Review of the AG/PT-233 fatigue test protocol and its link to structural pavement design

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Abstract

A reliable and robust fatigue characterisation method is a key component of performance based asphalt mix design. This paper reviews the procedures in Austroads AG/PT-233 four point bending test method for fatigue, based on a comparison to international test methods. Experiments are performed to compare material behaviour in the four point bending test under haversine and sinusoidal displacement controlled loading. The findings indicate that haversine displacement control testing using the AG/PT-233 protocol in effect results in a sinusoidal strain response of half the intended amplitude. This is an important consideration when comparing the results of AG/PT-233 testing to the asphalt fatigue equations in the Austroads Guide to Pavement Technology, which were developed based on sinusoidal testing. The paper further demonstrates the use of the four point bending beam equipment in the construction of complex modulus master curves.

Introduction

There is an international trend towards the introduction of performance based design and specification of asphalt mixes. The driver behind performance based specifications is the notion that asphalt mixes should be evaluated based on criteria that can be directly related to the performance of the mix under loading and environmental conditions representative of the field. Performance related specifications are typically less prescriptive with regard to the composition of the mix than conventional specifications, which reduces barriers to innovation and promotes efficient use of natural resources. Another advantage of the use of performance related specifications is that it allows a more direct link between the mix design process and asphalt pavement design. A key component of a successful performance-related specification for asphalt is a reliable and robust fatigue characterisation method. Some mechanistic empirical design methods allow the direct input of laboratory fatigue relationships developed for specific mix designs as input for the pavement design process.

The fatigue test procedure used within the Austroads Guide to Pavement Technology framework (Austroads, 2012) as well as in wider Australian practice, is Austroads method AG:PT/T233-2006. This test method uses a continuous haversine displacement load applied at a frequency of 10 Hz in four point bending configuration. Currently, the Austroads Guide does not provide guidance on how to use the results from the AG:PT/T233-2006 fatigue test directly as input for structural pavement design. The Guide uses models originating from the Shell Pavement Design Manual (Shell, 1978) to predict the fatigue performance of asphalt pavements. Practitioners have reported that the Shell fatigue prediction models underestimate the fatigue life of asphalt mixes when tested in accordance to the AG:PT/T233 (Saleh, 2012).There are however considerable challenges in comparing the results from the AG:PT/T233 to the models of the Shell Manual. One of the challenges is that the Shell equations were developed based on testing in two and three point bending configuration using a sinusoidal displacement load shape (Van Dijk & Visser, 1977), whereas the AG:PT/T233 uses a haversine displacement load shape in four point bending configuration. It is important to understand the differences in the configurations of the various fatigue test methods, to select a fatigue test that best complements the structural pavement design procedures in the Austroads Guide.

The objective of this paper is to critically review the procedures in the current Austroads AG/PT-233 fatigue test method and compare them to international best practice. A further aim is to identify opportunities for improvements to the fatigue test method to achieve better integration with the pavement design guide. Finally, this paper will seek to demonstrate the use of the four point bending equipment available in Australia for the construction of complex modulus master curves for asphalt.

This introductory section is followed by a discussion on the differences between the four point bending fatigue test procedures in the Australian AG:PT/T233-2006, the European EN 12697-24, and the American ASTM D7460-10 and AASHTO T321-07 test methods. Experiments were performed as part of this study to compare the material response under sinusoidal and haversine displacement loading. Further experiments were performed to demonstrate the use of the four point bending equipment to construct a modulus master curve in accordance with the EN 12697-26 standard. Finally, conclusions and recommendations are presented.

Comparison of standard fatigue test methods

According to the commentary in AG:PT/T233-2006, the method is based on SHRP method M-009 developed at the University of California Berkeley. This method was a predecessor to both AASHTO T 321-07 and ASTM D7460-10. The AG:PT/T233-2006 is therefore broadly in line with American fatigue test practices. In this section, the main differences between European, American and Australian four point bending fatigue test methods are discussed.

Load conditions

Four point bending fatigue tests are run either in constant stress mode or in constant displacement mode. Over time, the constant displacement test, better known as the constant strain test, has become the dominant mode of testing. The AG:PT/T233, AASHTO T 321-07 and the ASTM D7460-10 all use a haversine shape for the displacement controlled test. The sample is loaded until the desired maximum displacement is reached. Once the peak displacement is reached, the sample is forced back into its original position. Figure 1 shows an example of a haversine displacement pulse with a resulting 400 µm/m strain amplitude at a load frequency of 10 Hz. The maximum strain level is achieved at one side of the beam only. It can be readily understood how this strain shape is intended to simulate the deflection of an asphalt pavement and the resulting fatigue damage accumulation in the pavement.

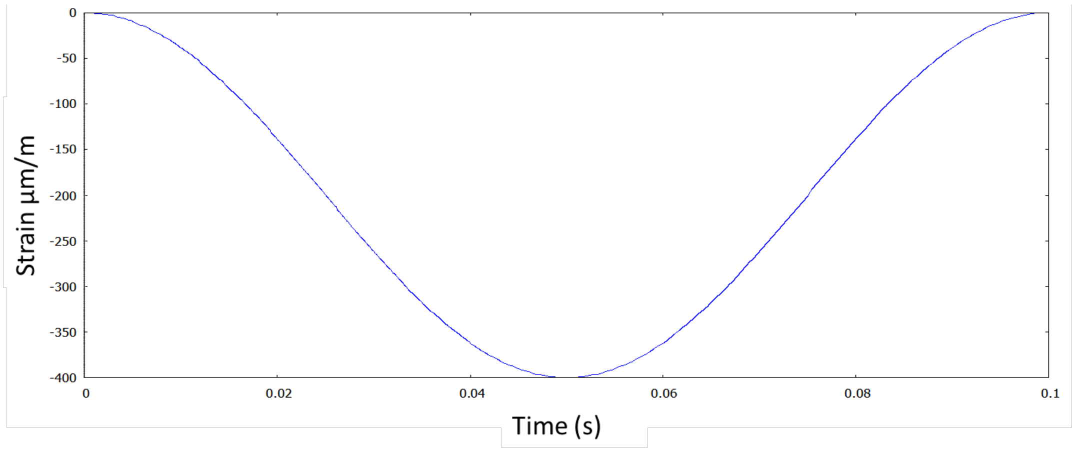

Figure 1: Haversine displacement pulse with amplitude of 400 µm/m and load frequency of 10 Hz

In the development of the Shell Pavement Design Manual, tests were performed using a sinusoidal displacement controlled load shape (Van Dijk & Visser, 1977). The current European test method EN 12697-24 also makes use of this load shape for four point bending testing. Figure 2 shows an example of a sinusoidal displacement pulse resulting in a 400 µm/m strain amplitude at a load frequency of 10 Hz. With sinusoidal loading, the 400 µm/m strain level is achieved on opposite sides of the beam.

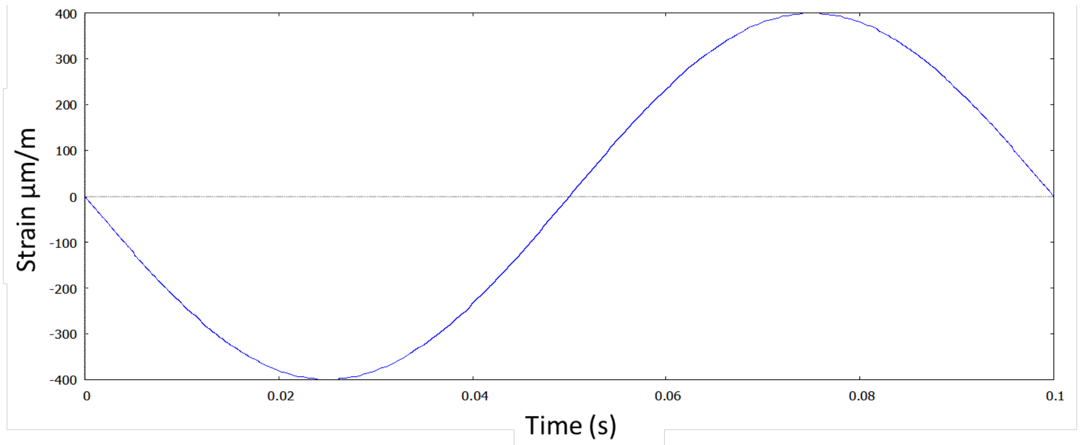

Figure 2: Sine load pulse with amplitude of 400 µm/m and load frequency of 10 Hz

Recently, evidence has surfaced that suggests that the haversine loading shape in effect turns into a sine load shape during the test. Pronk et al. (2010) have shown that it is not possible to induce a constant haversine strain response in the conventional four point bending fatigue test configuration. The phenomenon of the haversine load wave transforming into a sinusoidal wave had been reported earlier by practitioners, including in Australia (e.g.: Potter, 1997). However, the consequences of this behaviour are now being more fully understood.

Early in the test (within the first couple of load cycles), the beam deforms under the haversine load pulse. Due to the deformation, the haversine displacement pulse starts to induce a sinusoidal load response. In effect, the beam is subjected to a sinusoidal strain pulse of half the intended haversine strain amplitude (Pronk et al, 2010, Mateos et al, 2011). The resulting strain levels in a beam subjected to 400 µm/m strain loading are shown in Figure 3, the effective sinusoidal strain level in the beam is 200 µm/m. As a consequence, the fatigue life of specimens tested at 400 µm/m haversine loading should be equivalent to the fatigue life of specimens tested at 200 µm/m sinusoidal loading. This will be verified for AG:PT/T233 in the experimental part of this paper. The difference in effective strain level is a key factor to take into consideration when comparing the results of the AG:PT/T233 test (haversine) to the fatigue models in the Austroads Guide (developed based on sinusoidal tests).

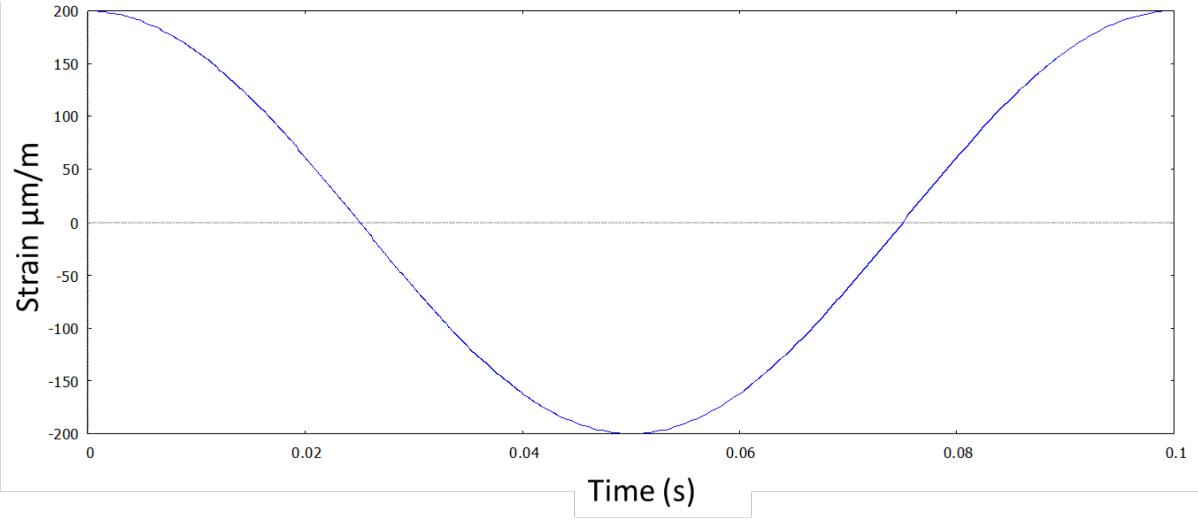

Figure 3: Resulting strain in specimen subjected to 400 µm/m haversine loading

Temperature conditions

Ideally, performance related tests should be run at a temperature representative of the field conditions. Fatigue tests are typically run at a standard temperature of 20 °C however. This is the case for AG:PT/T233, AASHTO T321-07 and EN 12697-24 (as specified in EN 13108-20). According to the ASTM D7460 standard, the fatigue test should be performed at the critical temperature (T_{eff}) for the pavement. It further states that for most of the US, T_{eff} will be around 20°C. ASTM D7460 provides a method to calculate T_{eff} from the mean annual pavement temperature (MAPT) as shown in Equation 1 and 2.

$$T_{eff\ Fatigue} = 0.8(MAPT) - 2.7 \quad (1)$$

$$MAPT = T_{20} = T_{air} - 0.00618(lat^2) + 0.289(lat) + 42.2(0.9545) - 17.78 \quad (2)$$

where

T_{20} = pavement temperature at 20 mm depth (°C)

T_{air} = mean annual air temperature (°C),

Lat = latitude of project location (degrees)

This equation is not valid for use in Australia, for example calculation of the MAPT in Brisbane will result in 46°C, while in reality the MAPT in Brisbane at a depth of 20 mm is approximately 27 °C (Austroads 2013). The identification of the critical temperature for fatigue damage accumulation in

Australian asphalt pavements is a topic that needs to be addressed. More research is needed to determine whether 20 °C is the most suitable temperature to characterise fatigue in pavements in all climatic regions of Australia.

Number of specimens

Fatigue test results are known for the high degree of inherent scatter. It is therefore critical to test sufficient samples to obtain a reliable estimate of the mean result. According to the standard test procedure in the AG:PT/T233 protocol 3 replicates are tested at a single strain level of 400 μm/m. The notes in the AG:PT/T233 document do state that for the full characterisation of fatigue performance of asphalt at least 9 specimens should be tested divided over at least 3 different strain levels. The ASTM D7460 requires at least 6 specimens to be tested at different strain levels to characterise the relationship between strain level and fatigue life. The EN 12697-24 test method requires a minimum of 18 specimens to be tested. The specimens should be tested divided over at least three different strain levels. At the highest strain level, the number of load cycles to 50% stiffness reduction should be at least 10^4, at the lowest strain level, the number of load cycles to failure should exceed 10^6. The European test method is aimed at determining, through interpolation, the strain level (ε^6) at which the number of cycles to failure is equal to 10^6 as well as the statistical confidence limits of the fatigue relation plotted through the data points.

Dissipated energy

Apart from the number of load cycles to 50% stiffness reduction, the energy dissipated in each load cycle is also often calculated as part of fatigue testing. The method to calculate the dissipated energy is not well defined in the current version of AG:PT/T233 however. It is explained only as 'the a*rea within the hysteresis loop formed from a plot of peak tensile stress versus peak tensile strain'* and is expressed in kPa, where other test methods typically express the energy in J/m^3. The table in Appendix A of this paper compares the calculation steps applied in the calculation of the dissipated energy in AG:PT/T233 to those in AASHTO T321-07. It is proposed that the description of the calculation of the dissipated energy in the AG:PT/T233 could be improved.

Experimental work

A limited number of laboratory experiments were performed at ARRB in Vermont South to explore the differences between four point bending fatigue tests using the sine and haversine load shapes. Sets of asphalt beams were tested using the AG:PT/T233 and EN 12697-24 test protocols. To demonstrate the construction of flexural complex modulus master curves using the four point bending equipment, temperature and frequency sweep testing was performed on a set of beams in accordance with EN 12697-26.

Fatigue tests

Figure 4 shows the load response of a beam subjected to haversine displacement loading of 400 μm/m using the AG:PT/T233 protocol. At the start of the test, the load cell reading was close to 0.0 kN. As can be observed in the figure, after 10 cycles the upward force is already similar to the downward force and it remains this way throughout the test. This is a strong indication that the standard 400 με haversine test used in Australia as part of asphalt mix design is in reality a 200 με sinusoidal test.

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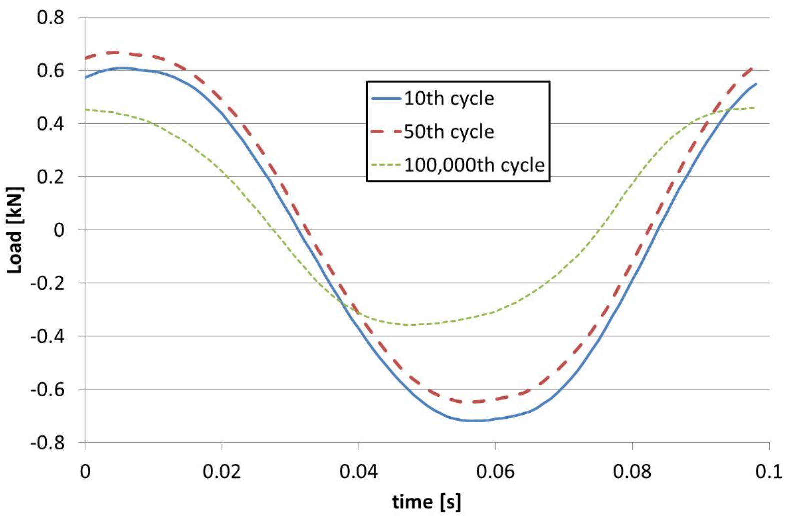

Figure 4: Recorded load response of specimen subjected to 400 µm/m haversine loading

Figure 5 shows the number of cycles to 50% stiffness reduction (N_{f50}) for fatigue testing according to the AG:PT/T233 and EN 12697-24. Sets of three beams were tested at 800, 400 and 200 µm/m strain levels using the AG:PT/T233 protocol. Tests were performed at 400, 200 and 100 µm/m strain levels using the EN 12697-24 method. Linear regression lines are plotted through the results using the procedure in EN 12697-24 shown in Equation 3.

$$\ln\left(N_{f50}\right) = A_0 + A_1 \times \ln\left(\varepsilon_t\right) \tag{3}$$

Where

A_0, A_1 = regression coefficients

ε_t = strain amplitude

The results in Figure 5 confirm that tests at a given strain level in the AG:PT/T233 haversine loading result in a similar N_{f50} as tests at half that strain in the European sinusoidal test configuration. In fact, if the AG:PT/T233 results are shifted vertically to half the strain level, the fatigue lines overlap as shown in Figure 6.

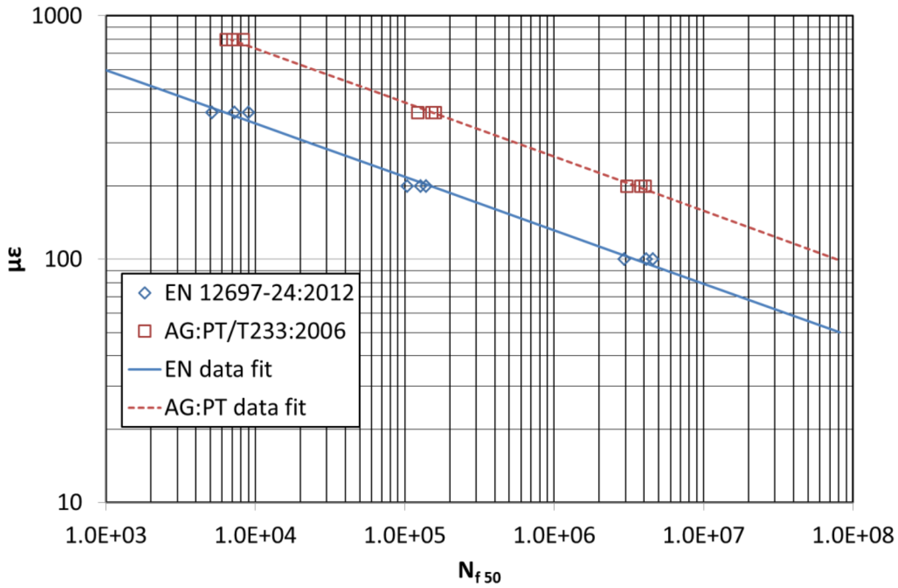

Figure 5: Results of fatigue tests run in accordance with AG:PT/T233 and EN 12697-24

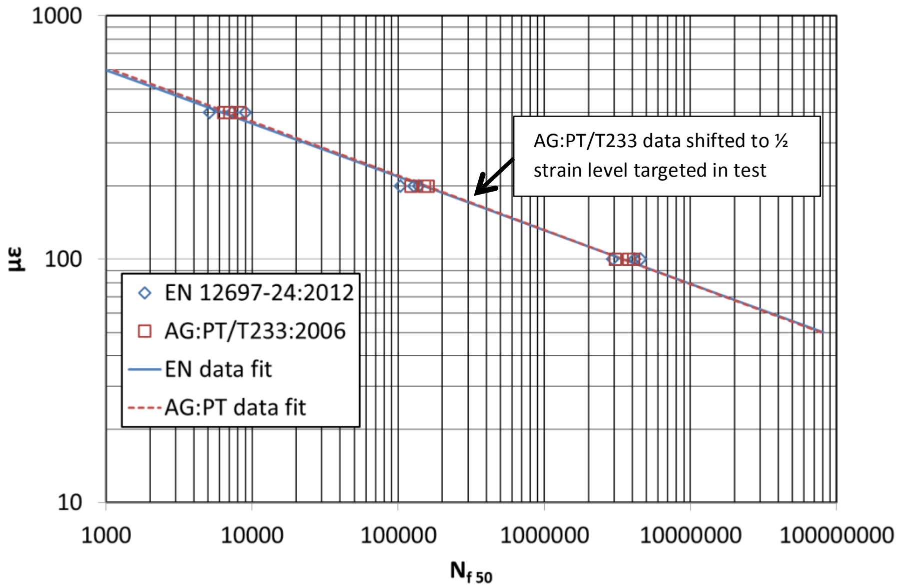

Figure 6: AG:PT/T233 results shifted to half the strain value

Modulus tests

The four point bending equipment used for fatigue testing in Australia can also be employed to construct complex modulus master curves. Master curves can be used to estimate the modulus of an asphalt at any combination of loading speed and temperature and therefore provide valuable input to the pavement design process. Apart from the fact that the required equipment is available in Australian laboratories, an additional advantage of using the four point bending configuration to construct master curves is that the modulus data is directly compatible with the current Austroads structural pavement design procedures.

EN 12697-26 contains detailed instructions for developing asphalt modulus master curves using four point bending equipment. For the purpose of this paper only a general summary is provided. To construct a master curve, flexural tests at a low strain level (typically 50 µm/m) are run at different load frequencies and temperatures. For this study a set of five specimens was tested at 0 °C, 10 °C, 20 °C, 30 °C and 40 °C. A frequency sweep was performed at each temperature using the following range of frequencies: 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz and 20 Hz. The average results of the temperature and frequency sweep for the five specimens are shown in Figure 7. The master curve is constructed by shifting the results using a temperature shift factor to form a single continuous function at a reference temperature (20°C in Figure 7). Once the master curve is developed, the modulus at any point of interest can be calculated; the process is typically automated through the use of software. In the example of Figure 7, the master curve is used to interpolate the modulus at 25 °C and 10 Hz, resulting in an estimate of 4995 MPa.

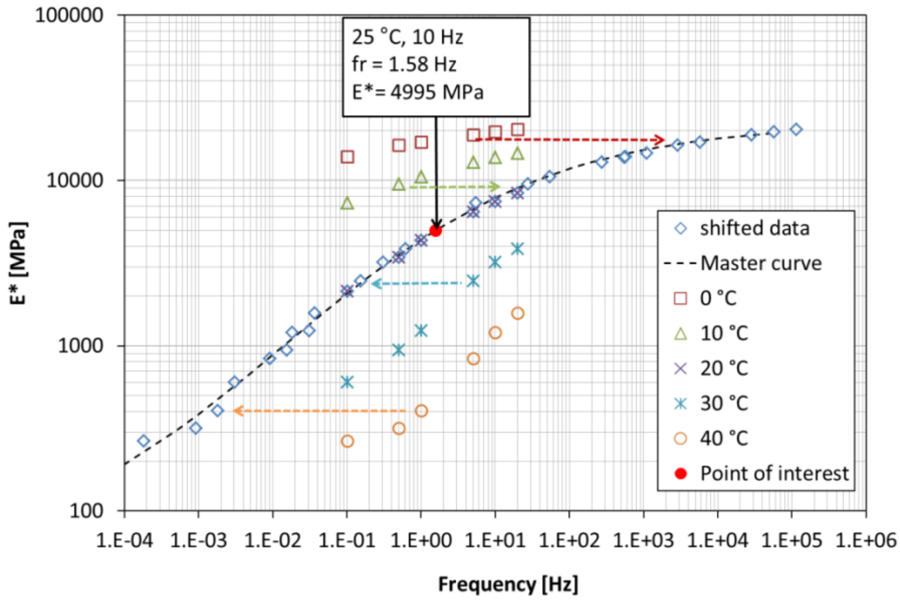

Figure 7: Complex modulus master curve based on flexural testing

Conclusions and recommendations

The objective of this paper was to critically review the procedures in the current Austroads AG/PT-233 fatigue test method and compare them to international best practice. A further aim was to identify improvements to the fatigue test method to achieve better integration with the pavement design guide. Finally, the paper sought to demonstrate the use of the four point bending equipment for the construction of complex modulus master curves for asphalt. This section presents the conclusions and recommendations based on the findings in the paper.

Conclusions

The findings indicate that haversine displacement control testing using the AG/PT-233 protocol in effect results in a sinusoidal strain response of half the intended amplitude. As a consequence, tests run at a given haversine strain amplitude under AG/PT-233 will result in a similar number of load repetitions to failure of a test run at half the strain amplitude using EN 12697-24. This should be an important consideration when comparing the results of testing in accordance with AG/PT-233 to the asphalt fatigue equations in the Austroads Guide to Pavement Technology. The models in the Guide were developed based on sinusoidal testing by Shell.

It is further concluded that the EN 12697-26 protocol can be successfully applied to develop complex modulus master curves using standard four point bending test equipment available in Australia.

Recommendations

It appears that it is not possible to run tests under constant haversine strain conditions in the conventional four point bending fatigue test configuration (a constant haversine displacement test does not result in a constant haversine strain condition). This, in combination with the fact that the fatigue models in the Austroads Guide to Pavement Technology are based on sinusoidal displacement testing leads this study to recommend that a change from haversine to sinusoidal mode testing should be considered in future revisions of AG/PT-233. This change should not be complicated as the results from both modes of testing can readily be transposed and therefore, existing mix design criteria can be readily adjusted. It may be worthwhile to adopt the European EN 12697-24 specification, rather than to revise AG/PT-233, as the European specification is well developed and comprehensive.

The description of the calculation of the dissipated energy in AG/PT-233 is in need of improvement.

The development of an Austroads method to construct master curves based on four point bending testing, or the adoption of EN 12697-26 for this purpose is recommended.

It is recommended that more research is undertaken to determine whether 20 °C is the most suitable temperature to characterise fatigue in pavements in all climatic regions of Australia.

Currently, the Austroads Guide to Pavement Technology does not provide detailed guidance on how to develop mix specific fatigue prediction relationships. As a result, mix specific fatigue relationships are rarely, if ever, used in Australia. Instead, the Shell fatigue criteria, as contained in the Guide are usually applied. This is unfortunate as mix specific fatigue curves allow more informed decisions on the relative design lives of different mix designs. Performance based mix design, including the development of mix specific fatigue curves could promote the use of innovative products. It is recommended that in the medium term guidelines are developed that will allow the user to create mix specific fatigue relationships for use in structural pavement design.

Acknowledgements

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APPENDIX A

Comparison of calculation steps in AG:PT/T233 and AASHTO T321-07

AG:PT/T233	**AASHTO T321-07**
Maximum tensile stress in extreme fibre of beam	
$\sigma_t = \frac{LP}{wh^2} \times 10^6$	$\sigma_t = \frac{LP}{bh^2}$
σ_t = Peak tensile stress (kPa)	σ_t = tensile stress (Pa)
L = beam span (mm)	L = beam span (m)
P = peak force excursion (kN)	P = load applied by actuator (N)
w = beam width (mm)	b = beam width (m)
h = beam height (mm)	h = beam height (m)
Maximum tensile strain in extreme fibre of beam	
$\epsilon_t = \frac{12 \times \delta h}{23L^2} \times 10^6$	$\epsilon_t = \frac{12 \times \delta h}{3L^2 - 4a^2}$
ε_t = peak tensile strain (microstrain)	ε_t = tensile strain (m/m)
δ = peak displacement (mm)	δ = displacement (m)
	a = space between clamps (m)
Flexural stiffness	
$S_{mix} = \frac{1000 \times \sigma_t}{\epsilon_t}$	$S_{mix} = \frac{\sigma_t}{\epsilon_t}$
S_{mix} = Flexural stiffness (MPa)	S_{mix} = Flexural stiffness (Pa)
Phase angle	
$\varphi = 360\ ft$	$\varphi = 360\ ft$
φ = phase angle (°)	φ = phase angle (°)
f = load frequency (Hz)	f = load frequency (Hz)
t = time lag between peak load and peak strain	t = time lag between peak load and peak strain
Dissipated energy	
Area within the hysteresis loop formed from plot of peak tensile stress versus peak tensile strain (kPa)	$D = \pi \sigma_t \epsilon_t \sin(\varphi)$
	D = dissipated energy (J/m^3)