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Temperature Susceptibility of Multigrade Bitumen Asphalt and an Approach to Account for Temperature Variation through Deep Pavements

Brody R. Clark, Chaminda Gallage, John Yeaman

***Abstract*—**Multigrade bitumen asphalt is a quality asphalt product that is not utilised in many places globally. Multigrade bitumen is believed to be less sensitive to temperature, which gives it an advantage over conventional binders. Previous testing has shown that asphalt temperature changes greatly with depth, but currently the industry standard is to nominate a single temperature for design. For detailed design of asphalt roads, perhaps asphalt layers should be divided into nominal layer depths and different modulus and fatigue equations/values should be used to reflect the temperatures of each respective layer. A collaboration of previous laboratory testing conducted on multigrade bitumen asphalt beams under a range of temperatures and loading conditions was analysed. The samples tested included 0% or 15% recycled asphalt pavement (RAP) to determine what impact the recycled material has on the fatigue life and stiffness of the pavement. This paper investigated the temperature susceptibility of multigrade bitumen asphalt pavements compared to conventional binders by combining previous testing that included conducting a sweep of fatigue tests, developing complex modulus master curves for each mix and a study on how pavement temperature changes through pavement depth. This investigation found that the final design of the pavement is greatly affected by the nominated pavement temperature and respective material properties. This paper has outlined a potential revision to the current design approach for asphalt pavements and proposes that further investigation is needed into pavement temperature and its incorporation into design.

***Keywords*—**Asphalt, complex modulus, fatigue life, flexural stiffness, four-point bending, master curves, multigrade bitumen, thermal gradient.

I. Introduction

THE properties and performance of asphalt are largely dependent on the temperature of the material. The stiffness of asphalt increases as temperatures decreases and the materials modulus decreases as temperature increases [1]. The stiffness or modulus of the material is a governing factor in determining how the pavement will perform under long term loading [2].

It is critical for modern pavement design to consider all factors that affect the performance of the asphalt. Previous testing [3], [4] has found that the surface temperature of asphalt pavements is considerably different to the base of the asphalt layer. Road authorities should take into consideration the effect of this temperature gradient when designing pavements.

B. R. Clark (PhD Candidate) is with the Faculty of Science and Engineering, Queensland Univ. of Technology, 2 George St., Brisbane, QLD 4001, Australia (corresponding author, e-mail: brody.clark@connect.qut.edu.au).

C. Gallage (Senior Lecturer) is with the Faculty of Science and Engineering, Queensland Univ. of Technology, 2 George St., Brisbane, QLD 4001, Australia (e-mail: chaminda.gallage@qut.edu.au).

J. Yeaman (Professor (retired)) is with the Science, Health, Education and Engineering Faculty, Univ. of the Sunshine Coast, Sippy Downs, QLD 4556, Australia (e-mail: jyeaman@usc.edu.au).

II. Background

A. Current Design Practice

It is the current best practice in Australia to adopt a single temperature for asphalt pavement design [5]. The Weighted Mean Average Pavement Temperature (WMAPT) was developed in 1978 by Shell [6] as a means of computing the performance of pavement with the technology at the time. As technology has advanced, as well as our understanding of asphalt pavements, we should be reviewing all aspects of design to ensure our methods accurately reflect the witnessed performance of pavements.

B. Effect of Temperature on Pavement Performance

All The surface temperature of asphalt pavement is influenced by solar radiation and the ambient air temperature on any given day. The blackness or emissivity of the bitumen also plays a part in the material's ability to transfer radiation energy [7].

Previous testing [8] has shown that dramatic shifts in temperature are likely to cause premature failure in asphalt. Herb et al. [9] found in their testing that the temperature of their trial pavements shifted quite rapidly due to increasing temperatures and the opposite effect of a slower transition through the pavement depth observed for cooling, with the exception of rainfall events causing a significant cooling of the pavement.

Future asphalt roads should be designed to be able to resist the shifting temperatures of the climate in the region it is to service. Innovative pavement materials, such as multigrade bitumen, need to be tested thoroughly and implemented into modern pavement design.

C. Multigrade Bitumen

Multigrade bitumen is an innovative pavement material, which is the combination of two grades of bitumen and is marketed as being capable of resisting temperature fluctuations. M1000 multigrade bitumen was analysed in this study, which has the characteristics of Class 320 binder at low service temperatures and has a typical viscosity at 60°C of approximately 1000 Pas at high temperatures [6], [10].

Multigrade bitumen is said to be a high performing binder, but limited testing has been conducted on the fatigue performance of this material. Like most modern pavement materials, the Shell 1978 studies [6] do not accurately reflect the calculated performance of multigrade bitumen pavements. Multigrade bitumen has been available on the market for some time, but due to lack of testing and confidence in its performance, the binder is not widely utilised.

To analyse the performance of the multigrade bitumen asphalt, fatigue curves [11] across a range of temperatures and modulus master curves [1] are to be produced. The laboratory testing data will then be analysed against the observed temperature gradient through a deep asphalt layer to determine the calculated performance of the innovative material. This method will then be compared to the current best practice of adopting the WMAPT for design.

III. Test Materials

For this study, M1000 multigrade bitumen is to be utilised to produce rectangular asphalt beams. The asphalt pavements included multigrade bitumen, aggregate, fine sand, crusher dust and rock flour and the weighted percentage of each material included in the pavement can be seen in Table I. To better represent the grading results of the sieve analysis of the mix design to be investigated, Fig. 1 was produced.

TABLE I
MIX DESIGN FOR ASPHALT SAMPLES

Mix	MG-0%
18 mm Aggregates (%)	9.2
14 mm Aggregates (%)	14.3
9 mm Aggregates (%)	20.7
7 mm Aggregates (%)	14
Crusher Dust (%)	31.8
Fine Sand (%)	9
Rock Flour (Baghouse Fines) (%)	1
Rap Content (%)	0
Multigrade Bitumen Type	M1000
Virgin Bitumen Content (%)	4.5
18 mm Aggregates (%)	9.2
14 mm Aggregates (%)	14.3

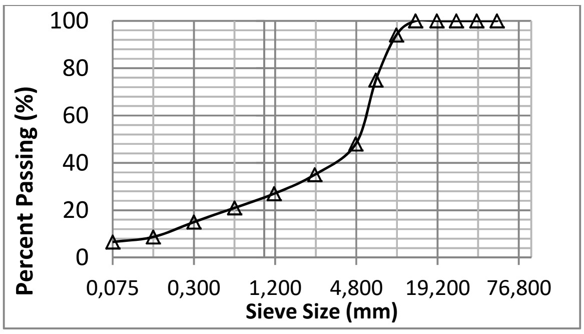

Fig. 1 Grain size distributions of aggregates in asphalt mix

The typical binder content of 4.5% was chosen for the asphalt mixture and M1000 multigrade bitumen was chosen as it is the most widely available multigrade in Brisbane, Australia [12]. The binder is believed to be supplied to meet the requirements of Australian Standard specification AS2008.

IV. Method

A. Thermal Gradient 'Heat Box'

To model the in-service thermal gradient of asphalt a 'Heat Box' was produced as outlined by Gray [13]. The 'Heat Box' is a timber construction with insulation layers surrounding the sample and a granite slab at the base to act as a heat sink, ensuring heat is transferred downwards. The 'Heat Box', as seen in Figs. 2 and 3, simulates the surface temperature of the asphalt sample on any given day by reproducing the recorded solar and thermal radiation by utilising a heat lamp, servo motor and microcontroller. The asphalt is compacted into a slab and thermocouples inserted at various depths to monitor internal temperature. For this testing, the Heat Box was programmed to replicate the thermal loading of the hottest day on record for 2015 on the Sunshine Coast, Queensland, which was the 9th of February 2015.

Fig. 2 Thermal gradient 'Heat Box' set up

B. Fatigue and Modulus Testing

To conduct the fatigue and modulus testing on the multigrade bitumen asphalt mix, a pneumatic four-point bending apparatus was utilised, as seen in Fig. 4. The apparatus applies loading to the centre of the beam to the point where it achieves the target vertical deflection. The loading is applied by a pneumatically controlled actuator that applies the oscillations in a sinusoidal pattern.

For the fatigue testing, the frequency of the testing was conducted at 10 Hz (10 loads applied per second) and the frequency for the modulus testing varied. The target vertical strain for the modulus testing was a constant 50 microstrain, where for the fatigue testing the applied strain varied. The fatigue testing determines how many loading cycles can be applied to the specimen before the material reaches half its original modulus. The fatigue testing was conducted on three temperatures (10°C, 20°C and 30°C) at three strain levels (100/150με, 200με and 300με). The modulus testing is run for 100 cycles at each frequency (0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz and 30 Hz) for each temperature (0°C, 10°C, 20°C, 30°C and 40°C). The methodology for this testing is derived from Austroads test method AGPT/T274 [14]). For each test the sample is housed inside an environmental chamber as displayed in Fig. 4. The environmental chamber maintains the target temperature for the test to within an accuracy of ±0.5°C.

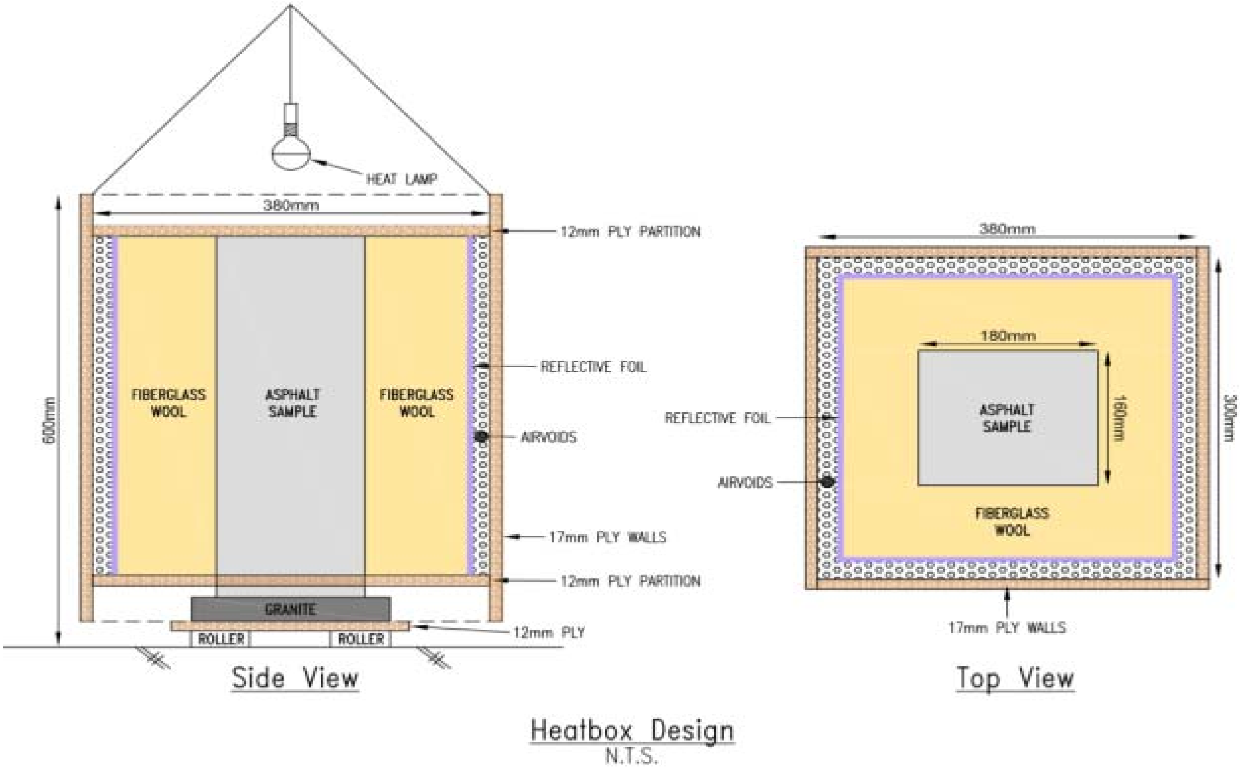

Fig. 3 Thermal gradient 'Heat Box' Details

(a) (b)

Fig. 4 Four-point bending apparatus (a) and environmental housing chamber (b)

V. Results and Discussion

The purpose for this testing is to determine the effects temperature has on the performance of multigrade bitumen asphalt pavements and if the currently adopted design methodology is still practical for today's uses. For this paper, a thermal gradient 'Heat Box' analysis was carried out to determine how the temperature changes throughout the depth of a pavement. To quantify the implications of the produced thermal gradient a series of fatigue tests were conducted on the same mix design to determine how the changing temperature affects the pavements fatigue life. These results were utilised in the pavement modelling program CIRCLY 6.0 to demonstrate the significance of this research.

A. Temperature Gradient within Multigrade Bitumen Asphalt

The 'Heat Box' apparatus was utilised to develop a thermal gradient of the asphalt mixture when the equivalent thermal loading of the hottest day in 2015 on the Sunshine Coast and calibrated to the actual recorded surface temperature on the day on a monitored asphalt road pavement.

The results of the thermal gradient testing are displayed graphically in Fig. 5. The temperature of the material appears to have two portions of gradient. From the surface to half way into the pavement (200 mm depth) the material lowers temperature quite rapidly through the asphalt slab. Beyond 200 mm depth the asphalt appears to plateau and lose temperature more gradually. This is likely due to the thermal mass properties of the asphalt, as well as the influence of the granite slab at the base of the thermal box. As actual asphalt pavements are usually above cement treated bases or similar, the influence of the granite slab below the asphalt box is likely indicative of actual field conditions. For CIRCLY modelling purposes, Fig. 6 displays a breakdown of the measured temperatures through the asphalt layers and compares the results against the current best design practice.

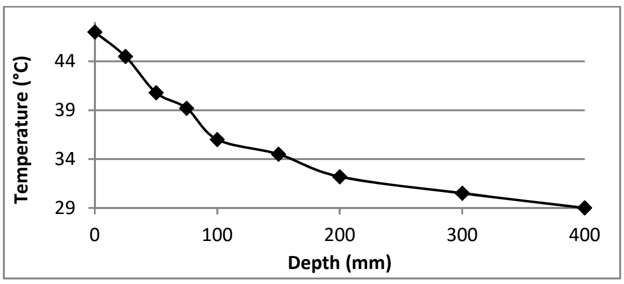

Fig. 5 Thermal gradient of the multigrade bitumen asphalt mixes

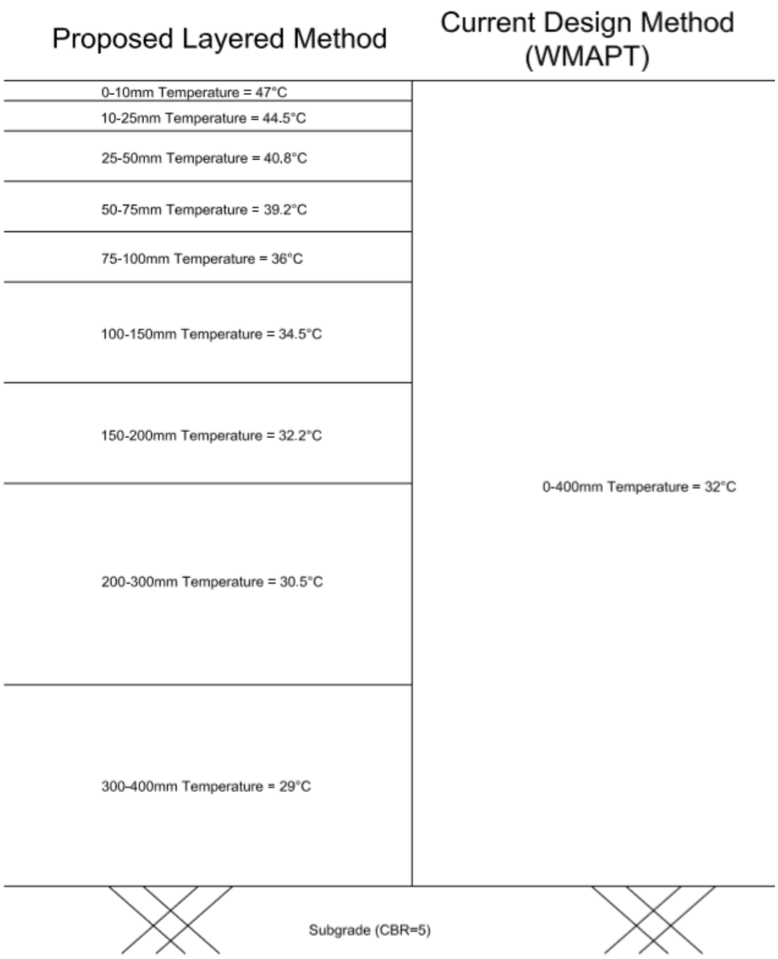

Fig. 6 Full depth asphalt pavements scenarios utilised in analysis

B. Effects of Temperature on Fatigue Performance of Multigrade Bitumen Asphalt

To determine the fatigue performance of the multigrade bitumen asphalt mixes a range of fatigue tests were carried out across a range of temperatures and loading strains for each mix. Fig. 7 graphically demonstrates the fatigue results obtained during testing for the multigrade bitumen asphalt mix. As can be seen in the graph, the higher temperature of 30°C has the biggest impact on the fatigue performance and significantly reduced the fatigue performance at two out of three of the strain levels. At 10°C and 20°C, the mixture performed similarly.

The reason for these results is likely due to the materials stiffness properties changing through temperatures. In previous testing [1], it was found that temperature has a large role in determining the materials stiffness. For future analysis, the fitting values for input into (1) can be found in Table II. These values are unique to this mix design and should only be used for verification purposes until such time as they are supported by further research.

C. Benefit of Considering Thermal Gradient within Asphalt Layer in Design

To quantify the significance of this testing the pavement modelling software CIRCLY 6.0 was utilised to show the difference in allowable loading between the currently adopted method of design and a proposed layering method. The results from testing are utilised in the modelling to determine the traffic loading allowable for a full depth asphalt pavement.

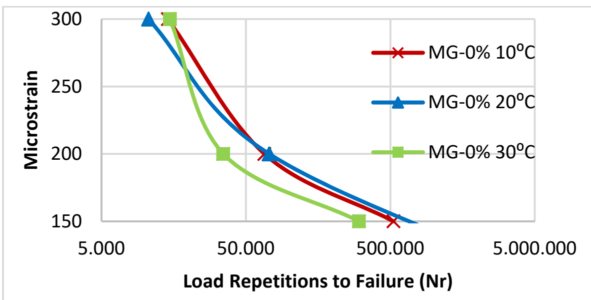

Fig. 7 Fatigue performance of multigrade bitumen asphalt mixes

TABLE II
FATIGUE FUNCTION FITTING PARAMETERS

Mix	Fitting Parameters for (1)				
	c_1	c_2	c_3	c_4	c_5
MG-0%	*0.328*	*-8.833*	*79.229*	*-192.516*	*-6.140*

The input exponent values required for CIRCLY 6.0

modelling were obtained by deriving the power functions of each individual fatigue curve for each temperature. The combinations of input parameters used for the pavement modelling can be found in Table III. It is interesting to note that the exponent values were near identical with the changing temperatures. This means the power curves were relatively the same shape regardless of temperature.

Fig. 8 graphically represents the result of the CIRCLY 6.0 analysis for a standard approach of adopting the WMAPT for the entire 400 mm of pavement and a layered approach adopting a layered approach using the thermal gradient found in testing. The results very clearly show that the current adopted method under predicts the design life of pavements and there could possibly be room to refine pavement design methodology which could lead to cost savings for projects. The design life increased by 32% for the MG-0% mix when adopting a layered approach.

To witness the same allowable traffic loading in a full depth analysis, using the WMAPT for the full pavement, the pavement thickness would need to increase by 3%. Although seemingly a small number, this simple analysis method could potentially save thousands of dollars for every project and provide more confidence in a pavements target design life.

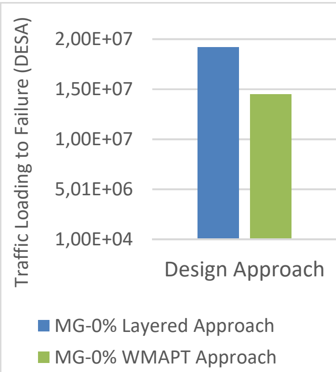

Fig. 8 MG-0% Design approach analysis

TABLE III
CIRCLY INPUT PARAMETERS

Depth (mm)	Temp. (°C)	E*(MPa)	Performance Exponent (b)	Performance Exponent (k)
0-10	47	757	6.13	1.27E-03
10-25	44.5	913	6.13	1.27E-03
25-50	40.8	1222	6.13	1.27E-03
50-75	39.2	1393	6.13	1.27E-03
75-100	36	1821	6.13	1.27E-03
100-150	34.5	2069	6.13	1.27E-03
150-200	32.2	2520	6.13	1.27E-03
200-300	30.5	2916	6.13	1.27E-03
300-400	29	3315	6.13	1.27E-03
WMAPT	32	2563	6.13	1.27E-03

VI. CONCLUSION

The fatigue behaviour and thermal characteristic properties of a multigrade bitumen asphalt mix was studied in this paper. Fatigue curves were developed for the mix at a variety of temperatures and strain levels and a thermal gradient developed for the asphalt. The results were adapted to analyse the equivalent design life of a 400 mm pavement compared to conventional methods. The main conclusions of this study are the following:

- Temperature plays a large role in determining the expected pavement life of the asphalt mix; 30°C had the largest impact on the materials fatigue performance.
- The thermal gradient throughout a 400 mm asphalt layer changes dramatically and a more considered approach to design should be adopted.
- The use of a layered approach for the determination of the asphalt design life produced clear results that the current best practice method of adopting one temperature for the entire depth of the pavement could be flawed.
- The layering method is a simple process for pavement designers to adopt that has been shown to be able to reduce the overall pavement thickness, while maintaining confidence in the performance of the asphalt.
- Future pavement designers should consider conducting thermal gradient testing for their region, as it could have large impacts on their pavement designs.
- Future testing should be conducted to determine the best conditions to adopt for determining the design life of a pavement.

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