-service air voids content of 4.5% was assumed for the EME2 layer.

The pavement design input parameters adopted are summarised in Table 4.1.

Table 4.1: Pavement design parameters

Input	Value/details
Pavement type	Full depth asphalt
Average annual daily traffic	75,000
Proportion heavy vehicles	10%
Direction factor	1.0
Lane distribution factor	0.65
Pavement design period	30 years
Heavy vehicle growth rate	3%
Traffic load distribution and load parameters	Presumptive (Queensland wide)
Average number of axle groups per heavy vehicle	2.85
Pavement design traffic	1.20×10^8 cumulative number of heavy vehicle axle groups
Heavy vehicle design speed	30 km/h, 50 km/h, 80 km/h
Reliability factor	6.0 (95% project reliability)
Shift factor	6.0

A low strength subgrade with a CBR of 3% (commonly found throughout the state) was assumed for the case study. A 170 mm thick select fill improved layer (consistent with the recommendations in TMR (2018) was included over the subgrade to achieve a minimum stiffness of 150 MPa below the working platform. A 150 mm thick lightly-bound working platform was also included below the EME2 basecourse.

Details of the pavement structure (including design parameters) adopted for the case study are summarised in Table 4.2.

Table 4.2: Pavement structure

	Pavement material	Layer thickness (mm)	Design modulus		
			30 km/h design speed	50 km/h design speed	80 km/h design speed
Surfacing	SMA14	50	1300 (WMAPT = 27°C) 1000 (WMAPT = 32°C) 1000 (WMAPT = 37°C)	1600 (WMAPT = 27°C) 1100 (WMAPT = 32°C) 1000 (WMAPT = 37°C)	1900 (WMAPT = 27°C) 1300 (WMAPT = 32°C) 1000 (WMAPT = 37°C)
Intermediate	AC14H	50	1500 (WMAPT = 27°C) 1000 (WMAPT = 32°C) 1000 (WMAPT = 37°C)	1900 (WMAPT = 27°C) 1300 (WMAPT = 32°C) 1000 (WMAPT = 37°C)	2200 (WMAPT = 27°C) 1500 (WMAPT = 32°C) 1000 (WMAPT = 37°C)
Base	EME2	refer Table 4.3	6300 (WMAPT = 27°C) 4700 (WMAPT = 32°C) 3400 (WMAPT = 37°C)	6900 (WMAPT = 27°C) 5200 (WMAPT = 32°C) 3800 (WMAPT = 37°C)	7400 (WMAPT = 27°C) 5700 (WMAPT = 32°C) 4200 (WMAPT = 37°C)
Working platform	lightly bound	150	210 MPa (with sub-layering)		
Improved layer	Select fill	170	70 MPa (with sub-layering)		
Natural subgrade	Clay	-	30 MPa		

The pavement design scenarios described in Table 4.1 and Table 4.2 were run to optimise the EME2 thickness. The results are summarised in Table 4.3 and shown in Figure 4.1 to Figure 4.3.

Table 4.3: EME2 Design Thickness

Design speed (km/h)	Fatigue relationship	EME2 design thickness (mm)		
		WMAPT 27 °C	WMAPT 32 °C	WMAPT 37 °C
30	Austroads (presumptive)	190	215	230
	'Typical' mix specific	190	210	225
	Difference	0	-5	-5
50	Austroads (presumptive)	175	200	225
	'Typical' mix specific	180	200	220
	Difference	+5	0	-5
80	Austroads (presumptive)	165	190	215
	'Typical' mix specific	175	195	215
	Difference	+10	+5	0

Figure 4.1 Design scenario 1 (30 km/h design speed)

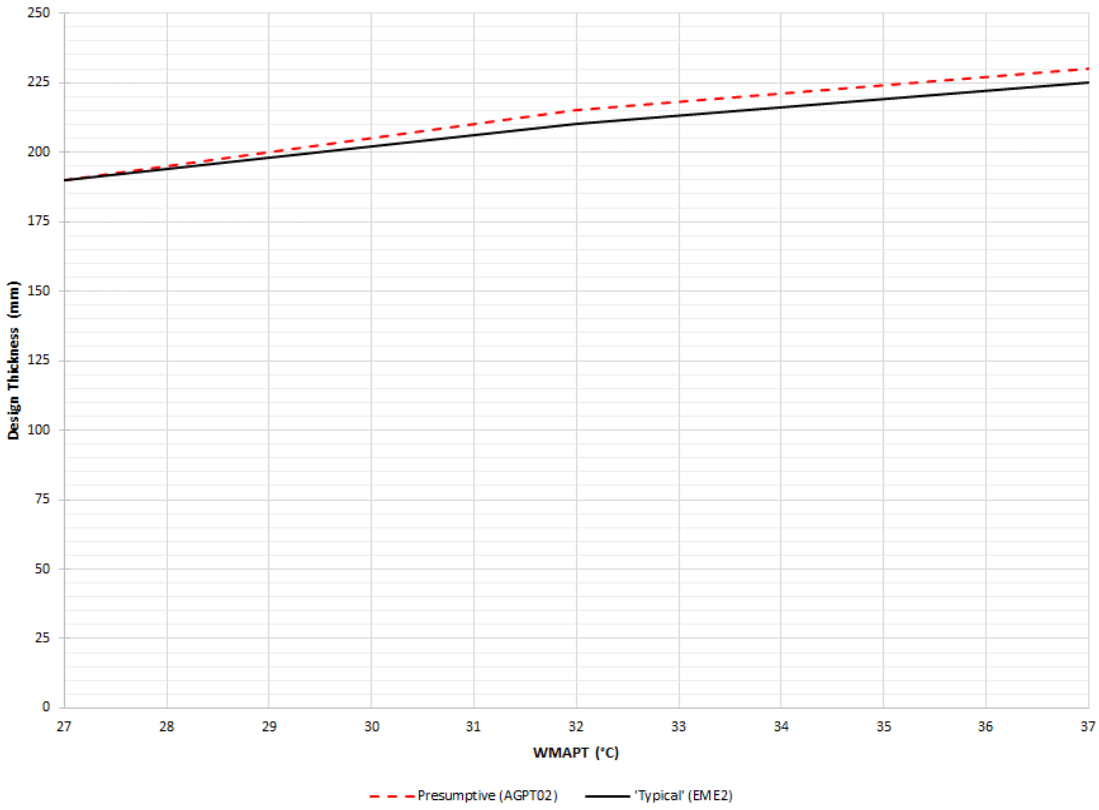


Figure 4.2 Design scenario 2 (50 km/h design speed)

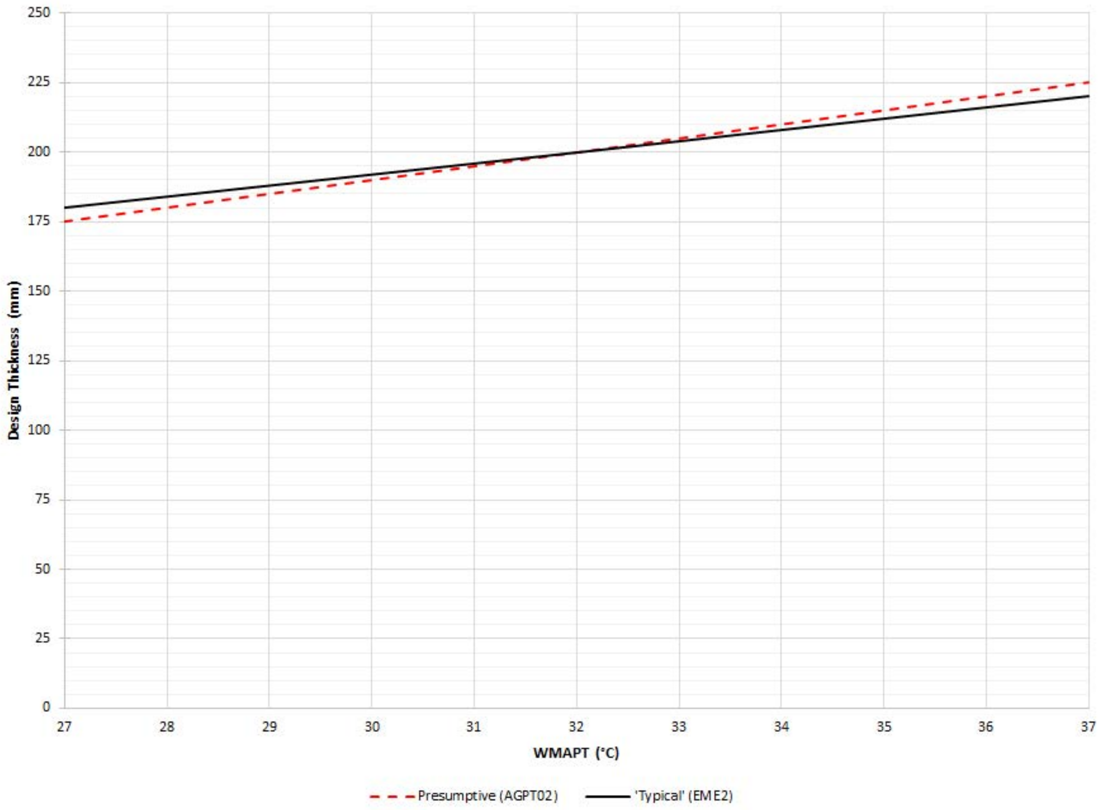
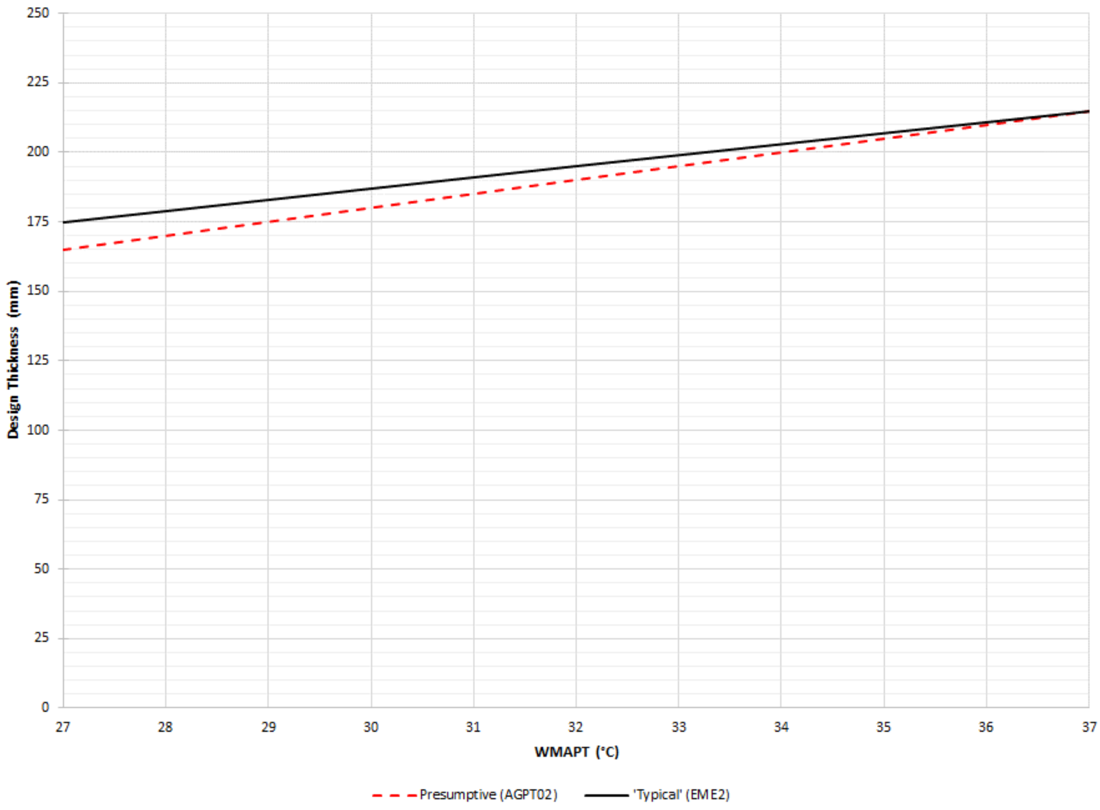


Figure 4.3 Design Scenario 3 (80 km/h design speed)



Adopting the ‘typical’ EME2 fatigue relationship developed resulted in similar thicknesses compared to the presumptive relationships currently being used by TMR, with a maximum difference of 10 mm observed for the design scenarios considered.

The difference in thickness between the ‘typical’ and presumptive relationships is not constant and varies with a change in heavy vehicle speed and WMAPT.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Year 5 (2018-2019) and Year 6 (2019-2020) of NACOE project P10 *Cost effective design of asphalt pavements and Queensland temperatures* involved the characterisation of the laboratory flexural modulus and fatigue performance of five EME2 asphalt mixes available in South-east Queensland. The laboratory results were used to develop a 'typical' modulus and fatigue relationship in accordance with TN167 (TMR 2017a) that can be used in the structural design of EME2 asphalt layers.

It was found that the fatigue model currently included in TN167 was not appropriate to predict the performance of EME2 at temperatures greater than 30 °C. The mix-specific fatigue model recommended by Austroads was therefore also investigated and found to better predict the behaviour of the asphalt mixes tested at elevated pavement temperatures. The test results indicate that modulus may not necessarily be a good predictor for the fatigue resistance of the EME2 mixes tested.

The project also included a case study that assessed the implications of using the 'typical' modulus and fatigue relationships developed for locally manufactured EME2 mixes in different design environments. It was found that the use of these 'typical' relationships provided similar EME2 thicknesses compared to the presumptive relationships currently adopted by TMR.

5.2 RECOMMENDATIONS

Based on the findings of the laboratory assessment undertaken as part of the project, it is recommended that TMR adopt the 'typical' flexural modulus master curve and fatigue relationship for the design of EME2 layers in Queensland.

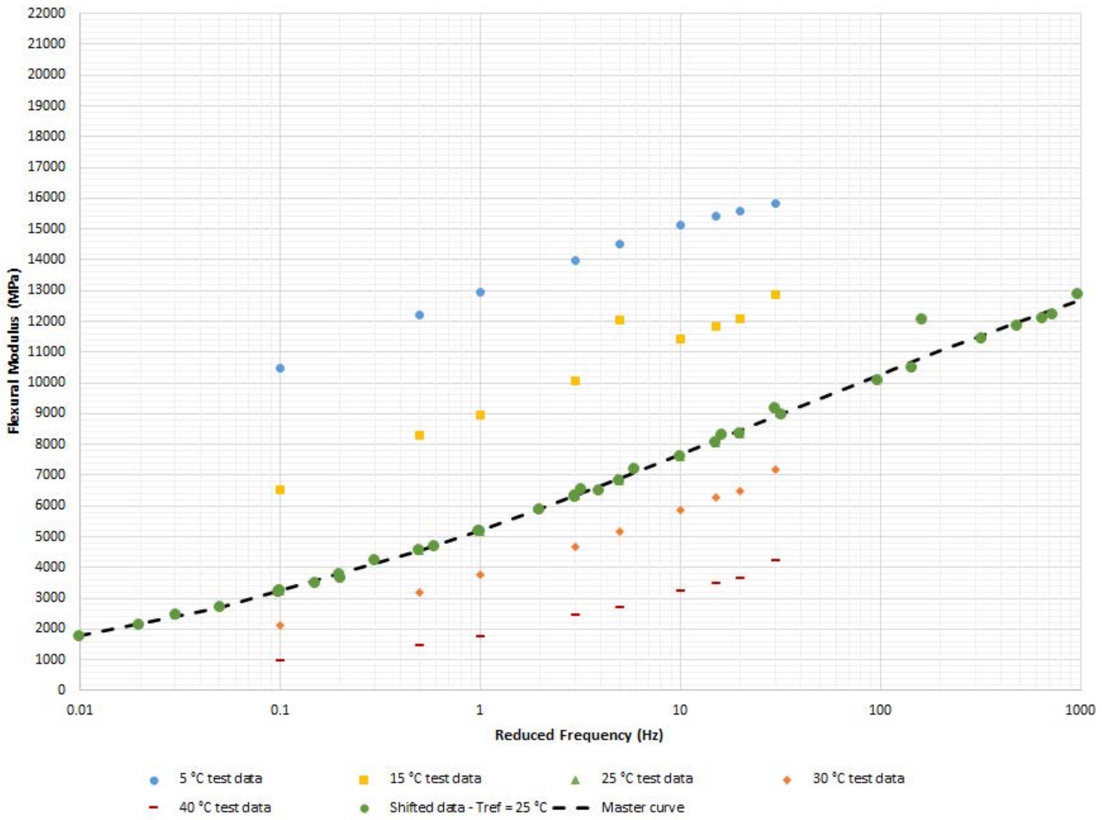
'Typical' flexural modulus master curve:

The 'typical' modulus master curve fitting parameters are summarised in Table 5.1 and the modulus values over a range of frequencies are shown in Figure 5.1. The minimum modulus adopted for pavement design purposes should be limited to 1000 MPa.

Table 5.1: EME2 'Typical' flexural modulus master curve fitting parameters

Mix type	Master curve fitting parameters							
	T_{ref} (°C)	α	β	γ	δ	a	b	R^2
EME2 at test air voids (5%)	25	2.759	-1.295	-0.409	1.550	7.049×10^{-4}	-0.143	0.999
EME2 at design air voids (4.5%)	25	2.759	-1.295	-0.409	1.563	7.049×10^{-4}	-0.143	0.999

Figure 5.1 EME2 'typical' flexural modulus master curve at test air voids



'Typical' flexural fatigue relationship:

The 'typical' EME2 fatigue relationship proposed for implementation is shown in Equation 16.

$$N_{field} = \frac{SF}{RF} \text{x} \left(\frac{57{,}500}{E^{0.36} \times \mu\varepsilon} \right)^{5.5} \quad (17)$$

where

N_{field}	=	number of cycles to failure in-service
SF	=	shift factor between mean laboratory and in-service fatigue lives (from AGPT02)
RF	=	reliability factor for asphalt fatigue (from AGPT02)
E		design modulus (MPa)
$\mu\varepsilon$	=	Predicted load-induced strain at bottom of asphalt layer (microstrain).

5.3 FUTURE WORK

Given the issues associated with extrapolating the performance of the EME2 mixes tested for temperatures greater than 30 °C, it is proposed that future studies further investigate the following:

- the appropriateness of testing asphalt mixes in four-point bending at temperatures greater than 30 °C
- the appropriateness of the third-order polynomial relationship included in TN167 to predict the fatigue resistance of asphalt based on mix specific test results
- the appropriateness of using modulus to predict the fatigue resistance of asphalt mixes.

It is also recommended that the appropriateness of using the reliability and shift factors developed by Austroads be verified when longer-term in-service performance data becomes available for EME2 mixes in Queensland.

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AS/NZS 2891.7.1:2015, *Methods of sampling and testing asphalt: determination of maximum density of asphalt: water displacement method.*

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Transport and Main Roads Test Method

Q308A, *Binder content and aggregate grading of asphalt: reflux method.*

APPENDIX A: DERIVATION OF ADJUSTED FLEXURAL MODULUS MASTER CURVE

The flexural modulus at the test air voids content is determined in accordance with:

$$log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log f_r}} \quad \text{C1}$$

where

E^*		Dynamic Modulus (MPa)
$\delta, \alpha, \beta, \gamma$	=	model fitting parameters
f_r	=	reduced frequency (Hz)
$a(T)$	=	shift factor as a function of temperature (°C)

Simplify Equation C1 as follows:

$$log|E^*| = \delta + Y \quad \text{C2}$$

where

E^*		Dynamic Modulus (MPa)
δ	=	model fitting parameter
Y	=	$\frac{\alpha}{1 + e^{\beta + \gamma \log f_r}}$ C3

Rearrange Equation C2 as follows:

$$|E^*| = 10^{\delta + Y} \quad \text{C4}$$

where

E^*		Dynamic Modulus (MPa)
δ	=	model fitting parameter
Y	=	$\frac{\alpha}{1 + e^{\beta + \gamma \log f_r}}$

The modulus at the test air voids are corrected to the design modulus (at the in-service air voids) in accordance with Equation 22 in AGPT02 (2017), as follows:

$$modulus\ at\ in\ service\ air\ voids\ = modulus\ at\ test\ air\ voids\ \times (\frac{21 - in\ service\ air\ voids}{21 - test\ air\ voids}) \quad \text{C5}$$

Multiply Equation C4 with Equation C5 to determine the design modulus:

$$|E^*{}_{design}| = 10^{\delta + Y} \times (\frac{21 - in\ service\ air\ voids}{21 - test\ air\ voids}) \quad \text{C6}$$

where

E^*		Dynamic Modulus at in-service air voids (MPa)
δ	=	model fitting parameter
Y	=	$\frac{\alpha}{1 + e^{\beta + \gamma \log f_r}}$

Equation C5 can be rearranged as follows:

$$|E^*{}_{design}| = 10^{\delta + Y} \times 10^{\log (\frac{21 - in\ service\ air\ voids}{21 - test\ air\ voids})} \quad \text{C7}$$

$$\left|E^{*}{}_{design}\right| = 10^{\delta} \times 10^{Y} \times 10^{\log\left(\frac{21-in\ service\ air\ voids}{21-test\ air\ voids}\right)} \quad \text{C8}$$

$$\left|E^{*}{}_{design}\right| = 10^{\delta+\log\left(\frac{21-in\ service\ air\ voids}{21-test\ air\ voids}\right)} \times 10^{Y} \quad \text{C9}$$

Substitute Equation C3 into Equation C9 and take the logarithm of both sides as follows:

$$log\left|E^{*}{}_{design}\right| = \delta + \log\left(\frac{21 - in\ service\ air\ voids}{21 - test\ air\ voids}\right) + \frac{\alpha}{1 + e^{\beta+\gamma \log f_r}} \quad \text{C10}$$

Now let:

$$\delta + \log\left(\frac{21 - in\ service\ air\ voids}{21 - test\ air\ voids}\right) = \delta_{in\ service} \quad \text{C11}$$

APPENDIX B: TRAFFIC LOAD DISTRIBUTION

Table D1: Traffic Load Distribution

Axle group load (kN)	Axle group type and proportion					
	SAST	SADT	TAST	TADT	TRDT	QADT
10	0.0407874	2.1351334	0.0041143	0.1248775	0.1277389	3.0508193
20	2.2934866	3.3067960	0.0442795	0.4444180	0.0678097	0.6085444
30	12.1724140	18.1297047	0.3977055	1.4347870	0.2738462	1.3062923
40	11.3436068	21.3164025	1.6027644	4.0474022	1.2727540	1.6817758
50	24.2595365	17.8189703	4.1598847	5.9788076	4.2860293	1.8446067
60	34.9488307	14.4022849	8.4574631	9.2094546	7.7072813	1.9536089
70	12.4469599	8.9458229	13.9974800	10.7273331	10.0310260	2.1911179
80	2.0487532	6.1247542	16.0651835	10.0677356	9.9369090	2.8246470
90	0.4456249	3.8680760	16.4489073	7.2520942	6.7800714	4.3571455
100		2.1430472	13.7865961	5.5692802	4.8841534	6.2294600
110		1.0053249	11.4685366	4.9630303	4.0250449	6.1780351
120		0.4289586	6.5114509	4.7109732	3.2297511	3.5834335
130		0.2247075	3.0970662	5.3405623	3.0687055	3.1478670
140		0.1061248	1.6544734	5.5580183	2.9404763	2.2066925
150		0.0431046	1.0683974	5.7718539	3.1310452	1.9712684
160		0.0005218	0.7553241	6.4317815	3.6769462	2.3161709
170		0.0002182	0.4803732	5.3620591	4.0406853	2.3441061
180		0.0000474		3.3146751	4.7447889	3.0172242
190				1.6911475	5.2487750	3.5527704
200				0.9086519	5.6864686	4.0278514
210				0.5130223	5.1962673	4.9666327
220				0.2548159	3.5600886	4.8081666
230				0.1379799	2.4015894	4.7501335
240				0.0768108	1.4353579	4.0769481
250				0.0468996	0.8831230	3.2896960
260				0.0304894	0.5489377	2.6608811
270				0.0173368	0.3085259	2.0598497
280				0.0093778	0.1883586	1.4871840
290				0.0036060	0.1121039	1.3267275
300				0.0005316	0.0699476	1.0236957
310				0.0000718	0.0492588	0.8794418
320				0.0000790	0.0301993	0.7863135
330				0.0000359	0.0203243	0.8241007
340					0.0131224	0.6395723
350					0.0081684	0.5792189
360					0.0057549	0.8015330
370					0.0035899	0.8744196
380					0.0025019	0.9193144
390					0.0015685	1.0228183
400					0.0009058	1.0370332
410						0.8943246
420						0.6158503
430						0.4543322
440						0.2854977
450						0.2082986
460						0.1379760
470						0.1216840
480						0.0749184
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
Proportion of each axle group (%)	**33.86**	**12.09**	**1.29**	**31.94**	**20.77**	**0.05**