ASPHALT PAVEMENT TEMPERATURE PROFILES IN THREE AUSTRALIAN LOCATIONS AND PRELIMINARY PAVEMENT TEMPERATURE MODEL

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ABSTRACT

From 2014 to 2016, a series of research projects have incorporated pavement temperature sensors and weather stations in order to better understand climate and weather parameters and their influence on pavement temperature and ultimately performance of asphalt pavements. As of March 2018, at least eighteen months of data is available for each of the three sites. It is understood that this is the most comprehensive Australian study of asphalt pavement temperatures since at least the 1970s, and is timely given the changes over recent decades to pavement design for heavier traffic, greater axle loads and new materials.

Observations from the instrumented sites reveal maximum temperatures near the surface of over 55 °C, and shows a strong influence of solar radiation on pavement temperature. Analysis shows that annual average pavement temperatures for thick pavements are generally lower than those used in current Austroads pavement design. The effect of climate change is also apparent when looking at long-term trends. Better temperature characterisation of both thin and thick asphalt pavements will allow for a more informed asphalt pavement design methodology, reduced asphalt thickness in some cases and reduced risk of premature failure where the assumed design temperature is not aligned with actual pavement temperatures.

A proposed general form of model has been presented, adapted from literature, which uses available climate data to calculate daily maximum and minimum pavement temperatures with a good fit. This is proposed to be incorporated into an hourly temperature prediction model and hourly traffic distribution to then calculate cumulative fatigue on an hourly basis over the pavement life-cycle. This is one key step in enabling a more detailed location and traffic specific asphalt pavement design leading to more accurate estimations of pavement performance and cumulative fatigue over time.

INTRODUCTION

Background

A significant proportion of our urban landscape consists of roads, footpaths and parking areas, which in an Australian context are predominantly constructed using bituminous materials that due to the thermal conductivity and low albedo (0.04 to 0.16 for typical asphalt pavements) (Pon 1999), reach very high temperatures in hot weather. This contributes to premature degradation of the pavement, and is a major contributor to the urban heat island effect (Gartland 2008). With reduced costs of instrumentation and real-time data analysis, there has been a renewed focus on understanding the temperature profiles of asphalt pavements and subsequently the impact on pavement performance.

Under current pavement design models, asphalt moduli are assumed to be lower at higher temperatures, which in turn generally results in higher strain levels generated in thick asphalt pavements and more rapid fatigue progression. Thus, all else being equal, a thick pavement designed in a hot climate is required to be constructed at increased thickness compared to a pavement constructed in a cooler climate. The consequences of this approach have been explored in Denneman & Lam (2015) and Austroads (2013), with evidence from overseas studies suggesting that fatigue damage does not accumulate more rapidly at higher temperatures. This may be at least partly attributable to slower crack propagation due to lower stresses and healing of the material, although this is dependent on factors including binder viscosity, temperature and the rest period between fatigue cycles. Across high temperature regions of Australia, there is little evidence of fatigue damage on thick asphalt pavements, which supports the theory that the reduced asphalt moduli are not significantly contributing to rapid fatigue damage at high temperatures (Austroads 2013).

While fatigue performance at elevated pavement temperatures may not be as poor as design models assume, other pavement failures may be more likely at high temperatures. Zou et al. (2017) undertook wheel tracking testing on a series of asphalt mixes with various binders, variable loading speed, different loading magnitude and temperatures ranging from 50-70 °C. The study found that the presence of modified binders was the most significant factor, but that temperature was the second most important factor in determining the progression of rutting in the pavement, with a pavement at 70 °C requiring 43% fewer passes to induce 1 mm of rutting compared to a pavement at 50 °C. Qi-sen et al. (2009) found through field observations and regression analysis that high temperature, along with high axle loads, was a factor in rut depth progression in thick asphalt layers.

High temperatures can also lead to premature loss of surface texture on sprayed seal pavements as the binder softens, allowing the aggregate to embed deeper into the surface. Lower viscosity binders are more vulnerable to this effect, leading to many road authorities to specify the use of modified binders on more sprayed seal pavements in hot regions.

Temperature in design

The Weighted Mean Annual Pavement Temperature (WMAPT) approach used in the Austroads (2017) design guide was developed with reference to the Shell Pavement Design Manual (Shell 1978), which itself was based on a small range of materials and pavement configurations. The background work contributing to this procedure also draws upon work by Dickinson (1981) with pavement temperature profiles and a series of back-calculated asphalt moduli from falling weight deflectometer (FWD) tests (Jameson 2013; Jameson, Sharp & Vertessy 1992).

The value for the WMAPT for a given location is found in Appendix B of the Austroads Guide to Pavement Technology (AGPT) Part 2, which in turn were calculated based on long-term air temperature monitoring at Bureau of Meteorology weather stations near each listed location, with the formula for converting weighted mean average air temperature (WMAAT) into WMAPT listed in Equation 1.

The relationship between temperature and asphalt modulus has been well established through many studies over the last several decades, with increasing temperature leading to a decreased modulus value. This relationship forms a core component of the pavement design process in Australia (Austroads 2017). The modulus at WMAPT is found through shifting the modulus at a nominal design temperature (typically 25 °C) according to the formula in Equation 1.

$$WMAPT = -12.4 + \frac{6.32(WMAAT)}{\ln(WMAAT)} \qquad \frac{\text{Modulus at WMAPT}}{\text{Modulus at test temperature}(T)} = \exp(-0.08[\text{WMAPT} - \text{T}])$$

Equation 1: WMAPT calculation and link to the asphalt modulus value

This produces a single design temperature – which does include some weighting to take into account daily and monthly variations, but does not adequately account for the effects of other weather factors such as solar radiation, relative humidity and rainfall. There is also no link between the diurnal temperature distribution and traffic – with pavements likely to experience more or less loading depending on when the bulk of traffic is experienced on that section. A valid reason for the approach has been the lack of reliable and long-term temperature monitoring of pavements in Australia, which could help to better characterise the impact of climate on pavement temperature (and subsequently the impact on asphalt modulus and performance).

In recent years, with better access to data and improved knowledge on how various factors impact on pavement performance, the potential to make improvements to the WMAPT has been highlighted (Austroads 2013). Several options for improvement were nominated, including models that can predict pavement temperatures at any time and at any depth based on local climate factors which are already easily accessible through Bureau of Meteorology weather stations. This can be combined with a traffic distribution to produce a pavement-specific estimate of damage accumulation in time intervals as short as 1 hour. Later in this paper, a preliminary model is presented, based on those originally nominated in Austroads (2013) and through an international literature search.

In the United States in particular, similar models have become more widely used as a part of more sophisticated pavement design methodologies, including the Mechanistic-Empirical Pavement Design Guide (MEPDG) (Li et al. 2011), which incorporates climate data including air temperature, precipitation, wind speed, sunshine percentage, relative humidity and some other climatic adjustment factors.

PAVEMENT TEMPERATURE MONITORING

As noted earlier, there has been limited research into characterising pavement temperatures in Australia. This is despite the importance of temperature in design and that our conditions are significantly different from those experienced in locations where the initial models (including in Shell 1978) were developed.

The work of Dickinson (1981) in the 1960s and 1970s is to date the most comprehensive pavement temperature recording for asphalt pavements. This study captured asphalt temperatures at 40-50 mm depth in six Australian cities, and at depths of up to 200 mm in Brisbane, Darwin and Canberra.

Pavement temperatures have been recognised as a potentially major source of pavement failure, and this has led to numerous other studies into pavement temperatures, which are not explored here in detail. Of note however, a Californian study on permeable pavements found that asphalt pavements, with a typical albedo of 0.1, can produce surface temperatures of 70-80 °C on a hot and sunny summer day in cities such as Phoenix in Arizona (Li et al. 2013). This is broadly reflective of the range of maximum temperatures found through other studies in hotter climates, and recognises the key role that albedo plays (i.e. the ‘whiteness’ of the pavement).

In recent years, the introduction of a range of new materials and construction practices into Australia has prompted a renewed effort to understand the temperature behaviour of asphalt pavements, with instrumentation of several pavements proposed alongside existing demonstration projects.

Pavement instrumentation 2014-18

There are three existing pavement temperature monitoring stations managed by ARRB, the first of which was installed in Eagle Farm (Brisbane) as a part of the first Australian trial of EME2 asphalt in early 2014. This was followed by a very similar instrumentation setup as a part of the first Victorian EME2 project on the South Gippsland Highway, around 65 km south-east of Melbourne. In late 2016, sensors were installed in the Kwinana Freeway near Jandakot, around 18 km south of the Perth CBD. Each of these projects was supported by the Australian Asphalt Pavement Association (AAPA), local road authorities, industry partners and the instrumentation provider Environdata.

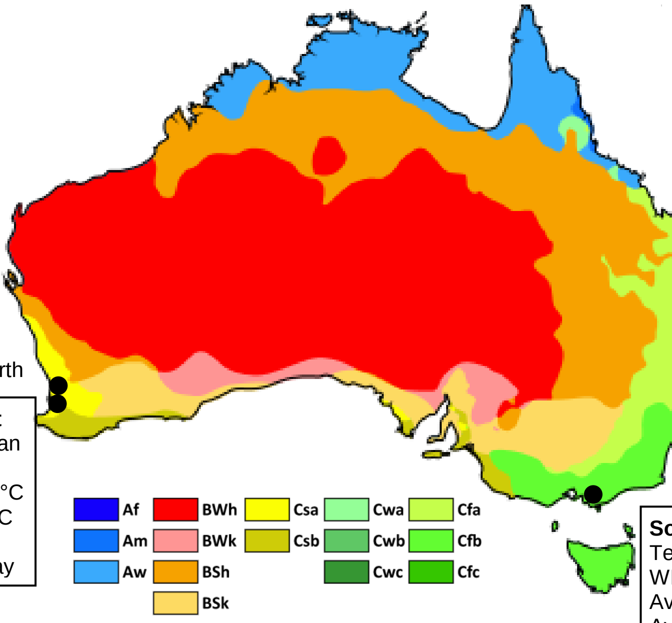
Prior to this, there have been at least two similar instrumentation projects, one at Sunshine Coast University in Sippy Downs (Azawi et al. 2014), and one by Curtin University installed on the Great Eastern Highway close to the Perth CBD. Table 1 includes details of each site.

These sites cover three distinct climate zones; a temperature oceanic climate in Victoria, humid subtropical climate in around Brisbane and a Mediterranean-style climate in Perth (Figure 1). These climate classifications encompass cities/towns that are home to a very high percentage of Australia’s population (80%+), and accordingly to a very high percentage of our full-depth asphalt pavement network. Instrumenting an additional pavement in a tropical location may provide insight for pavement design in far-north Australia.

At each of the three sites monitored by ARRB, Environdata has installed six pavement temperature sensors at various depths from 45–390 mm (Figure 2).

Table 1: Recent pavement instrumentation sites in Australia

Location	Date started	Depth of temp. sensors (mm)	Data interval	Air temp.	Solar radiation	Wind	Rain
Great Eastern Hwy, Perth, WA	28/3/13	40, 80, 150, 220, 290 & 360	5 min	No	No	No	No
Sippy Downs, QLD	13/9/13	Surface & approx. 75	1 min	Yes	Yes	No	No
Eagle Farm, Brisbane, QLD	20/2/14	50, 70, 110, 190, 290 & 390	10 min and 1 hr	Yes	Yes	Yes	Yes
South Gippsland Hwy, Caldermeade, VIC	26/6/15	55, 75, 120, 185, 235 & 325	10 min and 1 hr	Yes	Yes	Yes	Yes
Kwinana Fwy, Jandakot, WA	21/9/16	45, 85, 120, 160, 200 & 320	10 min and 1 hr	Yes	Yes	Yes	Yes



Eagle Farm (Brisbane)
Humid subtropical climate
WMAPT = 32 °C
Avg. Feb day: 21.3–30.0 °C
Avg. July day: 10.2–21.9 °C
Avg. 3.6 days > 35 °C
Daily solar 18.5 MJ/m^2/day

Kwinana Fwy, Jandakot
Hot summer Mediterranean
WMAPT = 29 °C
Avg. Feb day: 17.1–31.7 °C
Avg. July day: 6.7–17.9 °C
Avg. 25.3 days > 35 °C
Daily solar 19.1 MJ/m^2/day

South Gippsland Hwy
Temperate oceanic
WMAPT = 22 °C
Avg. Feb day: 14.0–25.7 °C
Avg. July day: 6.2–13.4 °C
Avg. 6.7 days > 35 °C
Daily solar 14.9 MJ/m^2/day

Source: Adapted from Peel et al. (2007); Bureau of Meteorology (2017)

Figure 1: Koppen climate classification map with location of instrumented pavements

Figure 2: Pavement temperature sensors and weather station at Jandakot

The 100 mm long probes are drilled into the asphalt mat and then backfilled with concrete and cold-mix asphalt with the surface reinstated to similar conditions to previous. The cables run through a channel back to a solar-powered weather station positioned in the road reserve, which includes the data logger and 4G modem. The weather station has sensors for air temperature, solar radiation, wind speed, relative humidity and rainfall. Data is provided in 10-minute or hourly intervals, and can be downloaded live from an online portal.

RESULTS AND IMPLICATIONS FOR PAVEMENT DESIGN

Since installation, each of the three sections has collected at least 12 months of data. At the Eagle Farm site, there have been several failures due to suspected water damage of the sensor cables, while in South Gippsland one sensor was damaged irreparably during construction. Table 2 presents some of the key climate factors and pavement temperatures at each sensor. Where there is more than 12 months available, the most complete data set is presented.

General Observations

The variance in climate across the three locations can be seen clearly – Perth and South Gippsland both possess a wide range between maximums and minimums, with a narrower typical temperature profile in Brisbane (Table 2). The average solar exposure is highest in Perth, while Perth also had the highest total rainfall and highest single month of rain. The seasons have a more even distribution of rainfall in Victoria.

Pavement temperatures exceeded 55 °C at the highest sensor (45–50 mm below surface) in Perth and Brisbane, which would suggest temperatures at the actual surface of 60 °C or more. This is a very high value, but still somewhat lower than values found in Dickinson (1981) and overseas studies in hot locations, which may be due to the albedo of the asphalt or the richness and texture at the surface.

Table 2: Climate factors and pavement temperature at depth at three sites

		Perth	Brisbane	South Gippsland
Air temperature (°C)	**Max**	41.9	36.8	36.4
	Avg	18.1	21.9	14.1
	Min	2.8	7.2	-2.3
Avg. daily maximum air temp (°C)		23.8	26.9	19.3
Avg. daily minimum air temp (°C)		12.6	17.6	8.9
Daily solar exposure (MJ/m^2)	**Max**	28.1	25.1	25.8
	Avg	15.8	14.1	11.8
	Min	1.5	1.4	1.9
Monthly rainfall (mm)	**Max**	196.4	178.0	108.4
	Avg	66.3	62.4	58.4
	Min	0.8	13.8	21.4
Sensor 1 (°C) (nearest surface)	**Max**	56.9	55.9	48.8
	Avg	25.4	30.6	19.3
	Min	6.0	10.9	2.8
Sensor 2 (°C)	**Max**	52.2	54.7	46.4
	Avg	25.4	30.7	19.3
	Min	7.4	12.0	3.5
Sensor 3 (°C)	**Max**	49.8	50.4	N/A *(damaged during construction)*
	Avg	25.4	30.5	
	Min	8.3	13.0	
Sensor 4 (°C)	**Max**	47.1	46.0	36.7
	Avg	25.3	30.4	19.3
	Min	9.3	15.0	7.2
Sensor 5 (°C)	**Max**	45.3	42.9	34.5
	Avg	25.2	30.4	19.2
	Min	9.9	17.0	8.0
Sensor 6 (°C) (deepest sensor)	**Max**	40.9	40.6	31.8
	Avg	25.0	N/A	19.3
	Min	11.6	18.5	9.4

The average temperatures for each location are very consistent across all depths, with the more significant diurnal variations near the surface producing a very similar annual average temperature compared to the 'tighter' distribution of temperatures in the bottom half of the asphalt layer (see Figure 3).

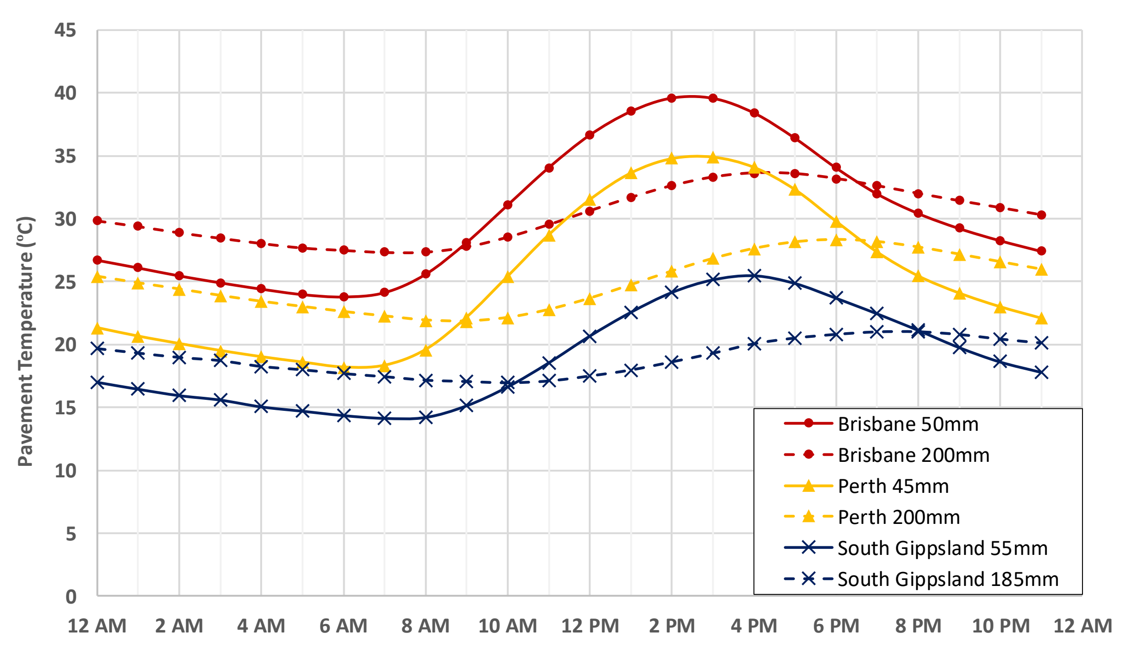


Figure 3: Temperature distribution at three depths at three sites

Wind Draught Effect on Surface Temperatures

Anecdotal evidence at the Kwinana Freeway site has shown that temperatures at the surface vary by traffic lane, with temperatures in the left lane being higher than those on the shoulder. One theory is that the surface temperature is significantly influenced by a wind draught and/or shading effect from passing vehicles. Further instrumentation and monitoring of surface temperatures across trafficked and non-trafficked lanes would allow for a better understanding of the true impact of this factor, which could then be allowed for in the calculation of pavement temperatures depending on the traffic volume and traffic distribution between lanes.

Solar Radiation and Rainfall

The impact of solar radiation and rainfall on pavement temperature was covered in a previous paper (Beecroft et al. 2015), with the observation that solar radiation had a major impact on pavement temperatures on days with otherwise similar ambient conditions. On a day with overcast conditions, the pavement temperature near the surface may peak at 5–10 °C above the maximum air temperature, while on a clear and sunny day, the pavement temperature often reached 15–25 °C higher than the maximum air temperature.

This can be visualised graphically in Figure 4, with the daily offset between maximum surface temperature (interpolated from two highest pavement sensors) and the maximum ambient air temperature plotted against the daily solar exposure. The strong correlation (R^2 of between 0.83 and 0.90) suggests that outside of ambient air temperature, the solar radiation is a dominant factor in determining pavement temperature. This does not account for any other factors, such as rainfall and time of year.

Beecroft et al. (2015) found that when rainfall was heavy enough to effectively leave the road surface wet for all daylight hours, this had the effect of reducing the pavement temperature near the surface to very similar values as the ambient air temperature. While the presence of rain necessarily coincides with periods of cloud cover and low solar radiation, the influence of low solar radiation alone does not account for the temperature drop witnessed due to the presence of surface moisture. It is important to understand the impact that rainfall has on heat transfer.

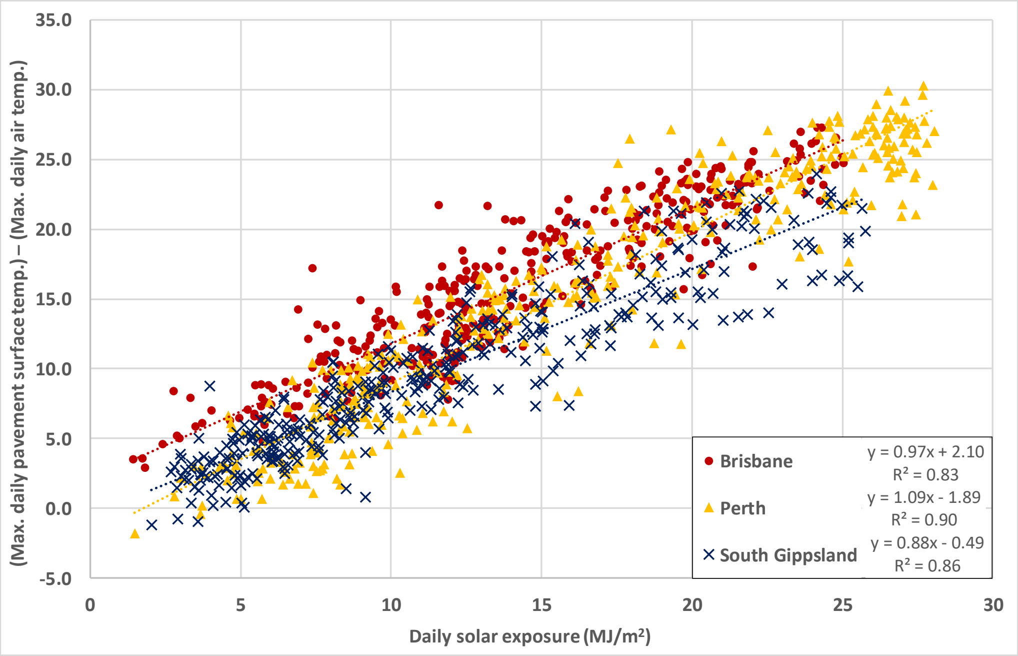


Figure 4: Influence of solar radiation on offset between maximum pavement and air temp.

Characterising Temperature and Loading Conditions

The diurnal pavement temperature distribution, seasonal and intra-seasonal climate factors, and traffic distributions centred around the morning and afternoon peaks, results in only a very small proportion of loading on a 'typical' day being matched to the modulus equivalent to the design temperature. Figure 5 presents a histogram of pavement temperatures at mid-depth of the asphalt (160 mm in this case) in discrete bins, along with the traffic distribution across those bins and subsequently the theoretical damage predicted to occur according to the Austroads methodology for the predicted modulus and volume of traffic loading. The estimated asphalt modulus value is presented along the secondary axis, with the modulus at the Perth WMAPT represented at around 3700 MPa.

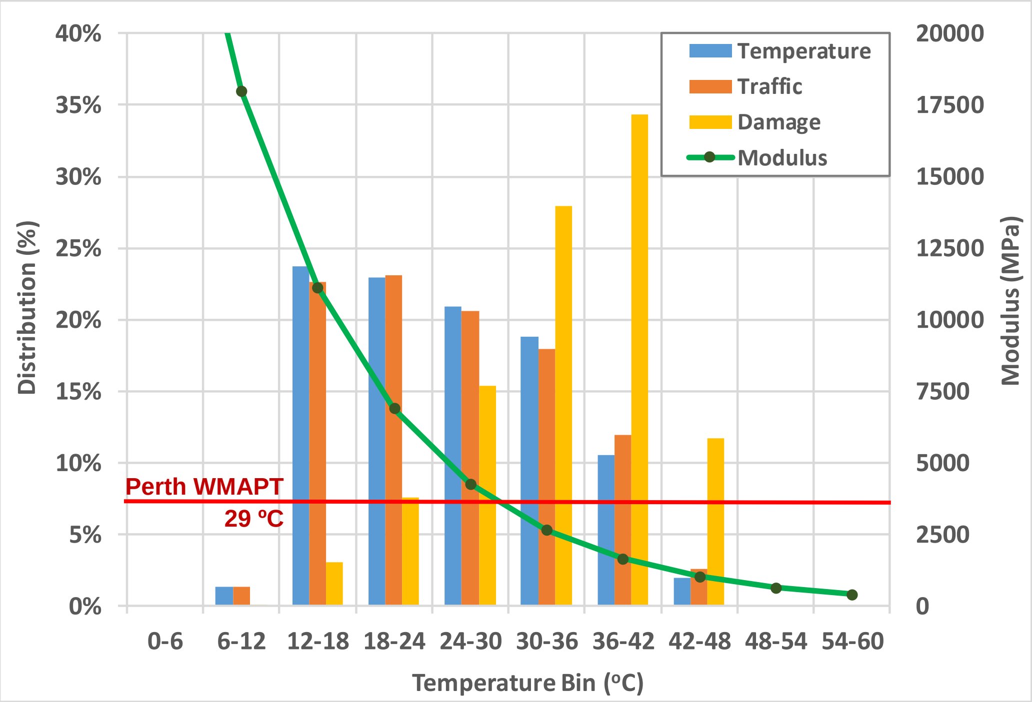


Figure 5: Histogram distribution of hourly pavement temperature, traffic, damage and modulus for Kwinana Freeway (southbound)

The first observation is that the pavement is sitting relatively close to the WMAPT (i.e. between 24 and 36 °C) for only around 39% of the year. There is close alignment between the distribution of pavement temperatures and traffic loading, with the notable exception of the bins over 36 °C where traffic is disproportionately high. This is largely due to the evening peak traffic, which lines up well with the peak pavement temperatures at mid-depth, which typically occur at between 5pm and 7pm (see Figure 3). The impact of this is that our current modelling estimates that significant fatigue damage is taking place in the pavement during this time – almost half of all damage in this example is incurred when the pavement is over 36 °C at mid-depth. This does not align with observations in the field, where fatigue damage rarely presents in thick asphalt pavements in hot climates.

This analysis highlights the disproportionate impact of ‘very hot’ days on pavement performance, at least in how it applies to fatigue prediction models. The WMAPT calculation uses a weighting to account for locations with larger differentials between warmer and cooler months, however even with this weighting, it is inherently difficult to capture the effect of these very hot single days when predicting pavement performance. The relative vulnerability of pavements to extreme heat or extreme cold can be attributed to a number of factors, including the mix type, traffic distribution, and albedo of the road surface; but an underlying theme is that there is a shift in behaviour that occurs in visco-elastic materials at high temperatures.

Although it has been noted that accumulated fatigue in thick asphalt pavements in hot climates is not common, these very high pavement temperatures can lead to rapid progression of rutting and flushing on asphalt pavements, and can result in stone embedment and bleeding of binder in spray seals. A permanent deformation model is not available for asphalt pavements in Australia, but advice in Austroads (2017) states that high-viscosity binders or other material and loading factors can reduce the risk of permanent deformation.

One implication of climate change across Australia is that days of extreme heat are predicted to increase (CSIRO 2015). Compared to a base period of 1981-2010, estimates for 2030 (just 12 years from today) based on a ‘slow emission reduction’ scenario, would see the number of daily maximum air temperatures over 35 °C rise from 11 up to 12-15 days per year in Melbourne, from 28 days up to 33-39 days per year for Perth and from 12 days up to 15-22 days per year for Amberley (near Brisbane). Projecting further out has wider error margins, but additionally suggests an accelerating rise in ‘very hot’ days. The incidence of days above 40 °C is predicted to rise by 50-100% by 2030 in many locations around the country.

WMAPT Comparison – Actual Asphalt Temperatures at Depth

The WMAPT calculation is intended to provide a reasonable estimate of pavement temperatures for a ‘typical’ asphalt pavement in a certain location. The formulas referenced in AGPT Part 2 (Austroads 2017) were initially developed for pavements at 100 mm depth. The Shell (1978) model from which the Austroads (2017) methodology was based also provides WMAPT curves for asphalt pavements up to 400 mm.

With access to 12 months or more of pavement temperature data at multiple sites, the actual recorded temperatures at 100 mm depth can be compared to the assumed WMAPT values from AGPT Part 2 as well as several proposed alternative calculation methods. The offset between the actual and calculated values can help inform potential adjustments to values adopted for future pavement designs. The average annual pavement temperature is almost identical at all depths, but the sensor closest to 100 mm depth was chosen for consistency across the sites. The five analysis cases presented in Table 3 are:

1. actual pavement temperature data from the sensor closest to 100 mm
2. WMAPT referenced from the closest site listed in Appendix B in Austroads (2017)
3. WMAPT value calculated from weather station data at the instrumented site (covers period October 2016 through end September 2017)
4. WMAPT calculated from *Chart RT* in the Shell Pavement Design Manual (Shell 1978), taking into account the five lines in the chart representing different depths and interpolating
5. as for Case 4, except using a WMAAT calculated using only the weather station data from October 2016 through end September 2017 (allowing for a better comparison with Case 1)

Table 3: Comparison of traditional and alternative WMAPT calculation methodologies

		Kwinana Fwy	**South Gippsland Hwy**		**Eagle Farm**		
Closest WMAPT site		**Perth**	**Warragul**		**Brisbane**		
Year		**2016/17**	**15/16**	**16/17**	**14/15**	**15/16**	**16/17**
1	Average annual pavement temperature at 100 mm (°C)	25.3	20.2	19.3	30.3	30.4	31.0
2	WMAPT (°C)	29.0	22.0		32.0		
	Offset to actual (°C)	3.7	1.8	2.7	1.7	1.6	1.0
3	WMAPT (°C)	28.2	24.0	22.7	33.0	33.4	33.8
	Offset to actual (°C)	2.9	3.8	3.4	2.7	3.0	2.8
4	WMAPT (°C)	26.8	20.6		29.0		
	Offset to actual (°C)	1.5	0.4	1.3	-1.3	-1.4	-2
5	WMAPT (°C)	26.0	22.4	21.3	29.8	30.2	30.6
	Offset to actual (°C)	0.7	2.2	2.0	-0.5	-0.2	-0.4

At each site, the WMAPT from Austroads (2017) (i.e. Case 2) is overestimating the pavement temperature by between 1 °C and 3.7 °C. It is possible that this is partly because of fluctuations year-to-year, however by looking at the 'local' single-year WMAPT using the weather station data, there is an even larger offset in all but one case. This would indicate that the Austroads values may be understating the WMAPT based on recent climate data, and that the error to the actual pavement temperatures is wider than current WMAPT values would suggest.

Shell (1978) allows for calculation of WMAPT at various asphalt thicknesses. Each of these pavements is over 300 mm in depth, and while it was noted earlier that the average annual temperature is almost identical at any depth in a given pavement, there may be some influence from the total thickness of the pavement to the mean annual pavement temperature. For example, a thin pavement would gain heat rapidly in sunshine periods, but also lose heat more quickly overnight. Thicker pavements require significant energy for the total mass to rise in temperature, but also tend to hold temperature overnight as heat is stored in lower layers.

Interpolating the WMAPT from the correct curves in Shell (1978) improves the fit to actual data, and it is closer still when also adjusting for the local single-year weather station data. This, Case 5 results in the closest average offset to actual recorded pavement temperatures (Table 4).

Table 4: Accuracy of WMAPT calculation methodologies

Case	**Methodology**	**Mean squared error**
2	WMAPT (Appendix B, Austroads 2017)	5.11
3	Calculate WMAPT (with actual weather station data)	9.76
4	Shell PDM Chart RT (correcting for depth)	1.96
5	Shell PDM Chart RT (with actual weather station data)	1.63

WMAPT variance over time

Single WMAPT values for Australian locations are based on temperature records from the second half of the 20th century. This may have been appropriate at the time, however recent trends of rising average air temperature across much of the planet may be significant enough to justify reconsidering WMAPT values, especially with pavement design lives of 40+ years. In Figure 6, the single-year WMAPT values have been calculated for three long-term Bureau of Meteorology stations near the three instrumented pavements, with the trend indicated with a dashed line and the current WMAPT in Austroads indicated by a solid line. There is a clear trend of rising air temperatures at two sites, while in Brisbane the pattern is less clear – although each of the last three years have been above the long-term trend.

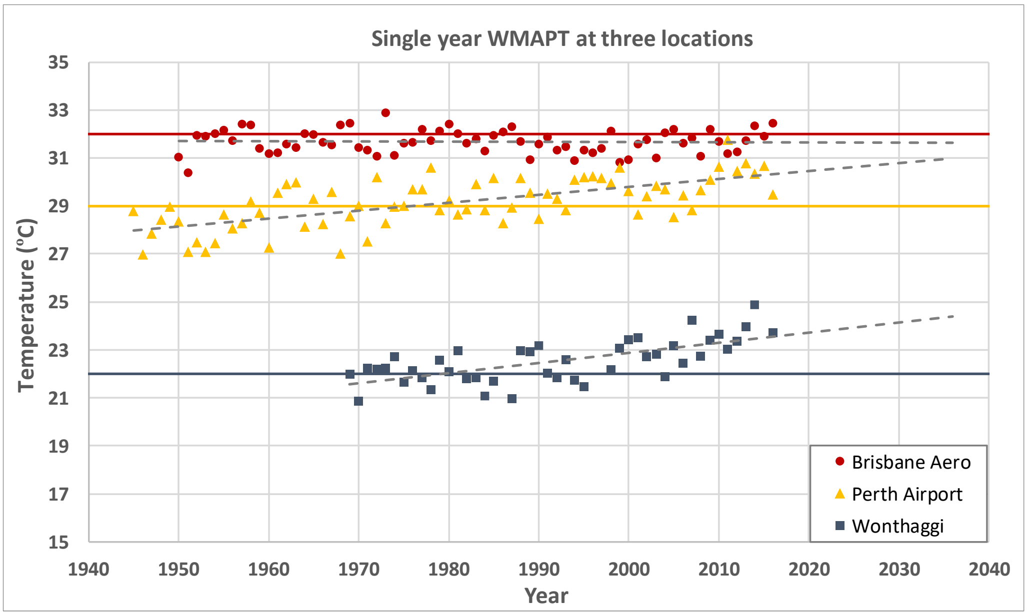


Figure 6: Single year WMAPT at three Australian locations with trend

This highlights the issue of whether pavements should be designed with higher WMAPT values where there is a warming trend in that location. The impact of changing the WMAPT to better reflect climate trends around Australia can be assessed by running simulations with the CIRCLY pavement design software. Using Perth for example (WMAPT of 29 °C), a hypothetical thick asphalt pavement designed for 120 million ESAs over a 40-year design life would have a reduction in design life of nearly 10% for a 1 °C increase in the WMAPT used in design.

If this trend is projected linearly (a conservative estimate given the evidence of *accelerating* warming in many regions) out to the 'mid-point' of a 40-year design life (i.e. the year 2037), this would suggest an appropriate WMAPT of just over 31 °C. This would result in a reduction in design life of around 17% – equivalent to nearly 7 years of design traffic.

It was noted earlier in this paper that this offset does have implications for pavement design. A theoretical pavement design can be determined through the CIRCLY pavement design software, using a presumptive modulus and changing the WMAPT to account for a potential offset in the WMAPT compared to 'actual' data. The hypothetical design includes asphalt with a presumptive modulus set at 2500 MPa, paved on a 500 mm sub-layered granular base at a modulus of 500 MPa, with a CBR10 subgrade. The results for this analysis for both a thick (300 mm) and thin (100 mm) asphalt pavement are presented in Figure 7.

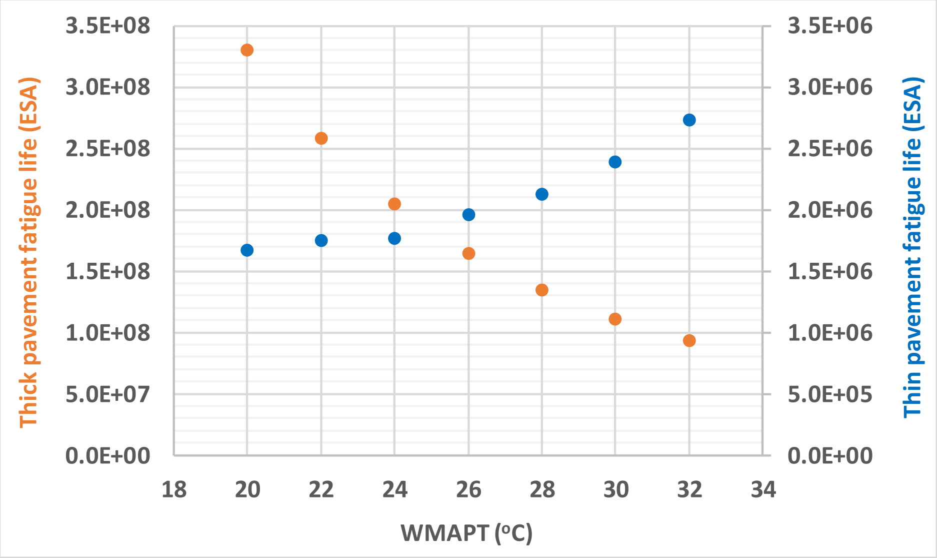


Figure 7: Change in predicted fatigue life for thin and thick pavements

This analysis suggests that under the current methodology, with WMAPT generally higher than what is being measured in thick asphalt pavements, the fatigue life of thick pavements is being underestimated. The effect is being offset in some cases by the fact that WMAPT values in Austroads (2017) have not kept pace with rising air temperatures in many parts of Australia. The graph shows that an underestimate of 2 °C may lead to that pavement having an estimated fatigue life 20-30% higher than predicted with the current WMAPT value.

The impact on thin pavements is actually reversed – a pavement with actual pavement temperature 2 °C below the WMAPT value would result in a predicted fatigue life *reduction* of 5-15%. The results for a specific pavement would depend on the support conditions and asphalt material properties, but it does show that the current methodology using a single WMAPT value for any asphalt pavement may be overly simplistic.

The impact of pavement depth on average annual temperature is also not well understood in relation to this project, as the three instrumented locations were all constructed at between 330-400 mm in total thickness. Instrumenting a thin pavement adjacent to a thick pavement may help in understanding the differences due to total asphalt thickness.

ASPHALT PAVEMENT TEMPERATURE MODEL

In recent years, there have been efforts to introduce a comprehensive pavement temperature model for use in the design of asphalt pavements in Australia (Austroads 2013), adapted from models available from previous research. This model would be compatible with the Austroads methodology, but would also allow for a more fundamental shift in philosophy towards pavement design. The model used a heat balance approach to estimate the pavement temperature at any depth, with inputs including location (latitude and longitude), pavement depth, pavement material properties, a proxy for sunshine/cloud cover, and the shape of the diurnal temperature profile. The accuracy of the model was noted as being limited without an increase in pavement temperature monitoring data, which has been addressed over the last four years with the addition of three instrumented sites.

The impact of solar radiation on pavement temperatures has been shown to be highly significant, and using solar exposure values recorded by the Bureau of Meteorology would be more accurate than utilising proxy values for cloud cover based on air temperature differentials to the monthly averages. In urban areas, there are many sites with daily solar exposure values recorded in addition to daily maximum and minimum temperatures.

Diefenderfer et al. (2002) developed two models, with the general form of the more complex version of the model incorporating maximum and minimum daily ambient temperature, the depth within the pavement and the calculated daily solar radiation. The model was calibrated against data from the Virginia Smart Road to generate a single set of coefficients, with the root mean squared error (RMSE) and adjusted R^2 for this model calculated to be 5.76 and 77%, and 4.28 and 80%, for the maximum and minimum pavement temperature models respectively. The model was evaluated against a range of other data sets including additional data from the Virginia Smart Road and two long-term pavement monitoring sites, with generally good fit of the model to independent data.

In developing a general model for Australian conditions, the following input variables have been used in calibration of the preliminary model based on the model proposed by Diefenderfer et al. (2002) (also expressed in general format in Equation 2):

- daily maximum air temperature (T_a max in °C)
- daily minimum air temperature (T_a min in °C)
- daily total solar exposure (SR in kJ/m^2/day)
- four constants each for calculating maximum and minimum pavement temperatures from climate data
  - an intercept coefficient (α)
  - an ambient temperature coefficient (β)
  - solar radiation coefficient (γ)

  - pavement depth coefficient (δ) to adjust for temperature at depth = *D* metres
- two-part (day and night) shape function to plot hourly distribution
- sunrise and sunset times to shift between day/night functions

$$T_{p\,max\,(at\ depth\ D)} = \alpha + \beta * (T_a\ \mathrm{max}) + \gamma * \frac{SR}{1000} + \delta * (D)$$

$$T_{p\,min\,(at\ depth\ D)} = \alpha + \beta * (T_a\ \mathrm{min}) + \gamma * \frac{SR}{1000} + \delta * (D)$$

Equation 2: General format of proposed max and min pavement temperature model

A version was tested with an additional factor for rainfall, which did show some small improvement on average, but was left out of this preliminary version of the model as the impact was highly variable across sites and across different rainfall levels.

The coefficients were calibrated against pavement temperature data from all three sites, with predicted temperatures returning RMSE of 2.5–4.0 °C and 1.7–2.1 °C across the three sites for the maximum and minimum daily temperatures respectively, and R^2 values of 92-94%. The model is under further development to refine the general format and values for coefficients for multiple years of observed data and by potentially including an additional factor to allow the model to better account for latent heat captured overnight within the pavement.

In order to predict the pavement temperature for each hour, a function was developed to include a ‘daylight’ equation, following a sine curve between sunrise and sunset – while during non-daylight hours, the pavement is cooled with a drop in temperature each hour proportionate to the difference between the current temperature and the predicted minimum. When the model’s hourly output is compared to the actual hourly pavement temperature data, the average errors is 2.5 °C. A sample output from 12-15 Dec. 2016 at the Kwinana Freeway site is shown in Figure 8. This part of the model is still in development and while it produces good results on ‘average’ days, days with extreme heat, extreme cold and rainfall lead to larger errors.

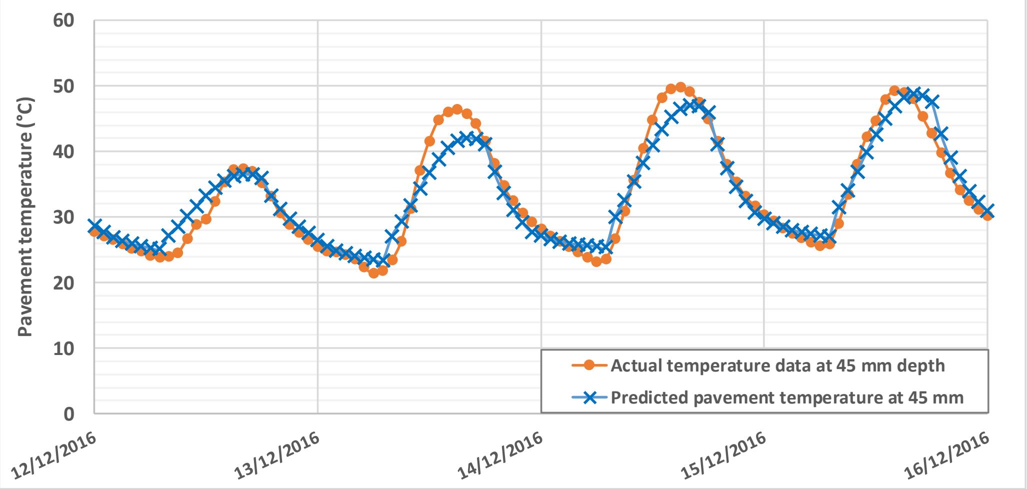


Figure 8: Actual and predicted pavement temperatures with proposed model

The resulting hourly temperature profile could then be run through CIRCLY analysis, combined with a measured or predicted hourly distribution of traffic (from a local weigh-in-motion site or vehicle counter with classifications), and produce a fatigue life estimate based on 8760 (24 hours * 365 days) pavement temperature data points using real climate data for a local weather station, rather than a single static WMAPT value for a given city/region.

It is hoped that once refined, the models and procedures proposed here can provide pavement designers with a better understanding of the impact of temperature and other weather factors on thick and thin asphalt pavements, and allow for more cost-effective pavement design. It will also build an understanding of critical factors affecting the predicted design life of pavements.

CONCLUSION

Recent demonstration projects around Australia have allowed for comprehensive asphalt pavement temperature monitoring. Pavement temperatures near the surface of 55 °C or higher are relatively common in summer, while it has been shown that for thick asphalt pavements, temperatures are very stable at greater depth. Solar radiation explains a high proportion of the difference between ambient and pavement surface temperature, while rainfall has been shown to have a rapid cooling effect on surface temperature.

It has been shown that very high temperatures can have a disproportionate effect on pavement damage, whether due to fatigue damage as predicted in the current design methodology or due to other factors such as accelerated rut progression or bleeding/flushing of binder. The impact of albedo and the urban heat island effect have also been raised, which are not presently a consideration when designing asphalt pavements. More sophisticated modelling of pavement temperatures will allow road authorities to better understand these factors.

The WMAPT currently used in pavement design provides a useful estimate, but fails to accurately represent the diurnal temperature behaviour in the pavement over the course of a year. The effect of climate change is also apparent when looking at long-term trends – and is predicted to lead to a theoretical under-design of new pavements with long design lives. This is likely offset in part by the fact that the WMAPT values used were developed for pavements at 100 mm thickness, while at 300+ mm there appears to be a systematic over-design.

A proposed general form of model has been presented, which uses readily available Bureau of Meteorology data for daily maximum and minimum air temperatures and solar radiation, and calculates daily maximum and minimum pavement temperatures with reasonably good fit. This is proposed to be combined with an hourly temperature prediction model and hourly traffic distribution to then calculate predicted cumulative fatigue on an hourly basis over the pavement life-cycle. This will allow for a better-informed asphalt pavement design methodology, reduced asphalt thickness in cases of over-designed thick pavements and reduced risk of premature failure where the WMAPT is not aligned with actual temperatures.

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