Technical Note 167

A New Approach to Asphalt Pavement Design

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1 Introduction

The purpose of this technical note is to facilitate the implementation of new procedures for the design of more cost effective asphalt pavements in Queensland. This technical note brings together the findings from several related research projects into a practical guide for pavement designers and asphalt contractors.

Pavement design procedures for asphalt pavements are still evolving. Hence, the procedures in this technical note are considered interim, and are likely to be updated following greater experience with their use, and as further research is completed. Users of this technical note are encouraged to consult with the Pavements, Research and Innovation Section of Transport and Main Roads.

This technical note is to be read in conjunction with the Transport and Main Roads *Pavement Design Supplement*.

The main features of the new procedures are:

1. Asphalt modulus is described through the use of a flexural modulus master curve
2. Asphalt fatigue life can be determined using a mix-specific fatigue relationship
3. An upper limit on design traffic for asphalt fatigue in full depth asphalt pavements
4. An improved method for considering heavy vehicle axle group loads.

2 Comparison with existing procedure

A comparison between the new procedures in this technical note and the existing procedures in the *Pavement Design Supplement* and *Part 2: Pavement Structural Design of the Austroads Guide to Pavement Technology* (AGPT02) (Austroads, 2012) is provided in Table 2.

Table 2 – Comparison of new procedures with existing procedures

Aspect	Existing Pavement Design Supplement / AGPT02	New Procedure
Asphalt design modulus	Presumptive values from indirect tensile test	Mix-specific flexural modulus master curve, or presumptive flexural modulus master curve
Asphalt fatigue relationship	Adjusted Shell relationship	Mix-specific fatigue relationship, or presumptive relationship
Limiting asphalt thickness	Thickness unlimited	Thickness capped by an upper limit on design traffic loading
Critical strain	Under standard axle	Under each axle in the traffic load distribution
Material and construction specifications	Standard specifications including MRTS30 *Asphalt Pavements*	Standard specifications with supplementary requirements

Each of the aspects listed in Table 2 is addressed in subsequent sections of this technical note. Worked examples are also provided in the appendices to further illustrate use of the new design procedures.

3 Asphalt design modulus

The new procedure introduces the concept of the flexural modulus master curve to describe the variation of asphalt modulus with varying temperature and load frequency. It is necessary to define a flexural modulus master curve for each asphalt mix used in the pavement structure.

The adopted form of the flexural modulus master curve is the sigmoidal function as shown in Equation 1.

$$\log_{10}|E^*| = \delta + \frac{\alpha}{1+e^{\beta+\gamma\log_{10} fr}} \quad (1)$$

where:

E^* = flexural modulus (MPa)

$\alpha, \beta, \gamma, \delta$ = master curve fitting parameters

f_r = reduced frequency, as defined in Equation 2

$$f_r = \alpha_T \times f_{T274} \quad (2)$$

where:

f_{T274} = frequency (Hz) in flexural modulus test (AGPT/T274)

α_T = temperature shift factor (°C) as defined in Equation 3

$$\log_{10}(a_T) = a\left(T - T_{ref}\right)^2 + b\left(T - T_{ref}\right) \quad (3)$$

where:

a, b = fitting parameters

T_{ref}= reference temperature (°C), typically 25°C

T = test temperature for development of the master curve; and also T = design temperature for determination of design modulus (°C). The design temperature is typically the weighted mean annual pavement temperature (WMAPT).

By combining Equations 1, 2 and 3, the flexural modulus can be determined at any combination of temperature and flexural modulus test frequency. Further to this, by defining the relationship between heavy vehicle speed and flexural modulus test frequency (Equation 5), the design modulus can be determined at any combination of temperature and heavy vehicle speed.

The flexural modulus master curve may either be mix-specific (from measured modulus, as detailed in Section 3.1) or presumptive (from published data, as detailed in Section 3.2). The flexural modulus master curve is used to determine the design modulus as detailed in the following sections.

3.1 Determination of design modulus from measured modulus values

Determination of a mix-specific design modulus involves the measurement of flexural modulus of test beams at a range of temperatures and load frequencies. Laboratory requirements for flexural fatigue testing are detailed in Section 7. Section 7 also details additional controls that are to be established in production and construction to ensure that the mix-specific design properties are consistently achieved.

The methodology for determining the mix-specific design modulus is as follows:

a) The flexural modulus of the asphalt mix is to be characterised in accordance with AGPT/T274.

b) Testing shall be performed on laboratory mixed asphalt, prepared in accordance with AS 2891.2.1, or plant mixed asphalt. Note that in accordance with AGPT/T220, reheating for sample preparation is not permitted.

c) A minimum of four specimens shall be tested. The temperature sweep shall include testing at 5°C, 15°C, 25°C, 30°C and 40°C. The frequency sweep shall be performed over as wide a range of frequencies as possible, but including at least eight frequencies between 0.1 Hz and 20 Hz (for example, 0.1, 0.5, 1, 3, 5, 10, 15, 20, 30, 1 Hz).

d) Using the flexural modulus data (averaged for each combination of test temperature and test frequency), derive the master curve using the sigmoidal function, as detailed in AGPT/T274. The fitting parameters in Equations 1 and 3 are determined by maximising the coefficient of determination (R^2) by correlating $\log_{10}|E^*|$ calculated from the test results with $\log_{10}|E^*|$ estimated using Equation 1. R^2 is as defined in Equation 4.

$$R^2 = 1 - \frac{\sum_i (y_i - z_i)^2}{\sum_i (y_i - \bar{y})^2} \qquad (4)$$

where:

$y_i = \log_{10}|E^*|$ values calculated from the flexural modulus test results

$z_i = \log_{10}|E^*|$ values estimated using Equation 1

$\bar{y}$ = average $\log_{10}|E^*|$ calculated from the flexural modulus test results

e) To determine the design modulus from the derived master curve and fitting parameters:

i. Determine the temperature shift (α_T) at the design temperature (WMAPT) using Equation 3

ii. Determine the flexural modulus test frequency (f_{T274}) equivalent to the load frequency under a heavy vehicle travelling at the design heavy vehicle speed (V) using Equation 5

$$f_{T274} = \frac{V}{2\pi} \qquad (5)$$

where:

V = design heavy vehicle speed (km/h)

f_{T274} = frequency (Hz) in flexural modulus test (AGPT/T274)

The design heavy vehicle speed in this technical note is the representative vehicle operating speed and not the geometric design speed.

iii. Determine the reduced frequency (f_r) at the design temperature and heavy vehicle speed using Equation 2

iv. Determine the flexural modulus (E*) at the design temperature and heavy vehicle speed using Equation 1

v. Adjust the modulus from the test air voids (typically 5.0%) to the modulus at the in-service air voids using Equation 6. In-service air voids for mixes placed in accordance with Transport and Main Roads specifications are typically assumed to be 7.0% for AC7 and AC10 mixes; 6.0% for AC14, AC20 and SMA10 mixes; 5.0% for SMA14 mixes; and 4.5% for EME2 mixes.

$$Modulus\ at\ in\ service\ air\ voids = Modulus\ at\ test\ air\ voids \times \frac{(21 - in\ service\ air\ voids)}{(21 - test\ air\ voids)} \quad (6)$$

f) The resulting value, typically rounded to the nearest multiple of 100 MPa, is the design modulus (E_d).

g) The design modulus (E_d) is typically limited to a minimum value of 1000 MPa for dense graded and stone mastic asphalt.

This procedure replaces the guidance provided in the *Pavement Design Supplement* for the determination of design modulus from measured modulus.

A worked example illustrating the construction of a master curve from test data, and subsequent determination of the design modulus, is provided in Appendices A and B.

For the establishment of construction compliance limits (refer to Section 7), the resilient modulus of the asphalt material at 25°C shall be determined in accordance with AS 2891.13.1. Testing shall be performed on laboratory mixed asphalt, prepared in accordance with AS 2891.2.1, or plant mixed asphalt. Reheating of asphalt mix for sample preparation is not permitted. A minimum of five specimens shall be tested, with the mean value used to establish construction compliance limits.

3.2 Design modulus from published data

Presumptive design modulus values are currently published in the *Pavement Design Supplement* for standard mixes. The *Pavement Design Supplement* values may continue to be used.

Alternatively, the parameters detailed in Table 3.2 can be used to define presumptive flexural modulus master curves for standard asphalt mixes. The presumptive design modulus (E_d) is determined following steps e), f) and g) in Section 3.1, but using the parameters from Table 3.2. Adjustment from test air voids to in-service air voids is not required as this step has already been undertaken in the development of the presumptive master curve parameters.

Table 3.2 – Presumptive flexural modulus master curve parameters for 25ºC reference temperature

Asphalt Mix Type	Binder Type	Volume of Binder (%)	E_{r25} (MPa)	α	β	γ	δ	a	b
SMA14	A5S	13.0	2400	15.3	0.0	-0.0958	-4.700	1.191×10^{-5}	-0.0951
AC10M	C320	11.5	3500	15.3	0.0	-0.0958	-4.536	1.191×10^{-5}	-0.0951
AC10M AC10H	A5S	11.5	2200	15.3	0.0	-0.0958	-4.738	1.191×10^{-5}	-0.0951
AC14M	C320	11.0	4500	15.3	0.0	-0.0958	-4.427	1.191×10^{-5}	-0.0951
AC14M AC14H	C600	11.0	5400	15.3	0.0	-0.0958	-4.348	1.191×10^{-5}	-0.0951
AC14M AC14H	A5S	11.0	2800	15.3	0.0	-0.0958	-4.633	1.191×10^{-5}	-0.0951
AC20M	C320	10.5	4800	15.3	0.0	-0.0958	-4.399	1.191×10^{-5}	-0.0951
AC20M AC20H	C600	10.5	5800	15.3	0.0	-0.0958	-4.317	1.191×10^{-5}	-0.0951
EME2	15/25	13.5	7800	15.3	0.0	-0.0958	-4.188	1.191×10^{-5}	-0.0951

The presumptive master curves in Table 3.2 were derived from the presumptive design moduli in the *Pavement Design Supplement*. Therefore, it is expected that the design moduli determined using the presumptive master curves will not change from the values in the current *Pavement Design Supplement* (noting some minor rounding errors are possible). Presumptive values in the *Pavement Design Supplement* were generally derived from indirect tensile test (ITT) results of Transport and Main Roads registered mix designs. For mixes where limited or no data was available, the presumptive values were determined based on relationships with other mixes. A presumptive design modulus of 800 MPa is typically used for open graded asphalt for all WMAPTs and heavy vehicle speeds. In Table 3.2, E_{r25} is the presumptive resilient modulus (ITT modulus) at 25°C (corrected to the typical in-service air voids).

A worked example illustrating the determination of the design modulus from the master curve is provided in Appendix B.

4 Asphalt fatigue relationships

The new procedure in this technical note provides for use of either a mix-specific or a presumptive asphalt fatigue relationship. Both approaches are detailed in the following sections.

Where a mix-specific design modulus is used, a mix-specific fatigue relationship must also be used. Likewise, where a presumptive modulus is used, the presumptive fatigue relationship must also be used.

4.1 Mix-specific fatigue relationship

Determination of a mix-specific fatigue relationship involves laboratory flexural fatigue testing of asphalt beams at a range of temperatures and strain levels. Laboratory requirements for flexural fatigue testing are detailed in Section 7. Section 7 also details additional controls that are to be established in production and construction to ensure that the mix-specific design properties are consistently achieved.

The methodology for determining the mix-specific fatigue relationship is as follows (NACOE, 2016a):

a) The fatigue performance of the asphalt mix is to be characterised in accordance with AGPT/T274.
b) A minimum of 27 specimens shall be tested, comprising nine specimens at each test temperature (10°C, 20°C and 30°C), with testing equally divided over three strain levels, using a test frequency of 10 Hz. The strain levels shall be chosen in such a way that the fatigue lives for all specimens exceed 10^4 cycles. The strain levels shall be selected so that the number of cycles to failure exceeds 10^6 for at least 22% of specimens tested at each temperature.
c) Fit the model in Equation 7 to the laboratory data (without any averaging of data). This model is known as the mix-specific laboratory fatigue relationship. Failure in the laboratory fatigue test is defined as a 50% reduction in modulus, where the initial modulus is the modulus at the 50th load cycle.

$$N_{lab} = EXP[c_1 \cdot ln^3(E) + c_2 \cdot ln^2(E) + c_3 \cdot ln(E) + c_4 + c_5 \cdot ln(\mu\varepsilon_{lab})] \quad (7)$$

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 (Equation 1)

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

$c_1 - c_5$ = fitting parameters

The fitting parameters in Equation 7 are determined by maximising the coefficient of determination (R^2) by correlating $\ln(N_{lab})$ calculated from the test results with $\ln(N_{lab})$ estimated using Equation 7. R^2 is as defined in Equation 4, except:

$y_i = \ln(N_{lab})$ values calculated from the flexural fatigue test results

$z_i = \ln(N_{lab})$ values estimated using Equation 7

$\bar{y}$ = average $\ln(N_{lab})$ calculated from the flexural fatigue test results

d) The mix-specific fatigue relationship used in pavement design is then determined from Equation 8.

$$N = RF \times EXP[c_1 \cdot ln^3(E_d) + c_2 \cdot ln^2(E_d) + c_3 \cdot ln(E_d) + c_4 + c_5 \cdot ln(\mu\varepsilon)] \quad (8)$$

where:

N = allowable number of repetitions of the load

E_d = design flexural modulus as determined in Section 3 (MPa)

$\mu\varepsilon$ = tensile strain produced by the load, determined by mechanistic design (µm/m)

$c_1 - c_5 =$ regression coefficients (fitting parameters) determined from Equation 7

$RF =$ reliability factor for asphalt fatigue, as per AGPT02

e) To mitigate some of the risk and uncertainty involved in implementing this new pavement design procedure, and without being unduly restrictive in its implementation, the mix-specific fatigue relationship used in pavement design is to be limited as follows:

   i. For pavements with multiple asphalt layers: the reduction in asphalt thickness obtained using the mix-specific modulus and mix-specific fatigue relationship is not to exceed 10% of the thickness determined using the presumptive design modulus and adjusted Shell relationship (Equation 11) in AGPT02 (including the presumptive binder volume).

   ii. For asphalt surfaced granular pavements: the predicted fatigue life of the asphalt using the mix-specific modulus and mix-specific fatigue relationship is to be no more than three times the fatigue life predicted using the presumptive design modulus and adjusted Shell relationship (Equation 11) in AGPT02 (including the presumptive binder volume).

   These comparisons are to be made prior to the addition of any construction tolerances. These limits are additional to any reduction in thickness, or increase in fatigue life, resulting from the improved method for considering multiple-axle group loads detailed in Section 6. It is anticipated that these limits will be reviewed in the future when more information on the fatigue performance of Queensland mixes is available.

A worked example illustrating the development of a mix-specific fatigue relationship is provided in Appendix C.

4.2 *Presumptive fatigue relationship*

The presumptive asphalt fatigue relationship is the adjusted Shell relationship included in AGPT02, except S_{mix} (asphalt resilient modulus) is replaced with the presumptive design flexural modulus (E_d), calculated using the parameters in Table 3.2.

Where the mix-specific modulus is used in pavement design, the presumptive asphalt fatigue relationship cannot be used. The mix specific modulus can only be used in combination with the mix-specific fatigue relationship determined in accordance with Section 4.1.

As further mix-specific fatigue testing is undertaken, it may be possible to develop presumptive fatigue relationships for various mix types incorporating specific binder classes.

5 Upper limit on design traffic for asphalt fatigue in full depth asphalt pavements

AGPT02 notes that there is increasing recognition of the notion that asphalt mixes have endurance strain limits for asphalt fatigue. This suggests that below a given applied strain, repeated cycles of loading no longer result in fatigue damage. Development of an Austroads-endorsed procedure to incorporate the fatigue endurance limit concept into AGPT02 is ongoing, with assessment of the latest relevant international research underway. This includes consideration of the draft outcomes from the

Australian Asphalt Pavement Association's *Asphalt Pavement Solutions for Life* project (Sullivan et al, 2015).

Until such time that an Austroads-endorsed procedure is published, as an interim approach for full depth asphalt pavements, a maximum (capped) asphalt thickness corresponding to a design traffic loading of 200 million equivalent standard axles (ESA) has been adopted by Transport and Main Roads for locations with a weighted mean annual pavement temperature (WMAPT) of 30°C or greater (NACOE, 2016b). This limit is relevant when the traffic loads are considered in accordance with Section 6.

Adoption of the upper limit on design traffic for asphalt fatigue in full depth asphalt pavements requires inclusion of the following minimum support conditions:

- An improved layer below the asphalt base course comprising a minimum 150 mm thick layer of Type 2.3 unbound granular material that is treated with a cementitious stabilising agent to achieve an unconfined compressive strength of 1.0 to 2.0 MPa at seven days (refer to PSTS103 *Lightly Stabilised Improved Layer*)
- An additional thickness of select fill or unbound granular material (if required), based on the bearing capacity of the underlying subgrade material, to increase the pavement support to an adequate level for long term pavement performance. Adequate support can be determined by using Equations 19 and 21 in AGPT02, ensuring that the modulus achieved at the top of the improved layer is not less than 150 MPa.

For example, where the design CBR of the existing in situ subgrade material is 3%, application of Equations 19 and 21 in AGPT02 indicates a select fill layer with minimum CBR 7% and thickness of 170 mm below a 150 mm thick lightly stabilised improved layer is necessary to achieve a modulus of 150 MPa at the top of the improved layer. Equation 19 results in a vertical modulus of 66 MPa for the top sublayer of select fill. Equation 21 then results in a vertical modulus for the top sublayer of the lightly stabilised improved layer of 151 MPa.

Where the design CBR of the existing in situ subgrade material is 7% or more, a 150 mm thick lightly bound improved layer is typically adequate without the need for any additional underlying selected material, unless required to address other issues such as expansive subgrade materials or excess moisture.

Foamed bitumen stabilised materials can be considered as an alternative to lightly bound materials. Where foamed bitumen stabilised materials are being considered, advice should be obtained from the Director (Pavement Rehabilitation) on the appropriate design methodology.

While this approach provides for a minimum amount of pavement support, more substantial treatments (to improve support conditions) are likely to have benefits in terms of overall asphalt thickness reduction. Therefore, more substantial treatments should also be considered by the pavement designer in assessing project-specific alternatives.

To achieve adequate compaction of the asphalt layers, additional support may be necessary depending on the bearing capacity of lower layers at the time of construction. As a minimum, proof rolling of the lightly bound improved layer and all other earthworks layers should be undertaken to confirm acceptable support has been achieved prior to the construction of overlying layers.

6 Improved method for considering multiple-axle group loads

This technical note adopts an improved method for considering multiple-axle group loads, developed as part of Austroads project TT1614 (Austroads, 2015) and further documented by Moffatt (2015).

Currently in AGPT02, axle group loads are converted to Standard Axle Repetitions (SARs) by the use of standard loads. Asphalt fatigue is then assessed on the basis of critical strains under a Standard Axle.

More recent Austroads research (Austroads Project TT1614) has developed an improved method that uses critical strains under each axle in the traffic load distribution, without any conversion to SARs. Estimated asphalt fatigue damage is then determined as the sum of damage from each and every axle in the traffic load distribution.

While the improved Austroads methodology may be applied to assess fatigue of both asphalt and cemented materials, for the purposes of implementation in this technical note it is only intended to be used for the assessment of asphalt fatigue. For fatigue of cemented materials, adoption of the improved method must be done in conjunction with other changes to the cemented materials pavement design procedure arising from Austroads project TT1664 (Austroads, 2014a and 2014b). These changes are not covered in this technical note, but will be adopted by Transport and Main Roads when the full method is published in AGPT02.

The new procedure for assessment of asphalt fatigue is detailed in Appendix D, and is also illustrated in the design example in Appendix E.

7 Implementation considerations for mix-specific modulus and fatigue relationships

Determination of the mix-specific flexural modulus master curve and the mix-specific fatigue relationship for an asphalt mix is optional and usually at the discretion of the Principal Asphalt Contractor (PAC). Where these are to be determined, the requirements in Sections 7.1 to 7.4 apply.

7.1 Mix registration

The mix-specific flexural modulus master curve and the mix-specific fatigue relationship require registration through the Transport and Main Roads asphalt mix design registration system. As well as meeting the requirements of TN148 *Asphalt Mix Design Registration* (Transport and Main Roads, 2016b), the PAC must include the following details in their asphalt mix design submission:

a) all test results and calculations to determine the mix-specific flexural modulus master curve

b) all test results and calculations to determine the mix-specific fatigue relationship

c) resilient modulus test results for the establishment of construction compliance limits

d) mix design certificate which includes the mix-specific master curve parameters and mix-specific fatigue relationship parameters.

Asphalt mixes with mix-specific parameters will be identified in the asphalt mix design register published on the Transport and Main Roads website. However, mix-specific parameters will not be included in the register due to their commercial-in-confidence nature.

7.2 Laboratory testing

Laboratory testing, including sample preparation, to determine the mix-specific flexural modulus master curve and the mix-specific fatigue relationship must be undertaken by one of the following:

a) Transport and Main Roads laboratory

b) ARRB Group laboratory

c) An independent laboratory with NATA certification for the tests undertaken.

7.3 Pavement design considerations

It is anticipated that presumptive moduli and the presumptive fatigue relationship will continue to be used for pavement designs where the specific mixes to be used are unknown (such as for preliminary designs and designs for construct-only-style contracts).

Mix-specific moduli and fatigue relationships should only be adopted in pavement designs where the specific mixes to be used are known at the time the pavement designs are undertaken, and the mix-specific parameters for the mixes have been registered by Transport and Main Roads. This is most likely to be possible in design and construct-style contracts.

For construct-only-style contracts, Contractors are encouraged to submit alternative tenders using mix-specific parameters for registered mixes, unless otherwise prohibited in the project-specific requirements.

7.4 Material and construction specifications

The new pavement design procedure presented in Sections 3.1 and 4.1 is based on the use of a mix-specific modulus and mix-specific fatigue relationship. This requires additional controls to be established in the production and placement of the asphalt to ensure design assumptions are consistently met. The following supplementary provisions must be specified in the contract documents when pavement designs have been determined using mix-specific parameters:

- Minimum and maximum limits on the average resilient modulus at 25°C must be specified. The limits are established using an allowable tolerance of ± 20% from the average resilient modulus at 25°C measured on the material used for the development of the mix-specific master curve and fatigue relationship.
- The resilient modulus of each mix shall be assessed for compliance on the first lot incorporated into the Works, and subsequently on every 5000 tonnes thereafter. If a non-compliance occurs then the next lot after the non-compliance shall also be tested, and subsequently on every 5000 tonnes thereafter.
- For the assessment of compliance, the resilient modulus of the asphalt material at 25°C shall be determined in accordance with AS 2891.13.1. Testing shall be performed on laboratory mixed asphalt, prepared in accordance with AS 2891.2.1, or plant mixed asphalt. Reheating for sample preparation is not permitted. The mean value of the resilient modulus shall be determined from tests on a set of five specimens (with samples spread evenly during production).

8 References

Australian Standards (2013), *Methods of sampling and testing asphalt - Determination of the resilient modulus of asphalt - Indirect tensile method*, AS 2891.13.1, Australian Standards.

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NACOE (2016a), *Improved characterisation of fatigue in asphalt at Queensland temperatures*, National Asset Centre of Excellence, Brisbane, Queensland.

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Transport and Main Roads (2016a), MRTS30 *Asphalt Pavements*, Transport and Main Roads Specifications, January 2016, Transport and Main Roads, Brisbane, Queensland.

Transport and Main Roads (2016b), TN148 *Asphalt Mix Design Registration*, Transport and Main Roads, Brisbane, Queensland.

Appendix A – Example construction of flexural modulus master curve

This appendix illustrates the construction of a flexural modulus master curve from flexural modulus test data for an AC20M(C600) asphalt mix. The master curve is determined for a reference temperature (T_{ref}) of 25°C at the test air voids content of 5.0%.

In this example, flexural modulus testing (AGPT/T274) has been undertaken on five laboratory mixed and compacted asphalt specimens. Each specimen has been tested at temperatures of 5, 15, 25, 30°C and 40°C, and at frequencies of 0.1, 0.5, 1, 3, 5, 10, 15, and 20 Hz.

The test results are presented in Table A.1, together with the average result and the logarithm of the average result, at each combination of test temperature and test frequency.

It is noted that the test data in the appendices of this technical note has been artificially produced to illustrate the calculation methodologies.

Table A.1 – Flexural modulus test results

Test Temp. (T) (°C)	Test Freq. (*f*) (Hz)	Flexural Modulus Test Results (MPa)					Average flexural modulus (E*) (MPa)	$\log_{10}\lvert E^*\rvert$
		Specimen A	Specimen B	Specimen C	Specimen D	Specimen E		
5	0.1	11,519	11,899	9,183	8,779	10,354	10,347	4.01
5	0.5	13,751	15,453	11,956	11,395	13,439	13,199	4.12
5	1	14,880	16,639	13,135	12,495	14,581	14,346	4.16
5	3	16,658	18,876	14,983	14,114	16,510	16,228	4.21
5	5	17,429	19,967	15,924	15,027	17,511	17,172	4.23
5	10	18,354	19,117	16,999	16,013	17,579	17,612	4.25
5	15	18,659	19,211	17,724	16,541	17,890	18,005	4.26
5	20	18,723	20,032	18,070	16,771	18,416	18,402	4.26
15	0.1	4,398	4,103	3,998	3,591	3,862	3990	3.60
15	0.5	6,850	6,653	6,308	5,900	6,290	6400	3.81
15	1	7,916	7,660	7,310	6,860	7,274	7404	3.87
15	3	10,159	9,544	9,340	8,761	9,167	9394	3.97
15	5	11,237	10,621	10,285	9,661	10,155	10,392	4.02
15	10	12,595	11,878	11,595	10,821	11,363	11,650	4.07
15	15	13,539	12,518	12,118	11,493	12,020	12,338	4.09
15	20	13,736	12,846	12,571	11,759	12,317	12,646	4.10
25	0.1	922	962	956	895	943	936	2.97
25	0.5	1,962	1,955	1,959	1,820	1,902	1,920	3.28
25	1	2,682	2,657	2,484	2,449	2,567	2,568	3.41
25	3	4,103	4,280	4,026	3,723	4,015	4,029	3.61
25	5	4,854	4,989	4,742	4,394	4,706	4,737	3.68
25	10	6,090	6,180	5,855	5,458	5,833	5,883	3.77
25	15	6,718	6,901	6,521	5,959	6,444	6,509	3.81
25	20	7,184	7,105	6,780	6,306	6,719	6,819	3.83
30	0.1	647	668	657	647	672	658	2.82
30	0.5	1,268	1,255	1,223	1,176	1,230	1,230	3.09
30	1	1,708	1,675	1,562	1,563	1,633	1,628	3.21
30	3	2,680	2,758	2,588	2,447	2,617	2,618	3.42
30	5	3,257	3,329	3,108	2,955	3,155	3,161	3.50
30	10	4,167	4,216	3,940	3,778	4,010	4,022	3.60
30	15	4,760	4,731	4,410	4,173	4,466	4,508	3.65
30	20	5,113	4,938	4,643	4,452	4,709	4,771	3.68
40	0.1	318	340	275	373	326	326	2.51
40	0.5	600	465	482	684	557	558	2.75
40	1	786	656	686	825	738	738	2.87
40	3	1,247	1,054	1,088	1,394	1,195	1,196	3.08
40	5	1,651	1,342	1,405	1,829	1,557	1,557	3.19
40	10	2,284	1,958	2,021	2,646	2,227	2,227	3.35
40	15	2,740	2,268	2,446	3,088	2,636	2,636	3.42
40	20	2,961	2,524	2,634	3,438	2,890	2,889	3.46

The next step is to calculate the temperature shift factor using Equation 3, the reduced frequency using Equation 2, and the predicated $\log_{10}|E^*|$ using Equation 1. In these calculations, the seed values for the master curve parameters from AGPT/T274, as reproduced in Table A.2, were initially used. Results are shown in Table A.3, alongside the actual $\log_{10}|E^*|$ from the test results (as per Table A.1). The last two columns in Table A.3 show the calculation of the sum of squared residuals and the sum of squared deviations from the mean, which are used in Equation 4 to calculate R^2.

Table A.2 – Seed values for master curve fitting parameters

Parameter	α	β	γ	δ	a	b
Seed Value	1.6	-1.0	-0.73	2.7	0.0003	-0.1

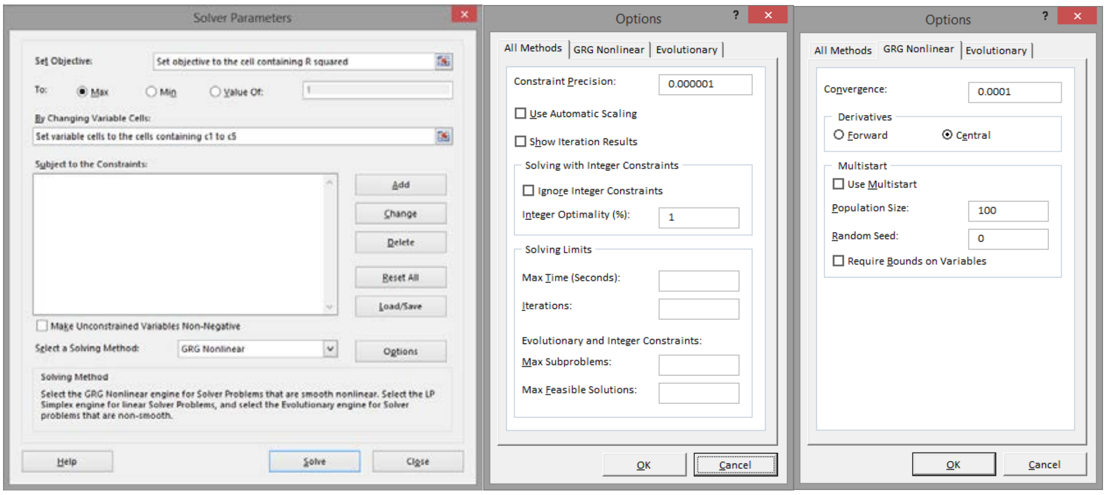
Table A.3 – Predicted $log_{10}|E^*|$ using seed values for master curve fitting parameters (T_{ref} = 25ºC)

Test Temp. (T) (ºC)	Test Freq. (*f*) (Hz)	Test Result $\log_{10}\lvert E^*\rvert$ (Table A.1)	Temperature shift (a_T) (Eq. 3)	Reduced Frequency (f_r) (Hz) (Eq. 2)	Predicted $\log_{10}\lvert E^*\rvert$ (Eq. 1)	$(y_i - z_i)^2$ (Eq. 4)	$(y_i - \bar{y})^2$ (Eq. 4)
5	0.1	4.01	131.83	13.18	4.08	0.00	0.15
5	0.5	4.12	131.83	65.91	4.16	0.00	0.25
5	1	4.16	131.83	131.83	4.18	0.00	0.28
5	3	4.21	131.83	395.48	4.22	0.00	0.34
5	5	4.23	131.83	659.13	4.23	0.00	0.37
5	10	4.25	131.83	1318.26	4.24	0.00	0.39
5	15	4.26	131.83	1977.39	4.25	0.00	0.40
5	20	4.26	131.83	2636.51	4.25	0.00	0.41
15	0.1	3.60	10.72	1.07	3.88	0.08	0.00
15	0.5	3.81	10.72	5.36	4.02	0.04	0.03
15	1	3.87	10.72	10.72	4.06	0.04	0.06
15	3	3.97	10.72	32.15	4.13	0.02	0.12
15	5	4.02	10.72	53.58	4.15	0.02	0.15
15	10	4.07	10.72	107.15	4.18	0.01	0.19
15	15	4.09	10.72	160.73	4.19	0.01	0.22
15	20	4.10	10.72	214.30	4.20	0.01	0.23
25	0.1	2.97	1.00	0.10	3.61	0.40	0.43
25	0.5	3.28	1.00	0.50	3.80	0.26	0.12
25	1	3.41	1.00	1.00	3.87	0.21	0.05
25	3	3.61	1.00	3.00	3.97	0.13	0.00
25	5	3.68	1.00	5.00	4.01	0.11	0.00
25	10	3.77	1.00	10.00	4.06	0.08	0.02
25	15	3.81	1.00	15.00	4.08	0.07	0.04
25	20	3.83	1.00	20.00	4.10	0.07	0.04
30	0.1	2.82	0.32	0.03	3.46	0.42	0.65
30	0.5	3.09	0.32	0.16	3.67	0.33	0.29
30	1	3.21	0.32	0.32	3.75	0.29	0.17
30	3	3.42	0.32	0.97	3.87	0.20	0.04
30	5	3.50	0.32	1.61	3.92	0.17	0.02
30	10	3.60	0.32	3.22	3.98	0.14	0.00
30	15	3.65	0.32	4.83	4.01	0.13	0.00
30	20	3.68	0.32	6.43	4.03	0.12	0.00
40	0.1	2.51	0.04	0.00	3.20	0.48	1.23
40	0.5	2.75	0.04	0.02	3.39	0.42	0.77
40	1	2.87	0.04	0.04	3.48	0.38	0.57
40	3	3.08	0.04	0.11	3.62	0.29	0.30
40	5	3.19	0.04	0.18	3.68	0.24	0.19
40	10	3.35	0.04	0.37	3.76	0.17	0.08
40	15	3.42	0.04	0.55	3.81	0.15	0.04
40	20	3.46	0.04	0.74	3.84	0.14	0.03
-	**-**	**3.62 (average)**	**-**	**-**	**-**	**5.66 (sum)**	**8.67 (sum)**

Using Equation 4, R^2 is calculated as 1 – 5.66/8.67 = 0.347.

The next step is to maximise R^2 by iterating the master curve fitting parameters. This was done by using the Solver function in Microsoft Excel to change the variable cells containing the seed values for the master curve fitting parameters. The "GRG Nonlinear" solving method using central derivatives and without automatic scaling was used as shown in Figure A.1.

Figure A.1 – Microsoft Excel Solver parameters and options



Tables A.2 and A.3 are then replaced by the results as shown in Tables A.4 and A.5.

Table A.4 – Mix-specific flexural modulus final master curve fitting parameters (T_{ref} = 25°C)

Parameter	α	β	γ	δ	a	b
Final Value	2.579	-0.6292	-0.6704	1.742	$2.156\text{x}10^{-3}$	-0.1157

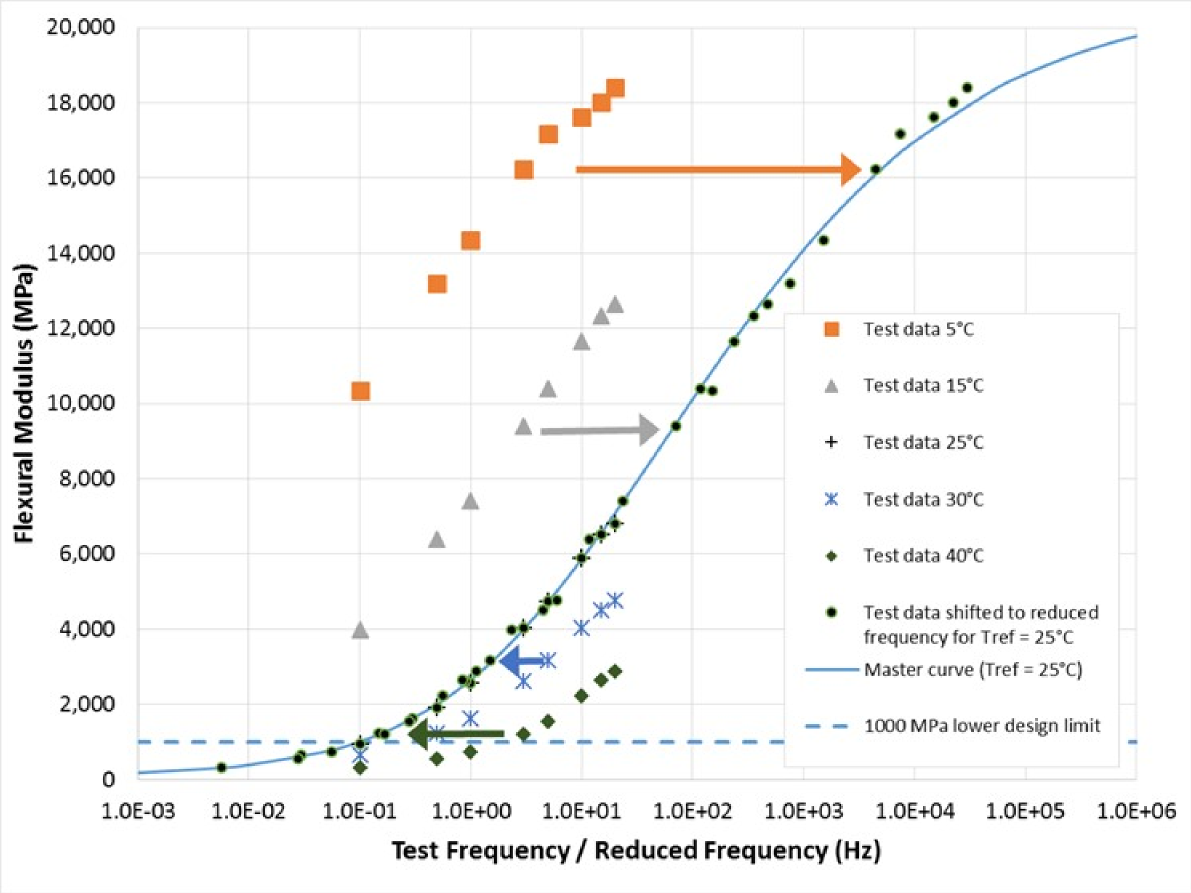
Table A.5 – Predicated $log_{10}|E^*|$ final master curve fitting parameters (T_{ref} =25ºC)

Test Temp. (T) (ºC)	Test Freq. (*f*) (Hz)	Test Result $\log_{10}|E^*|$ (Table A.1)	Temperature shift (a_T) (Eq. 3)	Reduced frequency (f_r) (Hz) (Eq. 2)	Predicted $\log_{10}|E^*|$ (Eq. 1)	$(y_i - z_i)^2$ (Eq. 4)	$(y_i - \overline{y})^2$ (Eq. 4)
5	0.1	4.01	1502.23	150.22	4.04	0.000	0.15
5	0.5	4.12	1502.23	751.12	4.13	0.000	0.25
5	1	4.16	1502.23	1502.23	4.17	0.000	0.28
5	3	4.21	1502.23	4506.70	4.21	0.000	0.34
5	5	4.23	1502.23	7511.17	4.22	0.000	0.37
5	10	4.25	1502.23	15022.34	4.24	0.000	0.39
5	15	4.26	1502.23	22533.52	4.25	0.000	0.40
5	20	4.26	1502.23	30044.69	4.25	0.000	0.41
15	0.1	3.60	23.59	2.36	3.56	0.001	0.00
15	0.5	3.81	23.59	11.80	3.79	0.000	0.03
15	1	3.87	23.59	23.59	3.87	0.000	0.06
15	3	3.97	23.59	70.78	3.98	0.000	0.12
15	5	4.02	23.59	117.96	4.02	0.000	0.15
15	10	4.07	23.59	235.92	4.07	0.000	0.19
15	15	4.09	23.59	353.88	4.09	0.000	0.22
15	20	4.10	23.59	471.84	4.11	0.000	0.23
25	0.1	2.97	1.00	0.10	3.00	0.001	0.43
25	0.5	3.28	1.00	0.50	3.30	0.000	0.12
25	1	3.41	1.00	1.00	3.42	0.000	0.05
25	3	3.61	1.00	3.00	3.60	0.000	0.00
25	5	3.68	1.00	5.00	3.68	0.000	0.00
25	10	3.77	1.00	10.00	3.77	0.000	0.02
25	15	3.81	1.00	15.00	3.82	0.000	0.04
25	20	3.83	1.00	20.00	3.85	0.000	0.04
30	0.1	2.82	0.30	0.03	2.78	0.001	0.65
30	0.5	3.09	0.30	0.15	3.08	0.000	0.29
30	1	3.21	0.30	0.30	3.21	0.000	0.17
30	3	3.42	0.30	0.90	3.41	0.000	0.04
30	5	3.50	0.30	1.49	3.49	0.000	0.02
30	10	3.60	0.30	2.99	3.60	0.000	0.00
30	15	3.65	0.30	4.48	3.66	0.000	0.00
30	20	3.68	0.30	5.98	3.70	0.000	0.00
40	0.1	2.51	0.06	0.01	2.50	0.000	1.23
40	0.5	2.75	0.06	0.03	2.77	0.001	0.77
40	1	2.87	0.06	0.06	2.90	0.001	0.57
40	3	3.08	0.06	0.17	3.10	0.001	0.30
40	5	3.19	0.06	0.28	3.20	0.000	0.19
40	10	3.35	0.06	0.56	3.32	0.001	0.08
40	15	3.42	0.06	0.84	3.39	0.001	0.04
40	20	3.46	0.06	1.12	3.44	0.000	0.03
-	**-**	**3.62 (average)**	**-**	**-**	**-**	**0.011 (sum)**	**8.67 (sum)**

Using Equation 4, R^2 for the final iteration is calculated as 1-0.011/8.67 = 0.999.

The master curve is defined by the parameters in Table A.4, in conjunction with Equation 1. These were used to draw the master curve for the AC20M(C600) mix, as shown in Figure A.2. Figure A.2 also shows the average flexural modulus test results at the five test temperatures, and the test data shifted to the reduced frequency (with T_{ref} = 25°C). Hence, Figure A.2 graphically illustrates the temperature shift (Equation 3) of the test data, and the fitting of the master curve (Equation 1) to the shifted data.

Figure A.2 - Mix-specific flexural modulus master curve for example AC20M(C600) at T_{ref} = 25°C



Appendix B – Example determination of design modulus from flexural modulus master curve

This appendix demonstrates the procedure for determining the design modulus from a flexural modulus master curve. The flexural modulus master curve constructed in Appendix A is used in this example. Table B.1 shows the design inputs for in-service air voids, temperature and heavy vehicle speed. The aim is to calculate the design modulus for an asphalt layer compacted to an in-service air voids content of 6.0%, for a design situation where the WMAPT is 32°C and the design heavy vehicle speed is 80 km/h. Calculations are shown in Table B.1.

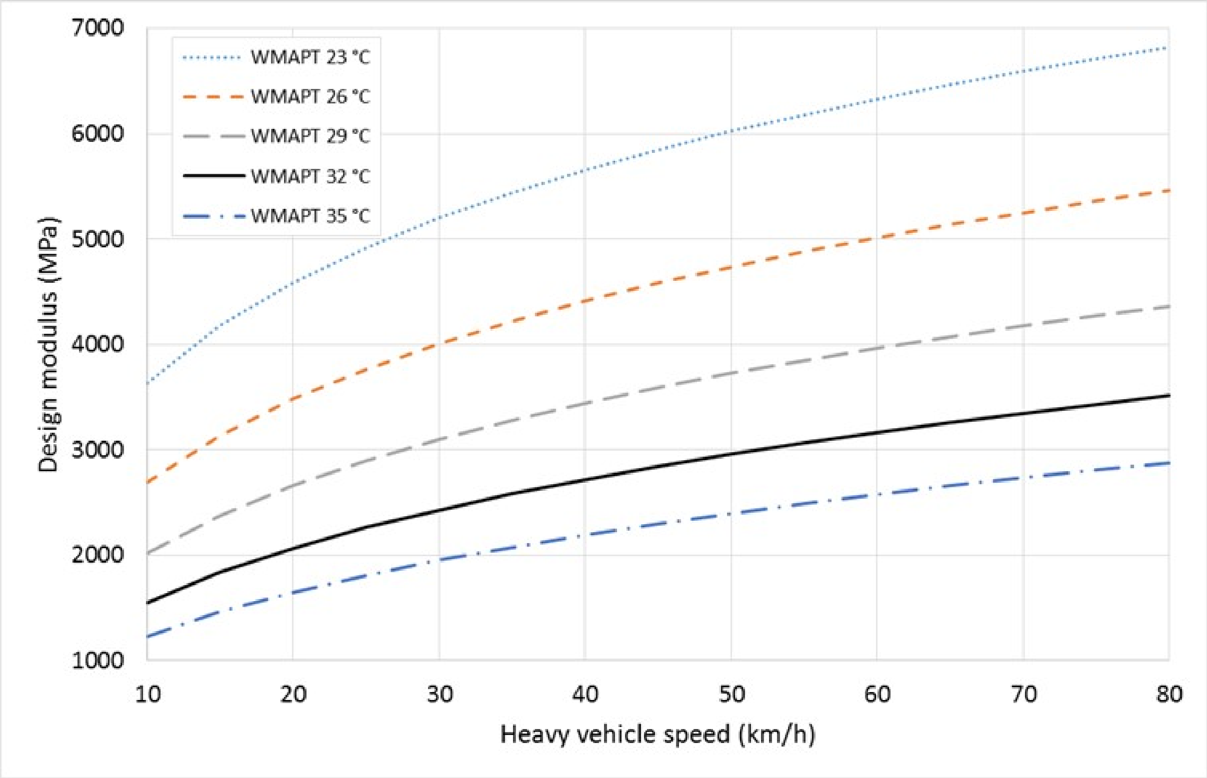
Table B.1 – Determination of design modulus

Step	Parameter	Reference	Value
Mix-specific flexural modulus master curve	Master curve coefficients	Table A.4	α = 2.579 β = -0.6292 γ = -0.6704 δ = 1.742 a = 2.156×10^{-3} b = -0.1157
	Master curve reference temperature (°C)	Table A.4	25
	Master curve reference air voids (%)	Appendix A	5.0
Design inputs	Design (in-service) air voids	Section 3.1	6.0
	Design temperature (WMAPT) (ºC)	-	32
	Design heavy vehicle speed (km/h)	-	80
Calculations	Temperature shift (a_T) at design temperature (ºC)	Equation 3	0.198
	Frequency at design heavy vehicle speed (Hz)	Equation 5	12.7
	Reduced frequency (f_r) at design temperature and design heavy vehicle speed (Hz)	Equation 2	2.515
	Flexural modulus (E*) at design temperature and design heavy vehicle speed (MPa)	Equation 1	3749
	Flexural modulus (E*) at design air voids, design temperature and design heavy vehicle speed (MPa)	Equation 6	3515
Result	**Design modulus (E_d) (MPa)**	Rounded to nearest 100 MPa	3500

For this example, the result shown in Table B.1 would be used in the pavement design calculations.

Further to the above example, by repeating the calculations in Table B.1, the mix-specific design modulus for the AC20M(C600) mix was also determined for other combinations of heavy vehicle speed and temperature. Results are shown in Figure B1.

Figure B.1 – Design modulus for various combinations of heavy vehicle speed and temperature



Appendix C – Example development of mix-specific fatigue relationship

This appendix illustrates the development of a mix-specific flexural fatigue relationship from flexural fatigue test data for the same example AC20M(C600) asphalt mix considered in Appendices A and B.

In this example, flexural fatigue testing (AGPT/T274) has been undertaken on 27 laboratory mixed and compacted asphalt specimens. The specimens were equally divided among three test temperatures (10°C, 20°C and 30°C) and three strain levels, and using a test frequency of 10 Hz for all tests. For each test, the laboratory number of cycles to failure (defined as when the modulus reduces to 50% of the modulus at the 50th load cycle) (N_{lab}) was an output of the test.

The test results are presented in Table C.1, together with the natural logarithm of N_{lab}.

A regression analysis was then undertaken. The fitting parameters in Equation 7 were determined by maximising the coefficient of determination (R^2) by correlating $\ln(N_{lab})$ calculated from the test results with $\ln(N_{lab})$ estimated using Equation 7. Seed values used for c_1 to c_5 were: 0.5, -10, 80, -150 and -6 respectively. The calculation process using the Solver function in Microsoft Excel was similar to that used in Appendix A for determining the master curve parameters (refer to Figure A.1).

In the calculation of the predicted $\ln(N_{lab})$, the moduli used in Equation 7 were determined using Equation 1, the master curve parameters from Table A.4 and the test frequency (10 Hz). The calculated moduli at the three test temperatures of 10°C, 20°C and 30°C were 14,827 MPa, 8,513 MPa and 3,983 MPa respectively.

Table C.1 also shows the predicted $\ln(N_{lab})$, and the calculation of the sum of squared residuals and the sum of squared deviations from the mean, which were used in Equation 4 to calculate R^2. The values shown are the resulting values after solving to maximise R^2.

Table C.1 – Flexural fatigue test results and predicted cycles to failure

Specimen	Test Temp. (T) (ºC)	Test strain amplitude ($\mu\varepsilon_{lab}$)	Lab number of cycles to failure (N_{lab})	Actual $\ln(N_{lab})$	Predicted $\ln(N_{lab})$ (Eq. 7)	$(y_i - z_i)^2$ (Eq. 4)	$(y_i - \bar{y})^2$ (Eq. 4)
1	10	130	1,127,940	13.9	14.1	0.039	2.72
2	10	130	2,199,483	14.6	14.1	0.222	5.37
3	10	130	1,240,735	14.0	14.1	0.010	3.05
4	10	180	281,429	12.5	12.5	0.002	0.07
5	10	180	201,021	12.2	12.5	0.083	0.01
6	10	180	408,072	12.9	12.5	0.177	0.40
7	10	280	57,992	11.0	10.3	0.473	1.74
8	10	280	19,330	9.9	10.3	0.169	5.84
9	10	280	15,465	9.6	10.3	0.402	6.96
10	20	170	504,219	13.1	13.6	0.202	0.71
11	20	170	1,232,537	14.0	13.6	0.197	3.02
12	20	170	784,342	13.6	13.6	0.000	1.66
13	20	200	236,754	12.4	12.8	0.152	0.01
14	20	200	184,668	12.1	12.8	0.407	0.03
15	20	200	497,184	13.1	12.8	0.124	0.69
16	20	300	27,607	10.2	10.7	0.253	4.24
17	20	300	138,034	11.8	10.7	1.225	0.20
18	20	300	49,692	10.8	10.7	0.007	2.17
19	30	200	1,945,031	14.5	14.6	0.021	4.82
20	30	200	1,264,271	14.1	14.6	0.332	3.11
21	30	200	4,862,575	15.4	14.6	0.594	9.68
22	30	380	64,794	11.1	11.4	0.105	1.46
23	30	380	143,842	11.9	11.4	0.224	0.17
24	30	380	90,711	11.4	11.4	0.000	0.76
25	30	450	34,380	10.4	10.6	0.012	3.39
26	30	450	26,446	10.2	10.6	0.138	4.42
27	30	450	50,248	10.8	10.6	0.073	2.13
-	**-**	**-**	**-**	**12.3 (average)**	**-**	**5.64 (sum)**	**68.8 (sum)**

Using Equation 4 (modified as per Section 4.1), R^2 for the final iteration is calculated as 1-5.64/68.8 = 0.918. Hence, the mix-specific fatigue relationship for pavement design is defined by the parameters in Table C.2 and Equation 8.

Table C.2 – Mix-specific flexural fatigue relationship fitting parameters

Parameter	c_1	c_2	c_3	c_4	c_5
Final Value	0.37663	-9.3728	75.086	-151.67	-5.0209

Appendix D – Improved method for considering multiple-axle group loads

D.1 Introduction

This appendix includes the procedure for the assessment of asphalt fatigue using critical strains under each axle in the traffic load distribution, as detailed in Section D.3. The procedure also requires amendments to the current procedure for assessment of loss of surface shape, as detailed in Section D.4. Associated changes to the method for calculation of pavement design traffic are provided in Section D.2.

A summary of changes to the damage units used in pavement design compared with the current Transport and Main Roads *Pavement Design Supplement* and AGPT02 procedure is provided in Table D.1.

Table D.1 – Comparison of damage units in new procedure with existing procedure

Type of Damage	Damage Unit	
	Existing Pavement Design Supplement / AGPT02	**New Procedure**
Fatigue of Asphalt	SAR5	HVAG[1]
Rutting and loss of surface shape	SAR7	ESA
Fatigue of cemented materials	SAR12	SAR12[2]
Unbound pavements – overall damage	ESA	ESA
Rigid pavements – fatigue and erosion	HVAG	HVAG[1]

1. Used in conjunction with the traffic load distribution.
2. Proposed to be replaced by HVAG in the future, as detailed in Section 6 of this technical note.

D.2 Pavement design traffic for assessment of asphalt fatigue

Pavement design traffic for the assessment of asphalt fatigue is defined by the following:

- Design number of heavy vehicle axle groups (N_{DT}), as defined in Section 7.4 of AGPT02, and
- Traffic load distribution, as defined in Section 7.5 of AGPT02.

From the above, the expected number of load repetitions in the design period is determined for each combination of axle group type and load level.

The new method no longer requires the calculation of SAR5 as used in the current AGPT02. Instead, the design number of heavy vehicle axle groups (N_{DT}) and the traffic load distribution are used to determine the number of expected repetitions of each axle group and load level combination in the design period.

The calculation of pavement design traffic is illustrated further in the design example in Appendix E.

D.3 Procedure for assessment of fatigue of asphalt

The procedure for assessment of asphalt fatigue damage is summarised as follows:

1. Select a candidate pavement structure and characterise all materials.

2. For each asphalt layer, determine critical tensile strains under each axle within each group in the traffic load distribution. This is done by first determining critical strains under the following single axle configurations:

   a. Single axle with single tyres (SAST)

   b. Single axle with dual tyres (SADT) (that is, the Standard Axle)

   These axle configurations are defined in Table D.2, with suggested x-coordinates for use in the mechanistic model to determine strains at the critical locations.

Table D.2 – Axle definitions for determination of critical strains

Axle Type	Axle Load (kN)	Tyre-Pavement Contact Stress (kPa)	Single Tyre Load Radius (mm)	Tyre Locations (x-coordinates) along Axle (mm)	Critical Strain Locations (x-coordinates) along Axle (mm)
Single axle with single tyres	53	800	102.4	0, 2130	0
Single axle with dual tyres (standard axle)	80	750	92.1	-165, 165, 1635, 1965	0, 165

As strains are linearly proportional to applied load in the linear-elastic model, the strains under axles in Table D.2 can be linearly scaled with load to determine strains for all axle loads in the traffic load distribution.

3. Using these strains, determine the allowable loading for each axle group and load combination in the traffic load distribution using either Equation D1 (modified Shell presumptive model) or Equation D2 (mix-specific model).

$$N_{ij} = \frac{1}{n} \times RF \left[\frac{6918(0.856V_b + 1.08)}{{E_d}^{0.36}\mu\varepsilon_{ij}}\right]^5 \qquad \text{D1}$$

$$N_{ij} = \frac{1}{n} \times RF \times EXP\left[c_1 \cdot ln^3(E_d) + c_2 \cdot ln^2(E_d) + c_3 \cdot ln(E_d) + c_4 + c_5 \cdot ln\left(\mu\varepsilon_{ij}\right)\right] \qquad \text{D2}$$

where:

N_{ij} = allowable number of repetitions of axle group *i* with total load equal to the *j^th^* load magnitude

n = number of individual axles within axle group *i* (for example, *n* = 2 for a tandem axle group)

RF = reliability factor for asphalt fatigue, as per AGPT02

V_b = percentage by volume of bitumen in the asphalt (%)

E_d = design flexural modulus as determined in Section 3 (MPa)

$\mu\varepsilon_{ij}$ = tensile strain at the bottom of the asphalt caused by a single axle from axle group *i*, with a load of the j^{th} load magnitude divided by *n* (µm/m)

$c_1 - c_5$ = regression coefficients determined from Equation 7

4. For each axle group and load combination in the traffic load distribution, determine the damage that will occur in the design period by dividing the expected loading repetitions of that combination (Section D.2) by the allowable loading repetitions for the combination (Step 3).
5. Sum the damage for all axle group types and load combinations in the traffic load distribution. If the sum is less than or equal to 1.0 for each asphalt layer, the candidate pavement structure is acceptable. If the sum is greater than 1.0 a new candidate pavement structure must be selected and the process repeated from Step 1.
6. If needed, the allowable loading for asphalt fatigue (in units of HVAG) can be determined by dividing the design number of heavy vehicle axle groups (N_{DT}) by the sum determined in Step 5. The allowable loading for asphalt fatigue (in units of ESA) can then be determined by multiplying the allowable loading in HVAG by the average number of ESA/HVAG determined from the traffic load distribution.

D.4 Procedure for assessment of loss of surface shape

The design traffic for assessment of loss of surface shape is now defined in units of ESA, which replaces SAR7 used in the current AGPT02. Therefore, the limiting subgrade strain criterion in Section 5.8 of AGPT02 is replaced with Equation D3.

The procedure for assessment of loss of surface shape is summarised as follows:

1. Calculate the design traffic in units of ESA by multiplying the design number of heavy vehicle axle groups (NDT) by the average number of ESA/HVAG determined from the traffic load distribution.
   The standard loads in Tables 7.5 and 7.6 of AGPT02, which are used in the calculation of ESA/HVAG, have been updated as shown in Table D.3 (Austroads, 2015). These updated standard loads should be used.

Table D.3 – Updated standard loads to replace AGPT02 tables 7.5 and 7.6

Axle Group Type	Standard Load (kN)
Single axle with single tyres (SAST)	53
Single axle with dual tyres (SADT)	80
Tandem axle with single tyres (TAST)	89
Tandem axle with dual tyres (TADT)	135
Triaxle with dual tyres (TRDT)	182
Quad-axle with dual tyres (QADT)	226

2. For the candidate pavement structure, estimate the compressive strain at the top of each subgrade and selected subgrade layer under an 80 kN single axle with dual tyres (i.e. the Standard Axle)
3. Using Equation D3, determine the allowable repetitions of the Standard Axle at each of the strain levels determined in Step 2

4. Compare the allowable repetitions (Step 2) to the design traffic (Step 1) in ESA. If the allowable repetitions is greater than or equal to the design traffic, the candidate pavement structure is acceptable. Otherwise a new candidate pavement structure must be selected and the process repeated from Step 2.

$$N = \left[\frac{9150}{\mu\varepsilon}\right]^7 \qquad \text{D3}$$

where:

$\mu\varepsilon$ = the vertical compressive strain (in microstrain), developed under a Standard Axle, at the top of the subgrade

N = the allowable number of repetitions of a Standard Axle at this strain before an unacceptable level of pavement surface deformation develops (units of ESA)

Appendix E – Example full depth asphalt pavement design

E.1 Introduction

This worked example demonstrates the design of a full depth asphalt pavement using the following:

- Presumptive design modulus for the asphalt surfacing and intermediate courses
- Mix-specific design modulus and mix-specific fatigue relationship for the base asphalt
- Improved method for considering multiple-axle group loads.

E.2 Design inputs

Design inputs are as listed in Tables E.1, E.2 and E.3.

Table E.1 – Design inputs

Parameter	Value
General pavement structure and materials	Table E.2
Annual average daily traffic (AADT)	70,000
Direction factor (DF)	0.5
Percentage of heavy vehicles (%HV)	10.0
Lane distribution factor (LDF)	0.65
Design period	30 years
Heavy vehicle growth rate	3%
Cumulative growth factor (CGF)	47.6
Reliability	95%
Weighted mean annual pavement temperature (WMAPT)	32°C
Heavy vehicle speed	80 km/h
Traffic load distribution	Table E.3

Table E.2 – General pavement structure

Course	Thickness (mm)	Description
Surfacing	50	SMA14 asphalt Presumptive master curve (25°C and in-service air voids): α = 15.3, β = 0.0, γ = -0.0958, δ = -4.700, a = 1.191x10^{-5}, b = -0.0951 (from Table 3.2)
Intermediate	50	AC14M(A5S) asphalt Presumptive master curve (25°C and in-service air voids): α = 15.3, β = 0.0, γ = -0.0958, δ = -4.633, a = 1.191x10^{-5}, b = -0.0951 (from Table 3.2)
Base	X	AC20M(C600) asphalt Mix-specific master curve (25°C and test air voids of 5%): α = 2.579, β = -0.6292, γ = -0.6704, δ = 1.742, a = 2.156x10^{-3}, b = -0.1157 (as determined in Appendix A) Mix-specific fatigue relationship: c_1 = 0.37663, c_2 = -9.3728, c_3 = 75.086, c_4 = -151.67, c_5 = -5.0209 (as determined in Appendix C)
Improved layer	150	Lightly bound granular (Type 2.3) material with a UCS of 1.0 to 2.0 MPa at 7 days
Select fill	170	Design CBR 10%
Existing subgrade	–	Design CBR 3%

Table E.3 – Traffic load distribution

Axle Group Load (kN)	Axle Group Type and Proportion (%)					
	SAST	**SADT**	**TAST**	**TADT**	**TRDT**	**QADT**
10	0.1	0.6				
20	3.7	3.6		0.4		
30	15.7	16.5	0.3	1.4	0.2	
40	12.4	18.7	1.4	2.6	0.4	
50	19.7	16.7	3.3	3.3	1.5	0.3
60	32.4	14.7	2.6	5.8	4.3	1.8
70	13.8	11.4	9.9	7.5	6.5	2.8
80	1.9	7.3	13.3	7.9	6.9	3.4
90	0.3	4.6	15.4	6.5	5.5	7.5
100		2.8	15.3	5.8	5.4	9.9
110		1.9	16.2	5.9	5.4	7.6
120		0.6	13.2	5.9	4.9	5.6
130		0.3	5.1	6.7	4.8	5.8
140		0.2	1.5	6.5	4.7	5.4
150		0.1	1.1	6.8	4.6	3.4
160			0.9	7.5	4.3	3.4
170			0.5	6.8	4.4	3.6
180				5.5	4.6	3.4
190				3.3	4.4	2.5
200				1.8	4.8	5.3
210				0.9	5.4	5.2
220				0.6	5.6	5.9
230				0.4	5.2	5.7
240				0.1	3.8	6.2
250				0.1	2.4	5.3
Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Proportion of each axle group (%)	**36.1**	**16.6**	**1.9**	**30.2**	**15.1**	**0.1**

E.3 Calculation of design traffic for asphalt fatigue assessment

Using Equation 14 from AGPT02, determine N_{DT} as follows:

$$N_{DT} = 365 \times AADT \times DF \times \%HV/100 \times LDF \times CGF \times N_{HVAG}$$

All inputs are known, except N_{HVAG} which was estimated from the traffic load distribution in Table E.3 as follows:

N_{HVAG} = 1/(proportion SAST + proportion TAST)

= 1/(0.361+0.019)

= 2.63 HVAG/HV

Therefore:

N_{DT} = 365 x 70,000 x 0.5 x 10.0/100 x 0.65 x 47.6 x 2.63

= 1.04 x 10^8 HVAG

The expected number of load repetitions in the design period for each combination of axle group type and load level was then determined by multiplying N_{DT} by the appropriate proportions from the traffic load distribution (Table E.3). For example, using N_{DT} and the highlighted values in Table E.3, the expected number of TADT at 180 kN is (1.04 x 10^8) x 30.2/100 x 5.5/100 = 1,727,440. This result is highlighted in Table E.4. Results for all combinations of axle group type and load level are also shown in Table E.4.

Table E.4 – Expected number of axle group loads in the design period

Axle Group Load (kN)	Expected Repetitions by Axle Group Type					
	SAST	SADT	TAST	TADT	TRDT	QADT
10	3.75E+04	1.04E+05				
20	1.39E+06	6.22E+05		1.26E+05		
30	5.89E+06	2.85E+06	5.93E+03	4.40E+05	3.14E+04	
40	4.66E+06	3.23E+06	2.77E+04	8.17E+05	6.28E+04	
50	7.40E+06	2.88E+06	6.52E+04	1.04E+06	2.36E+05	3.12E+02
60	1.22E+07	2.54E+06	5.14E+04	1.82E+06	6.75E+05	1.87E+03
70	5.18E+06	1.97E+06	1.96E+05	2.36E+06	1.02E+06	2.91E+03
80	7.13E+05	1.26E+06	2.63E+05	2.48E+06	1.08E+06	3.54E+03
90	1.13E+05	7.94E+05	3.04E+05	2.04E+06	8.64E+05	7.80E+03
100		4.83E+05	3.02E+05	1.82E+06	8.48E+05	1.03E+04
110		3.28E+05	3.20E+05	1.85E+06	8.48E+05	7.90E+03
120		1.04E+05	2.61E+05	1.85E+06	7.69E+05	5.82E+03
130		5.18E+04	1.01E+05	2.10E+06	7.54E+05	6.03E+03
140		3.45E+04	2.96E+04	2.04E+06	7.38E+05	5.62E+03
150		1.73E+04	2.17E+04	2.14E+06	7.22E+05	3.54E+03
160			1.78E+04	2.36E+06	6.75E+05	3.54E+03
170			9.88E+03	2.14E+06	6.91E+05	3.74E+03
180				1.73E+06	7.22E+05	3.54E+03
190				1.04E+06	6.91E+05	2.60E+03
200				5.65E+05	7.54E+05	5.51E+03
210				2.83E+05	8.48E+05	5.41E+03
220				1.88E+05	8.79E+05	6.14E+03
230				1.26E+05	8.17E+05	5.93E+03
240				3.14E+04	5.97E+05	6.45E+03
250				3.14E+04	3.77E+05	5.51E+03
Total (N_{DT})	**1.04×10^8**					

The calculation of design ESA is addressed in Section E.5.

E.4 Assessment of fatigue of asphalt

Step 1 – Select a candidate pavement structure and characterise all materials

The pavement structure is as shown in Table E.2.

A thickness of 230 mm (excludes construction tolerance) of AC20M(C600) is selected for the base course.

The design modulus for the AC20M(C600) mix was previously determined in Appendix B. Design modulus values for the asphalt surfacing and the intermediate course were determined from the master curve parameters provided in Table E.2. Calculations for these mixes are summarised in Table E.5.

Table E.5 – Asphalt design moduli for surfacing and intermediate course

Parameter	**Reference**	**Mix**	
		SMA14	**AC14M(A5S)**
Master curve coefficients	Table 2 / Table E.2	α = 15.3 β = 0.0 γ = -0.0958 δ = -4.700 a = 1.191x10^{-5} b = -0.0951	α = 15.3 β = 0.0 γ = -0.0958 δ = -4.633 a = 1.191x10^{-5} b = -0.0951
Master curve reference temperature (°C)	Table E.2	25	25
Master curve reference air voids (%)	Table E.2	5.0	6.0
Design (in-service) air voids	Section 3.1	5.0	6.0
Design temperature (WMAPT) (°C)	Table E.1	32	32
Design heavy vehicle speed (km/h)	Table E.1	80	80
Temperature shift (a_T)T) at design temperature (°C)	Equation 3	0.216	0.216
Frequency at design heavy vehicle speed (Hz)	Equation 5	12.7	12.7
Reduced frequency (f_r) at design temperature and design heavy vehicle speed (Hz)	Equation 2	2.753	2.753
Flexural modulus (E*) at design temperature and design heavy vehicle speed (MPa)	Equation 1	1292	1507
Flexural modulus (E*) at design air voids, design temperature and design heavy vehicle speed (MPa)	Equation 6	1292	1507
Design modulus (E_d) (MPa) (rounded to nearest 100 MPa)	-	**1300**	**1500**

Design inputs for the improved layer, selected fill and subgrade were as defined in the Transport and Main Roads *Pavement Design Supplement* and AGPT02.

Step 2- Determine critical tensile strains under each axle

In this example, asphalt fatigue was assessed for each asphalt type. However, only the calculations for the base asphalt are shown as this was the critical design layer.

Critical strains were calculated using CIRCLY, with results summarised in Table E.6.

Table E.6 – Summary of critical tensile microstrains at bottom of asphalt base

Axle Type	Axle Load (kN)	Tyre-Pavement Contact Stress (kPa)	Critical Tensile Microstrain
Single axle with single tyres	53	800	77.8
Single axle with dual tyres (Standard Axle)	80	750	106.1

The critical tensile microstrains under each axle in the traffic load distribution were determined by linearly scaling the values in Table E.6. For example, for the TADT at 180 kN, the strain was determined as follows:

- As the TADT group comprises two axles, the load on each axle is 180/2 = 90 kN.
- The microstrain under each 90 kN single axle (with dual tyres) was then determined using the value from Table E.6, as follows: 90/80 x 106.1 = 119.4. This value is highlighted in Table E.7.
- This calculation was repeated for all axle groups and load levels to complete Table E.7.

Table E.7 – Critical microstrain under each individual axle

Axle Group Load (kN)	Critical Microstrain under each Individual Axle (determined by linearly scaling Table E.6 values)					
	SAST	**SADT**	**TAST**	**TADT**	**TRDT**	**QADT**
10	14.7	13.3				
20	29.4	26.5		13.3		
30	44.0	39.8	22.0	19.9	13.3	
40	58.7	53.1	29.4	26.5	17.7	
50	73.4	66.3	36.7	33.2	22.1	16.6
60	88.1	79.6	44.0	39.8	26.5	19.9
70	102.8	92.9	51.4	46.4	31.0	23.2
80	117.5	106.1	58.7	53.1	35.4	26.5
90	132.1	119.4	66.1	59.7	39.8	29.8
100		132.7	73.4	66.3	44.2	33.2
110		145.9	80.8	73.0	48.6	36.5
120		159.2	88.1	79.6	53.1	39.8
130		172.4	95.4	86.2	57.5	43.1
140		185.7	102.8	92.9	61.9	46.4
150		199.0	110.1	99.5	66.3	49.7
160			117.5	106.1	70.7	53.1
170			124.8	112.8	75.2	56.4
180				119.4	79.6	59.7
190				126.0	84.0	63.0
200				132.7	88.4	66.3
210				139.3	92.9	69.6
220				145.9	97.3	73.0
230				152.5	101.7	76.3
240				159.2	106.1	79.6
250				165.8	110.5	82.9

Step 3 – Determine the allowable load repetitions

For the strains determined in step 2, the allowable loading (*Nij*) for each axle group and load combination was determined using Equation D2 and the mix-specific regression coefficients from Table C.2. For example, the allowable loading for SADT at 180 kN was determined as follows:

$N_{ij} = \frac{1}{2} \times 1.0 \times EXP[0.37663 \cdot ln^3(3500) - 9.3728 \cdot ln^2(3500) + 75.086 \cdot ln(3500) - 151.67 - 5.0209 \cdot ln(119.4)] = 2.12 \times 10^7$ (in units of axle group load repetitions)

This calculation was repeated for all axle group type and load combinations to complete Table E.8.

Table E.8 – Allowable load repetitions for each axle group and load combination

Axle Group Load (kN)	Allowable Axle Group Load Repetitions					
	SAST	SADT	TAST	TADT	TRDT	QADT
10	1.57E+12	2.62E+12				
20	4.85E+10	8.07E+10		1.31E+12		
30	6.33E+09	1.05E+10	1.03E+11	1.71E+11	8.74E+11	
40	1.49E+09	2.49E+09	2.42E+10	4.04E+10	2.06E+11	
50	4.87E+08	8.11E+08	7.91E+09	1.32E+10	6.72E+10	2.14E+11
60	1.95E+08	3.25E+08	3.17E+09	5.27E+09	2.69E+10	8.56E+10
70	8.99E+07	1.50E+08	1.46E+09	2.43E+09	1.24E+10	3.95E+10
80	4.60E+07	7.66E+07	7.47E+08	1.24E+09	6.35E+09	2.02E+10
90	2.55E+07	4.24E+07	4.13E+08	6.88E+08	3.51E+09	1.12E+10
100		2.50E+07	2.44E+08	4.06E+08	2.07E+09	6.58E+09
110		1.55E+07	1.51E+08	2.51E+08	1.28E+09	4.08E+09
120		1.00E+07	9.75E+07	1.62E+08	8.29E+08	2.64E+09
130		6.69E+06	6.52E+07	1.09E+08	5.55E+08	1.76E+09
140		4.61E+06	4.50E+07	7.49E+07	3.82E+08	1.22E+09
150		3.26E+06	3.18E+07	5.30E+07	2.70E+08	8.60E+08
160			2.30E+07	3.83E+07	1.96E+08	6.22E+08
170			1.70E+07	2.82E+07	1.44E+08	4.59E+08
180				2.12E+07	1.08E+08	3.44E+08
190				1.62E+07	8.25E+07	2.62E+08
200				1.25E+07	6.38E+07	2.03E+08
210				9.78E+06	4.99E+07	1.59E+08
220				7.74E+06	3.95E+07	1.26E+08
230				6.19E+06	3.16E+07	1.01E+08
240				5.00E+06	2.55E+07	8.12E+07
250				4.07E+06	2.08E+07	6.61E+07

Step 4 – Determine the damage for each axle group and load combination

The damage for each axle group and load combination that will occur in the design period was calculated by dividing the expected load repetitions of that combination (Table E.4) by the allowable load repetitions for the combination (Table E.8).

For example, for the TADT at 180 kN, the expected load repetitions is 1.73×10^6, and the allowable load repetitions is 2.12×10^7. The damage for this combination is $1.73 \times 10^6 / 2.12 \times 10^7$, which equals 0.081 as highlighted in Table E.9.

The results for all axle group types and load combinations are also shown in Table E.9.

Table E.9 – Asphalt fatigue damage for each axle group and load combination

Axle Group Load (kN)	Asphalt Fatigue Damage					
	SAST	SADT	TAST	TADT	TRDT	QADT
10	0.000	0.000				
20	0.000	0.000		0.000		
30	0.001	0.000	0.000	0.000	0.000	
40	0.003	0.001	0.000	0.000	0.000	
50	0.015	0.004	0.000	0.000	0.000	0.000
60	0.062	0.008	0.000	0.000	0.000	0.000
70	0.058	0.013	0.000	0.001	0.000	0.000
80	0.016	0.016	0.000	0.002	0.000	0.000
90	0.004	0.019	0.001	0.003	0.000	0.000
100		0.019	0.001	0.004	0.000	0.000
110		0.021	0.002	0.007	0.001	0.000
120		0.010	0.003	0.011	0.001	0.000
130		0.008	0.002	0.019	0.001	0.000
140		0.007	0.001	0.027	0.002	0.000
150		0.005	0.001	0.040	0.003	0.000
160			0.001	0.062	0.003	0.000
170			0.001	0.076	0.005	0.000
180				0.081	0.007	0.000
190				0.064	0.008	0.000
200				0.045	0.012	0.000
210				0.029	0.017	0.000
220				0.024	0.022	0.000
230				0.020	0.026	0.000
240				0.006	0.023	0.000
250				0.008	0.018	0.000
TOTAL	**0.99**					

Step 5 – Sum the damage for all axle group types and load combinations.

The total asphalt fatigue damage for the base asphalt is 0.99, as shown in Table E.9. As the damage is less than 1.0, the candidate pavement structure is acceptable.

Step 6 - Determine the allowable loading for asphalt fatigue in HVAG and ESA

In this example, the allowable loading for asphalt fatigue (in units of HVAG) was determined by dividing the design number of heavy vehicle axle groups (N_{DT}) by the total damage determined in Step 5.

Therefore, the allowable loading is $(1.04 \times 10^8)/ 0.99 = 1.05 \times 10^8$ HVAG.

The allowable loading for asphalt fatigue in units of ESA was then determined by multiplying the allowable loading in HVAG by the average number of ESA/HVAG (Table E.10).

Therefore, the allowable loading is (1.05×10^8) x 1.08 = 1.13×10^8 ESA.

E.5 Assessment of loss of surface shape

Step 1 – Calculated the design traffic in units of ESA

The design traffic in units of HVAG (N_{DT}) was determined in Section E.3 to be 1.04×10^8 HVAG.

This was converted to units of ESA for assessment of loss of surface shape, as follows:

$DESA = ESA/HVAG \times N_{DT}$

N_{DT} has already been determined in Section E.3.

ESA/HVAG was calculated from the traffic load distribution and using Equation 16 from AGPT02. For each combination of load level and axle group type, the following calculation was undertaken. By way of example, the calculation is shown for tandem axles with dual tyres (TADT) with an axle load (L_{ij}) of 180 kN, and a standard load (SL_i) of 135 kN from Table D3.

$ESA_{ij} = (L_{ij}/SL_i)^4$

$= (180/135)^4$

$= 3.16$ ESA

This result is weighted according to the proportion of TADT and proportion of TADT at 180 kN, as follows:

Weighted ESA_{ij} = 3.16 x proportion of TADT x proportion of TADT at 180 kN

= 3.16 x 30.2/100 x 5.5/100

= 0.0525 (as highlighted in Table E.10)

This calculation was repeated for all combinations of load level and axle group type, then the average ESA/HVAG was calculated as the sum of all weighted ESA_{ij} values. The results from this calculation are shown in Table E.10.

Table E.10 – Calculation of average ESA/HVAG

Axle Group Load (kN)	Weighted ESA_{ij}					
	SAST	**SADT**	**TAST**	**TADT**	**TRDT**	**QADT**
10	0.0000	0.0000				
20	0.0003	0.0000		0.0000		
30	0.0058	0.0005	0.0000	0.0000	0.0000	
40	0.0145	0.0019	0.0000	0.0001	0.0000	
50	0.0563	0.0042	0.0001	0.0002	0.0000	0.0000
60	0.1921	0.0077	0.0001	0.0007	0.0001	0.0000
70	0.1516	0.0111	0.0007	0.0016	0.0002	0.0000
80	0.0356	0.0121	0.0016	0.0029	0.0004	0.0000
90	0.0090	0.0122	0.0031	0.0039	0.0005	0.0000
100		0.0113	0.0046	0.0053	0.0007	0.0000
110		0.0113	0.0072	0.0079	0.0011	0.0000
120		0.0050	0.0083	0.0111	0.0014	0.0000
130		0.0035	0.0044	0.0174	0.0019	0.0000
140		0.0031	0.0017	0.0227	0.0025	0.0000
150		0.0021	0.0017	0.0313	0.0032	0.0000
160			0.0018	0.0447	0.0039	0.0000
170			0.0013	0.0516	0.0051	0.0000
180				0.0525	0.0066	0.0000
190				0.0391	0.0079	0.0000
200				0.0262	0.0106	0.0000
210				0.0159	0.0145	0.0000
220				0.0128	0.0181	0.0001
230				0.0102	0.0200	0.0001
240				0.0030	0.0174	0.0001
250				0.0036	0.0129	0.0001
Total	**0.4653**	**0.0862**	**0.0366**	**0.3646**	**0.1288**	**0.0004**
ESA/HVAG (Sum)	**1.08**					

DESA was then calculated as follows:

$$\text{DESA} = \text{ESA/HVAG} \times N_{DT}$$

$$= 1.08 \times (1.04 \times 10^8)$$

$$= 1.13 \times 10^8 \text{ ESA}$$

Step 2 – Critical subgrade strains

For the candidate pavement structure, the compressive strain under the 80 kN Standard Axle was determined to be 212.8 microstrain at the top of the selected subgrade, and 298.6 at the top of the existing in situ subgrade material. The larger of these two strains is the critical strain and is used in subsequent calculations.

Step 3 – Determine the allowable loading for loss of surface shape

Using Equation D3, the allowable repetitions (N) in units of ESA is $(9150/298.6)^7 = 2.54\text{x}10^{10}$ ESA.

Step 4 – Compare the allowable repetitions to the design traffic

The allowable repetitions is greater than the design traffic, hence the pavement structure is acceptable in relation to loss of surface shape.

E.6 Construction tolerance

To complete the design, a construction tolerance of 10 mm was added to the design base thickness. Hence the final base thickness (X in Table E.2) is 240 mm.

E.7 Comparison of result with existing design procedures

The new design procedure documented in this technical note permits up to 10% reduction in total asphalt thickness attributable to the use of the mix-specific modulus and mix-specific fatigue relationship, when compared to the result using the presumptive modulus and modified Shell presumptive relationship (as detailed in Section 4.1).

Therefore, the thickness required using the presumptive modulus and modified Shell presumptive model (Equation D1) was also determined by repeating steps 3 to 5 in Section E.4.

It was determined that the pavement base thickness needs to be increased to 255 mm (excluding construction tolerance) if the presumptive modulus and presumptive fatigue relationship are used. Hence, in this example an asphalt thickness reduction of 255-230 = 25 mm was achieved by the use of the mix-specific modulus and mix-specific fatigue relationship. This equates to a 7% reduction in total asphalt thickness, and is less than the permitted maximum reduction in thickness of 10% (35 mm) specified in Section 4.1, so the proposed pavement design is acceptable in accordance with this technical note.

For information purposes only, a comparison of the result was also made with existing procedures, as defined in the Transport and Main Roads *Pavement Design Supplement* and AGPT02, including use of the presumptive modulus and binder volume for the asphalt base, presumptive asphalt fatigue relationship and calculation of critical strains under a standard axle. In this case, the required base asphalt thickness is 285 mm (excluding construction tolerance). Hence, it can be concluded that the new procedures in this technical note lead to a total asphalt thickness reduction of 55 mm (14% of total asphalt thickness of 385 mm) for this example. Approximately half of this reduction is attributable to the improved method for considering multiple-axle group loads, while the other half is attributable to the use of the mix-specific modulus and mix-specific fatigue relationship.