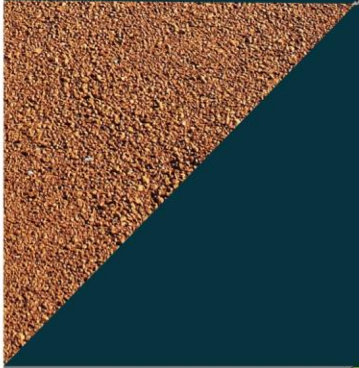
WARRIP
WESTERN AUSTRALIAN ROAD RESEARCH
AND INNOVATION PROGRAM



Investigation of Asphalt Pavement Temperatures in WA

Final Report

AN INITIATIVE BY:

THE GOVERNMENT OF WESTERN AUSTRALIA

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Investigation of Asphalt Pavement Temperatures in WA

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for Main Roads Western Australia

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SUMMARY

Under the current asphalt pavement fatigue design methodology, asphalt pavements are designed using a single design temperature, namely the Weighted Mean Annual Pavement Temperature (WMAPT). The WMAPT are provided for major population centres in Australia.

As a result of the current relationship between higher pavement temperatures and lower asphalt moduli, pavements in hotter climates are being constructed at a greater total thickness compared to pavements in cooler climates. The current methodology does not consider many location specific factors, including the underlying substrate properties, localised weather over the year and traffic distribution throughout each day.

In hotter climates across Australia, this has led to very thick asphalt pavement designs, even though there is limited evidence of comparable thick asphalt pavements in hot climates showing significant fatigue damage. There have been previous efforts to enhance the Austroads design methodology for asphalt pavements in hot climates, however these efforts have been somewhat hampered by a lack of real pavement temperature data.

Two pavements, one in Perth (installed September 2016) and a second in Karratha (June 2018), have been instrumented with temperature sensors and linked to roadside weather stations. The data from these sites, combined with data from several sites around Australia, have been used to better understand the range and extremes of pavement temperatures likely to be experienced for a given location.

After a very hot series of summers from 2012-16, Perth has experienced cooler summers since installation, however the instrumented pavement in Perth still reached a surface temperature of approximately 60 ºC on the hottest day. Annual average mid-layer temperatures over this period measured at around 25.3 °C for 2016/17 (measured October to September) and 25.5 °C for 2017/18. While the Perth WMAPT of 29 °C is weighted so may not be directly comparable, the offset between the actual temperature and assumed WMAPT was greater than anticipated and some potential amendments to how WMAPT is calculated have been explored.

The site at Karratha experienced issues with its power supply in December 2018, and as such any detailed analysis of pavement temperatures will need to be revisited in February 2020.

The data has also been harnessed to produce maximum and minimum pavement temperature models, which can be used at any location across WA with a nearby Bureau of Meteorology weather station. This information could then be combined with basic material characteristics and traffic data to predict the fatigue life for a given asphalt layer, and compare alternative design configurations. This report explores various implications of this model. A key outcome is that this approach will enable better informed decisions regarding the design of thick asphalt pavements.

This project also highlights areas for potential future research, including the relationship between surface temperature and various location specific factors, how improved knowledge of extreme temperatures in pavements can lead to better-informed design for permanent deformation, how we can account for a changing climate, and how this research can feed into overall improvements to asphalt pavement design in Australia.

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

The temperature of asphalt pavements has a significant impact on pavement design, with pavements in hotter climates designed at greater thicknesses to compensate for the lower asphalt design moduli at elevated temperatures. The simplified design temperature adopted in the current methodology, namely the Weighted Mean Annual Pavement Temperature (WMAPT), represents a single design temperature value for a given location, which does not take into account asphalt thickness, underlying substrate properties, localised weather and other location-specific factors.

Efforts have already been made to enhance this process with more sophisticated modelling and mix-specific design measures, to bring Australian practice in line with design procedures adopted in other countries (Austroads 2013b). A big step in this process will be to develop location-specific designs which are able to model pavement temperatures at depth and for various traffic loading scenarios. To achieve this with a satisfactory level of confidence, real pavement temperature data are required from a range of representative locations.

In 2013, Curtin University conducted a pavement temperature study through instrumenting an asphalt pavement in Perth. Pavement temperature data has more recently also been gathered at two Australian sites; at Eagle Farm in Brisbane and on the South Gippsland Highway around 50 km south-east of Melbourne. Further instrumentation was required to supplement the Curtin University dataset and for use in conjunction with the other Australian pavement temperature data to establish comprehensive pavement temperature profiles for asphalt pavements across Western Australia (WA).

In locations with higher pavement temperatures and heavy traffic, resulting in very thick asphalt pavements of 300+ mm, there is little documented evidence of significant fatigue damage, suggesting that many of these pavements may currently be overdesigned relative to pavements in milder climates. Thus, large cost savings may be realised by implementing a design methodology that better reflects the relationship between pavement temperature and asphalt fatigue performance. A better understanding of the extreme temperatures in asphalt pavements, the distribution of temperatures throughout a pavement, and the distribution of temperatures across a day and throughout the year, will enable an incremental shift in improving the design methodology and facilitate better-informed asphalt pavement designs.

1.1 Anticipated Benefits

This project was expected to deliver benefits in several areas, including:

1. improved estimations of pavement damage over time due to a better understanding of the relationship between pavement temperature at depth and pavement performance (initially developed through Austroads project TT1826), leading to more accurate predictions of the resilient response and fatigue life of asphalt layers
2. reduced uncertainties in design models may allow for reduced pavement thickness, particularly in areas with thick asphalt pavements and relatively high pavement temperatures (such is the case in most areas of WA). Thinner asphalt pavements have the potential to save money due to:
   - (a) reduced material costs
   - (b) reduced haulage and personnel costs
   - (c) reduced number of paving runs and reduced construction time

3. improved modelling of pavement life-cycles will facilitate more efficient and predictive asset management frameworks
4. preliminary modelling may be developed in the future into a more complete design tool for asphalt pavements, incorporating the findings of this and other projects through WARRIP, Austroads and NACOE.

1.2 Project Scope

The project scope involved the following key tasks:

1. **Review Curtin University data**
   Obtaining and reviewing instrumented pavement data from Curtin University, and consideration of the potential applications of this data.
2. **Instrumentation of asphalt pavements**
   Instrumenting and supervision of installation of pavement temperature monitoring equipment at a site in the Perth area, and at a second location in Western Australia.
3. **Preliminary data analysis**
   Analysis of preliminary data from the newly instrumented pavement (after three months of operation), including an analysis of the highest temperatures during the summer in 2016/17.
4. **Pavement temperature modelling**
   Development of a pavement temperature model to predict temperatures in asphalt pavements at any depth, location or time of year; and subsequently develop estimates for pavement life based on temperature modelling and traffic volume.
5. **Pavement temperature modelling follow-up**
   Further analysis and refinement based on latest temperature data, including addition of data from a second instrumented pavement.

The second set of instrumentation was scheduled to be installed north of Perth in 2017, but it was decided to move this equipment to a location in the northern part of WA to include data from a hotter, drier part of the state. The installation was completed at a site in Karratha in June 2018, with 12 months of data now available. This Final Report will present the findings of these five tasks relating to the two instrumented sites.

Additionally, the processed pavement temperature and weather station data with graphical outputs for each month has been provided to Main Roads Western Australia (MRWA) on a monthly basis, through June 2019. It has been proposed that this monitoring continue for another two years (through June 2021). Experience from previous instrumented pavements has shown that sensors are vulnerable to damage from water ingress and wear and tear, particularly after 2-3 years in operation. Should there be a significant number of failed sensors by June 2020, the value from continuing the temperature monitoring at one or both sites will be reassessed.

1.3 Report Outline

Firstly, the report includes some background information that has led to this study, and highlights the challenges that have been faced in developing improved design procedures for asphalt pavements in Australia (refer Section 2).

Section 3 reports on the outcomes of Task 1 of the project scope, which involves an analysis of the data received from the site instrumented by Curtin University in 2012/13, and how this may link in to the new sites that have been instrumented.

Section 4 documents the process of site selection and the installation of the two sites in Perth and Karratha in September 2016 and June 2018 respectively, with a more detailed installation process provided in Appendix A.

The preliminary pavement temperature analysis for the first summer of data at the Perth site, and the more detailed analysis after 12 months of data which incorporates the data from the sites in Brisbane and South Gippsland, is documented Section 5. Interim observations for Karratha are also explored, with these to be updated in early 2020.

Section 6 presents some alternative approaches to the use of temperature in asphalt pavement design, both in terms of altering the way we calculate WMAPT and in terms of more complex modelling. It also includes a summary of the key factors that have been considered when developing the proposed model and design tool for this project.

The proposed pavement temperature model is introduced in Section 7, which includes an explanation of the key components of the model, the calibration process, some worked examples and a discussion of the future work required in this area.

Section 8 closes with conclusions and recommendations for the project, building on the interim conclusions and recommendations from the Interim Report in January 2019.

2 PROJECT BACKGROUND

2.1 Design of Asphalt Pavements

There is a well-established relationship between temperature and asphalt modulus, with a series of studies over the last several decades confirming that asphalt moduli decrease as the asphalt temperature increases. To account for this behaviour in pavement design, the Austroads Guide to Pavement Technology (AGPT) (Austroads 2017a) includes a single temperature for design purposes for each city or major town in Australia, known as the Weighted Mean Annual Pavement Temperature (WMAPT).

The original WMAPT concept 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 the WMAPT concept in Australia 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).

While the single value approach is a reasonable approximation for the effects of temperature on asphalt pavements, it cannot account for diurnal variations in temperature and traffic, it cannot account for the temperature distribution throughout different pavement thicknesses, nor can it adequately account for the effects of other weather factors such as solar radiation, relative humidity and rainfall. It also represents a reasonable approach from a time when a more advanced approach may have been prohibitively complex and impractical. With lower instrumentation costs and the ease of data analysis and processing, this is no longer the case, and there is scope to improve our design procedures through making use of readily available information and technology.

An earlier Austroads project demonstrated that there are several avenues to improve the design of asphalt pavements for temperature, including models that are capable of predicting the temperature at any time and depth with only basic weather input data (Austroads 2013b). This can be combined with the traffic distribution to produce estimates of damage accumulation for every hour. This work requires a significant amount of data, which was not available at the time of the Austroads project. As such, interim models were developed but it was recommended to maintain the WMAPT approach until more data was gathered. As discussed in Section 4, there are now multiple sites with two or more years of weather and pavement temperature data, across climate zones accounting for a large proportion of the Australian population and the full-depth asphalt pavement network.

While it is not the primary intention of this WARRIP project to propose comprehensive models to replace the methodology within the AGPT, it is believed that the models and procedures proposed in this section can provide MRWA with a better understanding of the impact of temperature and other weather factors on full depth asphalt pavements, and allow for more cost-effective pavement design. These outcomes may also help inform revisions to the AGPT in future.

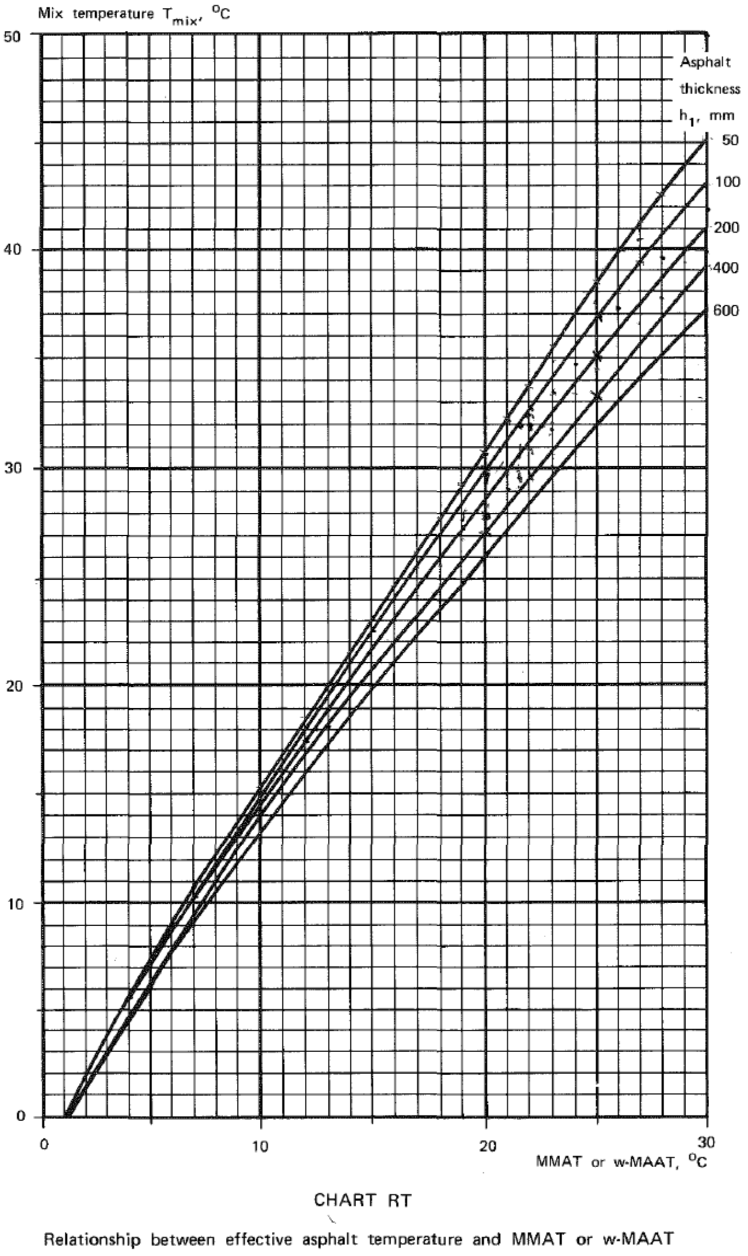
2.2 Weighted Mean Annual Pavement Temperature (WMAPT)

2.2.1 History of WMAPT

The current Australian asphalt pavement design methodology only considers temperature through a single input value, the WMAPT. This value was developed in accordance with the methodology and tables in the Shell Pavement Design Manual (Shell 1978). Austroads (2008) outlines the history behind the adoption of WMAPT in our current design methodology.

The values in Shell take into account daily and monthly variations in air and pavement temperature through the Weighted Mean Annual Air Temperature (WMAAT) and WMAPT, with the formula for WMAPT in Austroads (2017a) being an approximation of the 100 mm asphalt thickness curve in *Chart RT* (see Figure 2.1).

Figure 2.1: WMAAT and corresponding WMAPT at five depths - Chart RT



Source: Shell (1978).

The methodology in Austroads (2017a) only considers the relationship for a 100 mm thick asphalt layer, which may have been reasonable several decades ago when pavements were thinner due to lighter axle loads and lower heavy vehicle volumes. In 2017, highways in urban areas are designed for 40 years of traffic or more, and thickness design calculations under the current Austroads design method produce required pavement thicknesses of 300 mm or greater.

It has been demonstrated previously that the distribution of temperatures over the course of a year and their corresponding modulus values cover a wide range. The weighting of air temperatures in the WMAPT approach, with a corresponding single modulus value, may not sufficiently account for this wide distribution of pavement characterisations across a range of different loading and climate conditions (Austroads 2013b).

Figure 2.2 and Figure 2.3 show the potential impact of a skewed distribution for sample pavements. Under the current Austroads WMAPT approach, both pavements would be designed to have the same asphalt thickness. However, it can clearly be seen that the first pavement has a greater proportion of traffic loading while the asphalt has a lower modulus. Under current assumptions, this would lead to more rapid fatigue progression, however this is not necessarily supported by evidence in the field.

Preliminary models developed in the Austroads (2013b) project were not sufficiently validated against pavement temperature data to publish a proposed update to the WMAPT approach. However, the availability of at least a full year of data from three sites across Australia may allow for the adoption of a more sophisticated pavement temperature prediction model in pavement design in Australia.

Figure 2.2: Temperature, traffic and damage calculated hourly and distributed (heavier afternoon peak traffic)

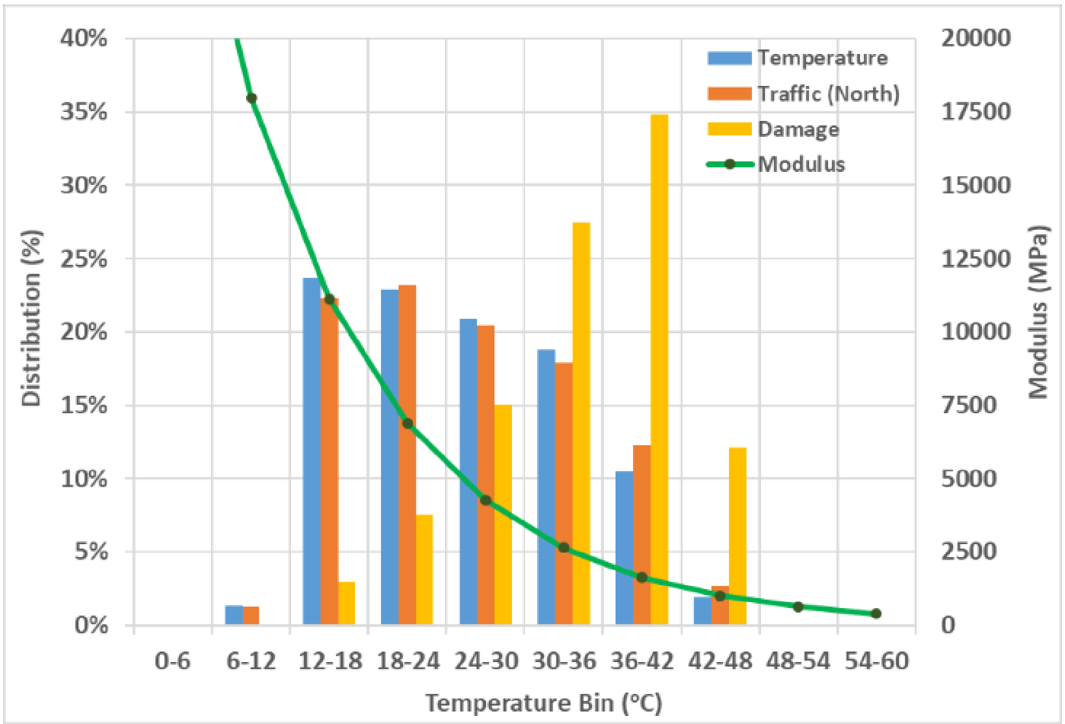
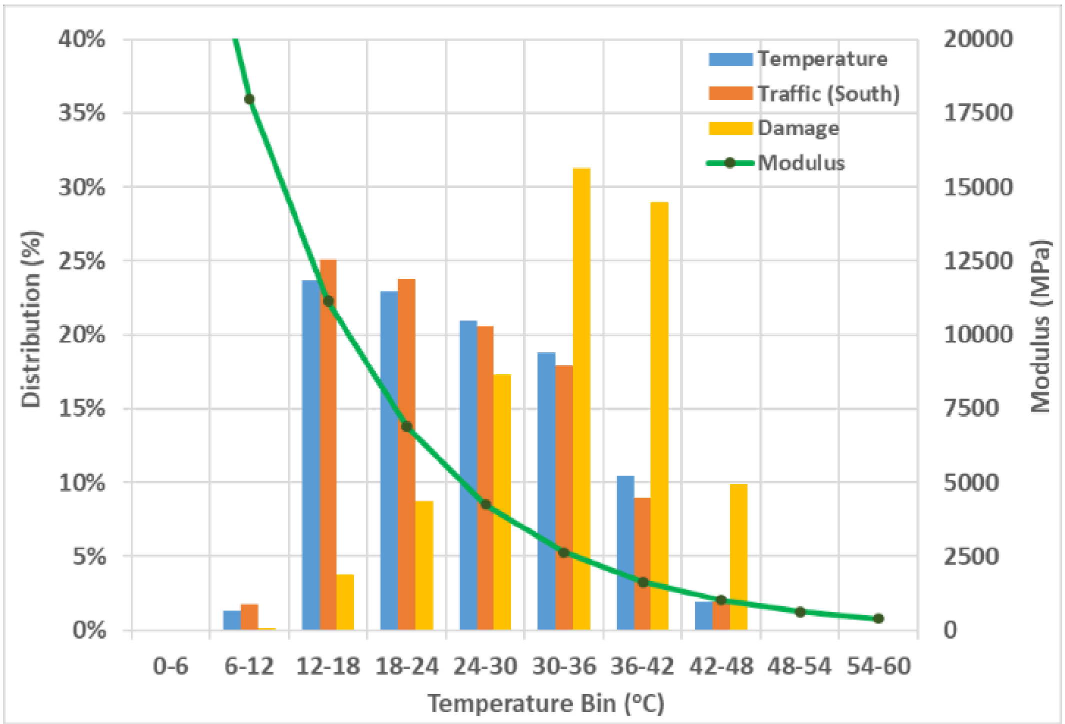


Figure 2.3: Temperature, traffic and damage calculated hourly and distributed (heavier morning peak traffic)



3 CURTIN UNIVERSITY PAVEMENT INSTRUMENTATION

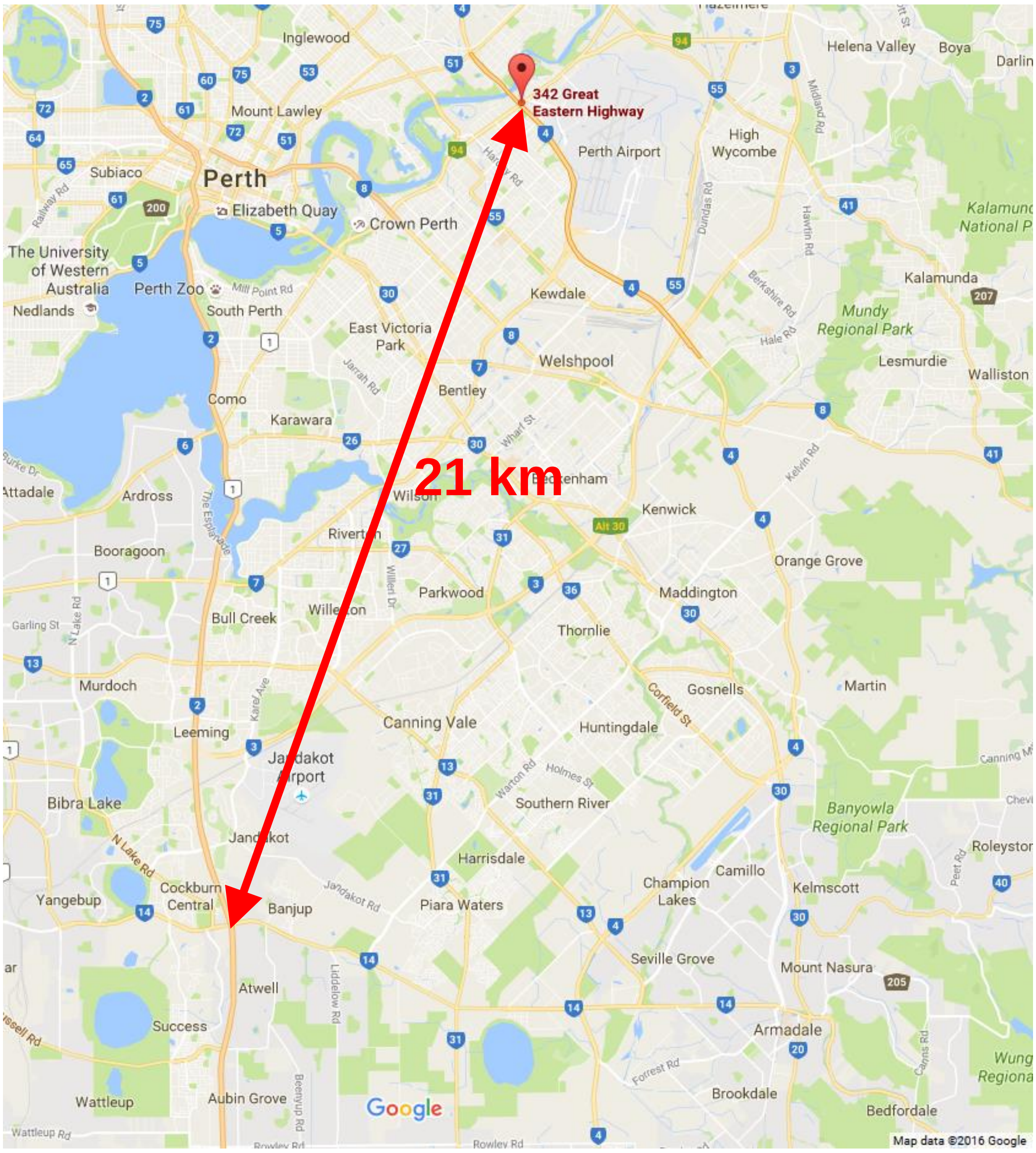
3.1 Background

In late 2012, Curtin University collaborated with the City East Alliance and Main Roads to install a series of temperature sensors and strain gauges at two sites along a new pavement as part of the Great Eastern Highway widening project. Information regarding this project and sensor instrumentation has been provided by Colin Leek (personal communication 27 February 2014).

The installation took place in November 2012, although it appears that apart from testing that the data was being received, there was no continuous data captured until the 28th March 2013.

The site is near Perth Airport, approximately 21 km North-North East of the new instrumentation site on the Kwinana Freeway that was installed in 2016 (Figure 3.1). Perth Airport weather data was used for comparison purposes to verify the instrumented site data.

Figure 3.1: Distance between Curtin Uni. instrumentation and Kwinana Fwy site



Source: Google (2018)

The two instrumented sites were labelled ‘Site 3’ and ‘Site 5b’. At Site 3, there are five temperature sensors installed at 40 mm, 80 mm, 150 mm, 220 mm and 290 mm depth, while at Site 5b sensors were installed at 40 mm, 80 mm, 150 mm, 220 mm, 290 mm and 360 mm depth. An air temperature sensor was installed in the pit used for equipment, although this will not necessarily be representative of the air temperature measured near the road surface. For that reason, Perth Airport air temperature data may be a more appropriate proxy for the air temperature at the Great Eastern Highway site.

The two installations were done in conjunction with construction, essentially by placing temperature sensors and strain gauges on the top of previously compacted layers (protected by a shallow layer of loose-mix asphalt). Cables ran to the edge of the pavement through a conduit attached to a steel riser at each level.

Early observations from the project team (personal communication, Colin Leek) included:

- During testing of the strain gauges, white tape was laid on the pavement to guide trucks so that they would pass over the strain gauges. It was found that the white tape had much higher reflectivity than the asphalt pavement, and pavement temperatures were lower as a result. This tape was removed shortly after the strain gauge testing but may have influenced some early results.
- The temperature changed rapidly when trucks are parked over the pavement, indicating a strong effect of solar radiation on the temperature at depth, and that traffic levels will possibly influence temperature at depth (particularly for urban areas).

The intention of this task was to obtain as much data as possible from the University, and review this data to determine its potential applications, which may include:

- methodologies employed, lessons learnt during installation, calibration, data acquisition etc.
- comparisons between the Curtin University data and data from other existing instrumentation sites (e.g. Brisbane and South Gippsland)
- comparison with the existing WMAPT values recommended for Perth
- analysis of temperature profiles at depth and how this may impact asphalt pavement design
- investigate the influence of other weather factors through linking the Curtin University data with data from the nearest Bureau of Meteorology weather station.

Unfortunately, the instrumentation suffered major damage due to a heavy rainfall event in 2013, and data has not been collected since June 2013. It is not clear whether the sensors are still operational, and they may only require a new data logger to start recording data again. It appears that all of the key personnel involved in this installation are no longer employed at Curtin University.

3.2 Temperature Analysis

The pavement temperature output from a single day, 4 April 2013, is presented in Figure 3.2. The time distribution of relative temperatures at various depths reflect the relationships identified in previous research and through the data captured at existing temperature monitoring sites.

It is not easy to conduct a comprehensive temperature analysis as the pavement temperature data at six depths only covers a small portion of the year (approximately end of March – June 2013). It is, however, interesting to note the differences between the two sites over the time period where both sites have complete data.

Site 3 has higher average temperatures at every depth (Table 3.1), and this is despite Site 3 including data for two additional weeks in winter (period of 7–20 June). The reasons for this are not clear, however it may be due to slight variation in the actual depth of asphalt covering each site. The method of installation relies on accurate layer depths from the asphalt paving crew to determine the overall and relative depth of each sensor.

The method adopted at the Kwinana Freeway site instrumented as part of this project involved coring out the existing asphalt and accurately measuring the installation depth of each sensor. This assisted to reduce the degree of uncertainty during data analysis.

Figure 3.2: Sample day at Site 3 – pavement temperatures at five depths

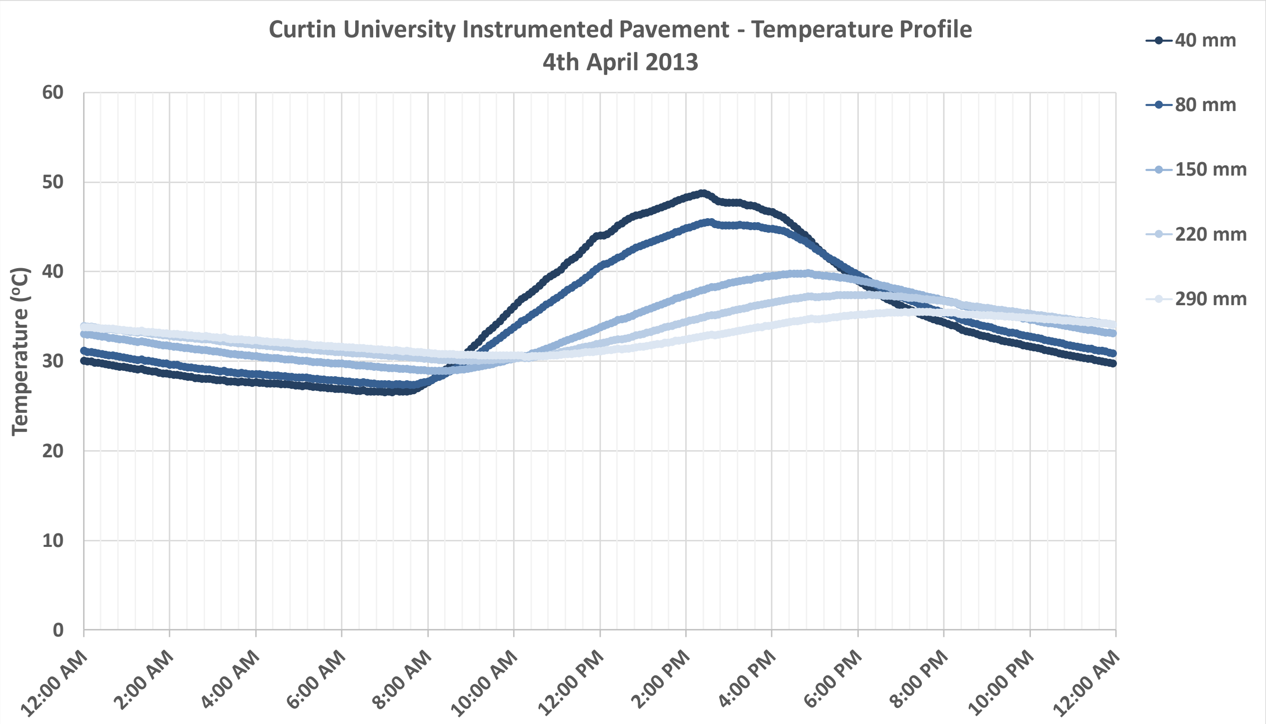


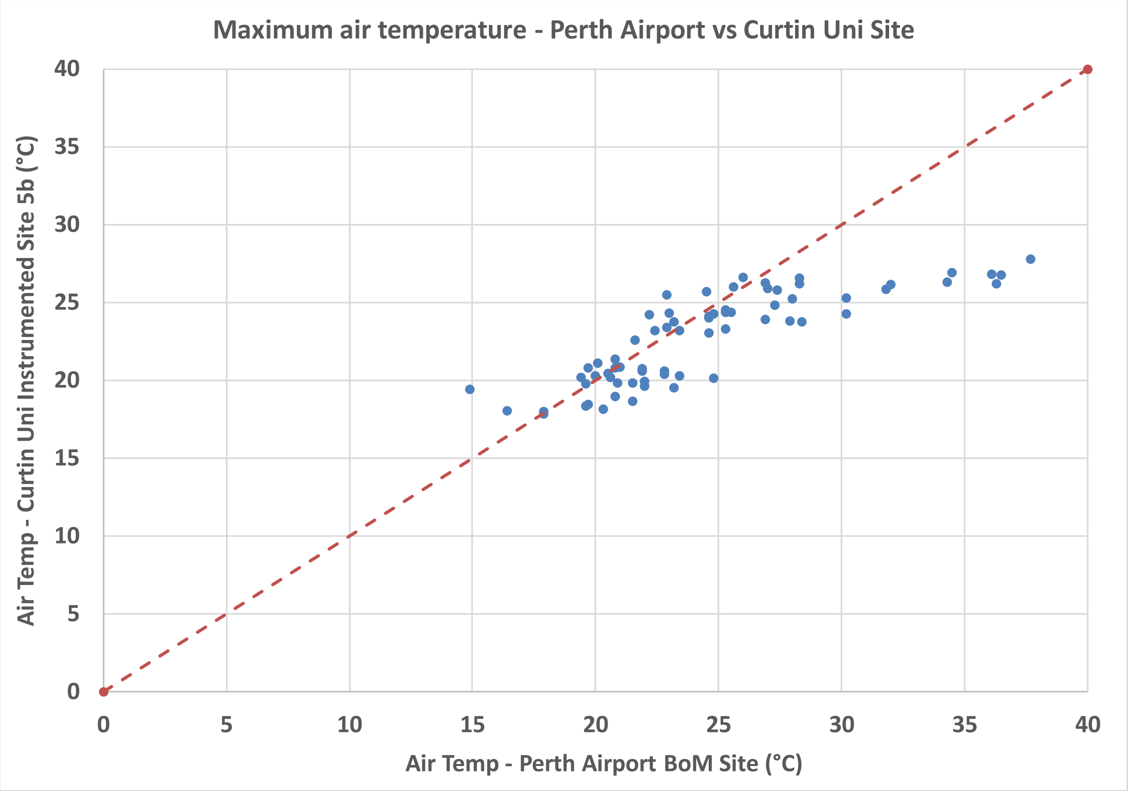
Table 3.1: Average temperatures at depth at Great Eastern Highway instrumentation site (March – June 2013)

	Site 3	Site 5b
Perth WMAPT (°C)	29	
40 mm (°C)	23.8	21.3
80 mm (°C)	23.8	21.5
150 mm (°C)	23.7	21.9
220 mm (°C)	24.0	21.9
290 mm (°C)	24.0	22.2
360 mm (°C)	N/A	22.3

Comparing the temperature in Table 3.1 to the WMAPT is not possible at this stage, as the WMAPT value is representative of an entire year of data rather than several months in autumn. Even though the autumn temperatures should be fairly reflective of annual averages, the fact that the WMAPT value is *weighted* means that summer and winter months must be included to take extreme temperature variations into account.

The data also presents some irregularities when compared to the air temperatures recorded at Perth Airport (Figure 3.3). The two sources are strongly correlated up to around 25 °C, while on hotter days at Perth airport the air temperature sensor at the site returns a consistently lower reading. The exact reasons for this are not known, although it may be influenced by the location of the sensors on site.

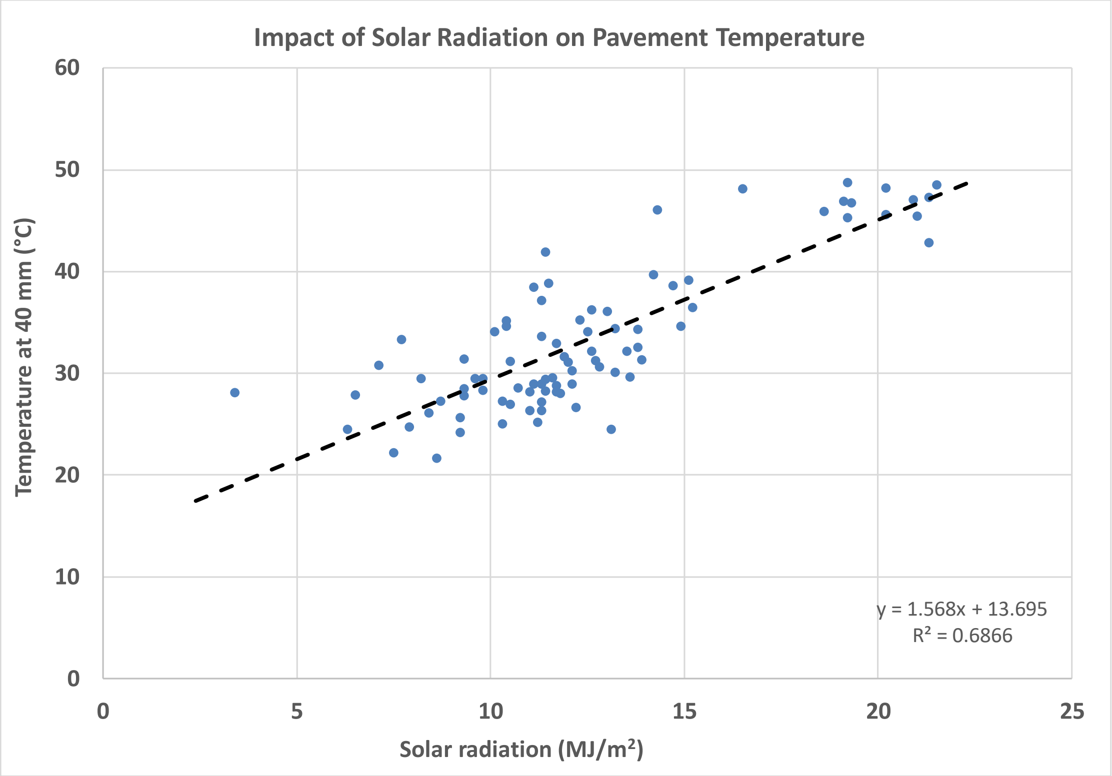
Figure 3.3: Comparison of maximum air temperatures – Great Eastern Hwy site vs Perth Airport



3.3 Solar Radiation

Solar radiation data were obtained from the Perth Airport weather station 009021 (Commonwealth of Australia 2018a). The daily solar radiation data were compared to the daily maximum temperature to evaluate the impact of solar radiation on pavement temperature at this site (Site 3 plotted in Figure 3.4). The relationship (as would be expected) is strong at this location, indicating that sunny days are conducive to hotter pavement temperatures.

Figure 3.4: Solar radiation impact on near-surface pavement temperature – Great Eastern Hwy



3.4 Lessons Learnt

The data obtained from Curtin University was not sufficient to satisfy all the objectives of this portion of the project, however it still allowed for some important lessons to be learnt that assisted in subsequent tasks.

3.4.1 High Degree of Variance Between Sites

Site 5b appears to be returning values that are significantly lower than those at Site 3, particularly from the start of data collection (28 March) through 11 April 2013 where the difference between the two sites at the 40 mm sensor was greater than 10 °C on most days. This is evident in Figure 3.5 and Figure 3.6, which shows the difference between maximum pavement temperatures at the two sites against both total daily solar exposure and maximum daily temperatures, with the first two weeks mostly represented by the data points to the far right (hotter days in March/April).

This discrepancy may be influenced by the presence of white tape on the road surface, which was used to guide trucks over the sensors. However, this does not explain why the temperature was higher at 80 mm than at 40 mm for much of this period. Even so, it was important that the surface at the new location was consistent with the remainder of the road surface, to minimise the impact of surface albedo[1] on the results.

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[1] Albedo is defined as 'the fraction of incident radiation (such as light) that is reflected by a surface or body (such as the moon or a cloud)' (Merriam-Webster 2018), in this case a road surface with lighter coloured aggregate or binder would have a higher albedo (reflect more incident radiation) while a darker pavement would have a lower albedo (reflect less solar radiation and therefore absorb more solar energy).

Figure 3.5: Mismatch between sites with maximum pavement temperature and solar radiation – Great Eastern Hwy

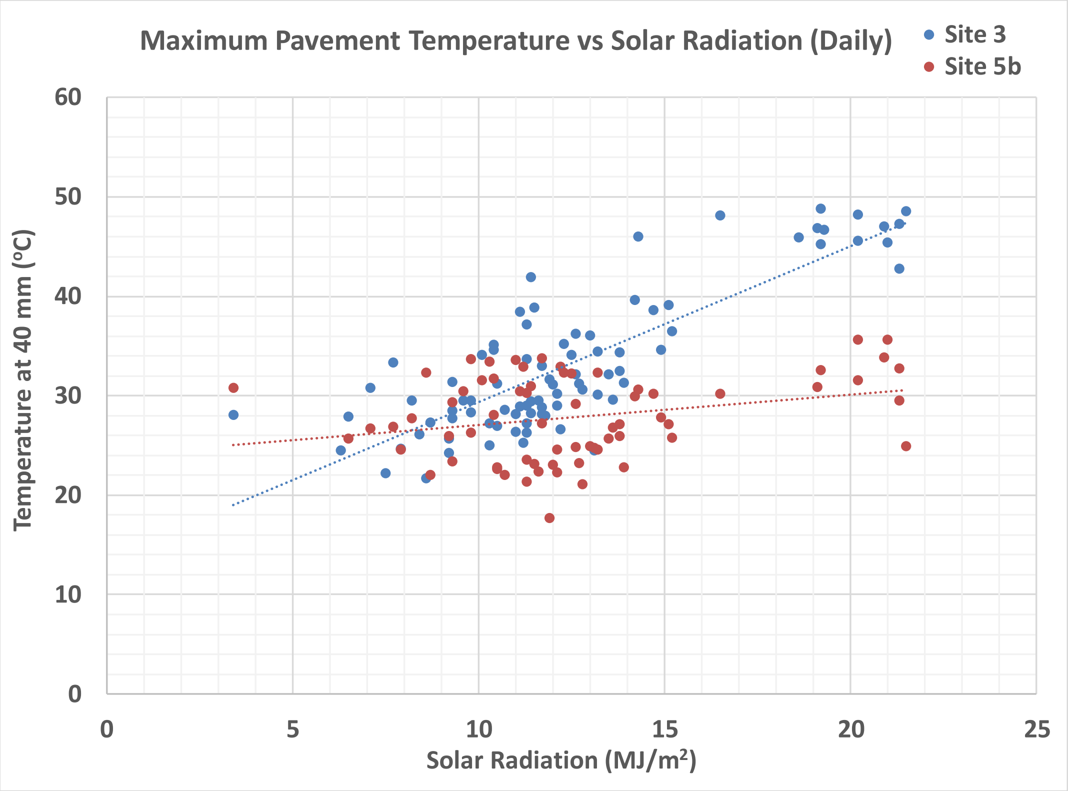
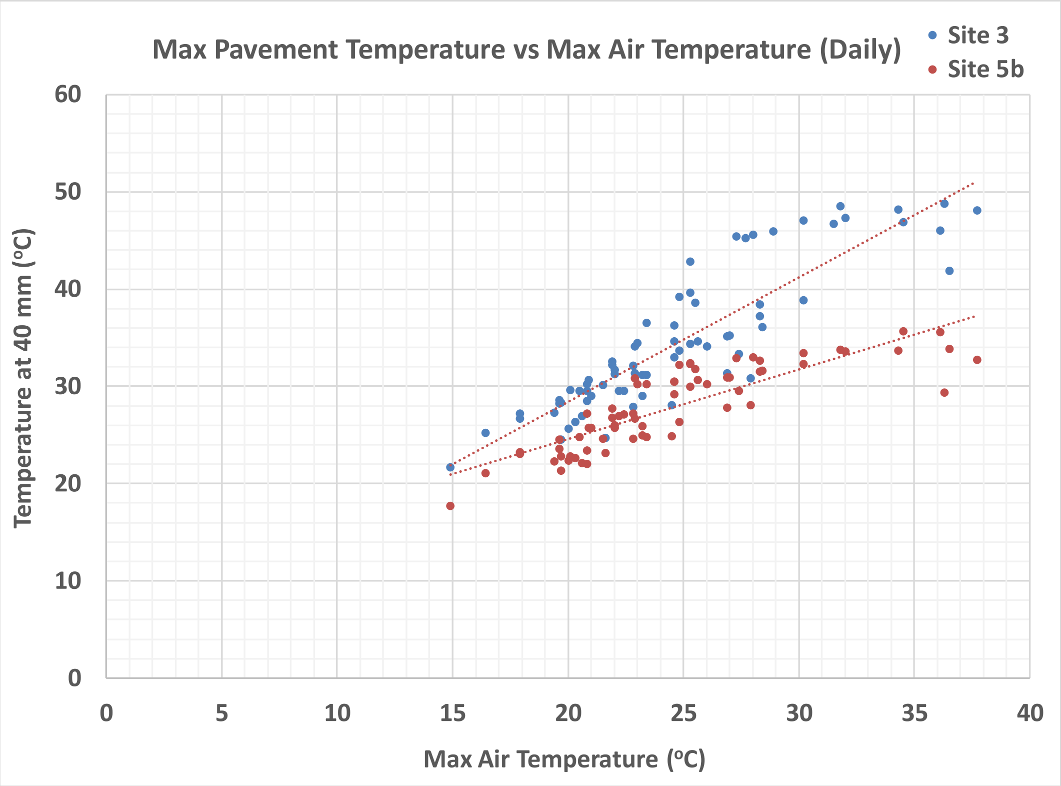


Figure 3.6: Mismatch between sites with maximum pavement and air temperatures – Great Eastern Hwy



3.4.2 Other

As with the data recorded at Eagle Farm and South Gippsland, the average temperatures at this site for each depth are very similar to each other, but the relative ranges vary considerably (i.e. more extreme maximum and minimum temperatures near the surface). The pavement temperature measurements from the Great Eastern Highway have limited value in terms of this analysis for a number of reasons, including:

- the data only covers 85 days of data, and mostly through the temperate autumnal months (summer and winter being the critical times for temperature maxima and minima)
- data was lost at Site 5b between 4 and 8 April 2013 due to a flat battery in the data logger
- the site does not appear to have been linked to an on-site weather station, which would provide readings for air temperature and solar radiation
- the location is in an urban area and is quite heavily trafficked, which may introduce low-speed vehicle shading effects that are hard to incorporate into the modelling.

Despite these factors, the analysis has revealed that the temperature behaviour of asphalt pavements follows relatively predictable trends and relationships, and there is sufficient potential to develop a model that could predict the distribution of pavement temperatures at depth across the year. This confirms the findings of previous studies (Austroads 2013b) that there is considerable scope for increased sophistication in temperature modelling of asphalt pavements in Australia, and that the WMAPT approach may not be adequate to accurately predict the behaviour of in-service pavements.

As noted, the instrumented sites are no longer operational. Nonetheless, the experience obtained during this installation was valuable for avoiding some of the same issues faced at the Great Eastern Freeway site, including:

- ensuring that sensors and electronics are safe from inundation under heavy rain, and exposed parts are waterproof
- sensors are carefully calibrated and tested before installation
- preferably use live data logging with email alerts to quickly identify issues with faulty sensors/equipment.

4 TEMPERATURE MONITORING INSTRUMENTATION

4.1 Background

There are four known existing sites around Australia with pavement temperature instrumentation. In addition to the site on the Great Eastern Highway, the University of the Sunshine Coast has at least one instrumented pavement near their campus at Sippy Downs. A site near Darwin has recently been instrumented by the Northern Territory's (NT) Department of Infrastructure Planning and Logistics (DIPL) and this data were made available for this project.

The Australian Road Research Board (ARRB) has previously been involved in the installation and monitoring of two similarly instrumented pavements, one in Eagle Farm (close to the Brisbane CBD) and the other on the South Gippsland Highway, approximately 65 km south-east of Melbourne. Table 4.1 contains a summary of the key data at these locations, as well as the installations as a part of this project at the Kwinana Freeway south of Perth, and in Karratha.

These ARRB installations are documented in previous reports (Austroads 2017b).

Table 4.1: Pavement instrumentation sites – summary data

Location	Managed by	Date started	Depth of sensors (mm)	Data interval	Air temp	Solar radiation	Wind	Rain
Great Eastern Highway, Perth, WA	Curtin University	28/3/2013	40, 80, 150, 220, 290 & 360	5 min	No	No	No	No
Sippy Downs, Queensland	University of the Sunshine Coast	13/9/2013	Surface & approx. 75mm	1 min	Yes	Yes	No	No
Eagle Farm, Brisbane, Queensland	ARRB	20/2/2014	50, 70, 110, 190, 290 & 390	10 min	Yes	Yes	Yes	Yes
South Gippsland Highway, Victoria	ARRB	26/6/2015	55, 75, 120, 185, 235 & 325	10 min	Yes	Yes	Yes	Yes
Kwinana Freeway, Jandakot, WA	ARRB	21/9/2016	45, 85, 120, 160, 200 & 320	10 min	Yes	Yes	Yes	Yes
Coolalinga, Darwin, NT	NT DIPL	14/8/2017	50 shoulder, 50 wheelpath, 150, 250	15 min	No	No	No	No
Karratha, WA	ARRB	26/6/2018	45, 85, 120, 160, 200 & 260	10 min	Yes	Yes	Yes	Yes

Early analysis of the data from the two earlier ARRB installations revealed that air temperature alone was not enough to explain the variance in pavement temperatures. Other factors such as solar radiation, rainfall, relative humidity and pavement configuration were also shown to be important (summarised in Table 4.2).

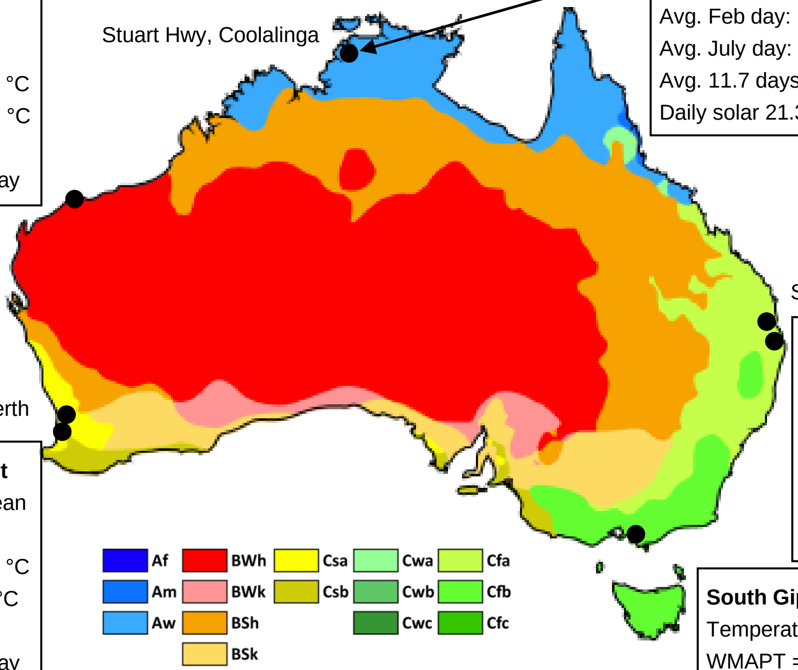
For this reason, it was considered especially valuable to secure a weather station and instrumentation site in a location with hot, dry summers and mild, moist winters (such as in Perth). The site in Perth represents much of the populated areas of South Australia and Western Australia (represented by *Csa* and *Csb* in Figure 4.1). Along with the sites in *oceanic* (South Gippsland Highway) and *humid subtropical* (Eagle Farm and Sippy Downs) climates, this allowed the project team to study the climate effects on asphalt pavements in regions covering 85% or more of the Australia population, and a similar percentage of the full-depth asphalt road network. The addition of a site in Darwin further increased the proportion of climate zones represented in the study.

Table 4.2: Climate data across the four ARRB installation locations

City	Perth, WA[1]			Karratha, WA[2]			Brisbane, Queensland[3]			South Gippsland, Victoria[4]		
Köppen climate classification	*Hot-summer Mediterranean*			*Hot desert*			*Humid subtropical*			*Temperate oceanic*		
	Feb	Jul	Year	Feb	Jul	Year	Feb	Jul	Year	Feb	Jul	Year
Record high (°C)	46.6	25.9	46.6	47.7	34.0	48.2	41.7	29.1	41.7	46.0	22.5	46.0
Average high (°C)	31.7	17.9	24.5	35.7	26.3	32.4	30.0	21.9	26.5	25.7	13.4	19.4
Mean days ≥ 35 °C	6.7	0.0	25.3	16.0	0.0	111.6	0.6	0.0	3.6	1.7	0.0	6.7
Average low (°C)	17.1	6.7	11.5	26.7	13.8	20.8	21.3	10.2	16.3	14.0	6.2	9.7
Record low (°C)	6.5	−2.8	−3.4	19.4	6.9	6.9	16.5	2.6	2.6	6.7	-0.7	-2.5
Mean days ≤ 2 °C	0.0	5.9	15.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	4.6
Mean 3pm temperature (°C)	29.7	16.7	22.9	33.7	25.0	30.6	28.2	20.8	24.8			
Mean 3pm rel. humidity (%)	36	58	47	55	40	43	59	44	52			
Rainfall (mm)	16.0	173.1	824.3	77.1	14.0	300.4	142.5	24.0	1021.6	49.5	71.1	819.9
Average precipitation (days)	2.3	17.6	108.8	5.3	2.0	27.4	13.3	7.3	124.7	8.6	19.9	183.4
Mean daily solar exposure (MJ/m²)	26.0	9.7	19.1	25.4	16.9	22.8	21.1	13.0	18.5	21.3	6.7	14.9

1: 1989-2016 at Jandakot Airport - BoM site number 009172
2: 1993-2018 at Karratha Aero – BoM site number 004083
3: 1999-2016 at Brisbane - BoM site number 040913
4: 1990-2016 at Cranbourne – BoM site number 086375

Figure 4.1: World Koppen Climate Classification map (Australia)



Karratha
Hot desert
WMAPT = 40 °C
Avg. Feb day: 26.7–35.7 °C
Avg. July day: 13.8–26.3 °C
Avg. 111.6 days > 35 °C
Daily solar 22.8 MJ/m²/day

Coolalinga (Darwin)
Tropical savanna
WMAPT = 41 °C
Avg. Feb day: 24.7–31.4 °C
Avg. July day: 19.3–30.6 °C
Avg. 11.7 days > 35 °C
Daily solar 21.3 MJ/m²/day

Sippy Downs

Eagle Farm (Brisbane)
Humid subtropical
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/m²/day

Great Eastern Hwy, Perth

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/m²/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/m²/day

Source: Adapted from Peel, Finlayson and McMahon (2007), Commonwealth of Australia (2018a)

To maximise the benefits of the instrumentation previously installed by ARRB, the new sites installed as part of this project had a similar instrumentation configuration to the existing ARRB instrumented sites. This included installing six temperature probes at depths ranging from as close to the surface as practically possible, down to just above the base of the lowest asphalt layers. The weather stations were commissioned with sensors for solar radiation, air temperature, wind, rainfall and relative humidity, all with remote monitoring in both 10 minute and 1 hourly intervals. The same equipment supplier and installer, Environdata, was engaged for all four ARRB projects.

The online portal to access temperature data is provided for an annual fee from the weather station provider, Environdata. The readings are available through a live feed and can be downloaded in 10-minute or hourly increments. The temperature readings for each site represent the average reading over the preceding 10-minute or 1-hour interval. The system allows for alerts via email should (for example) the temperature exceed a certain critical value, or rainfall exceed a threshold value in the preceding hour.

4.2 Kwinana Freeway, Perth

4.2.1 Site and Instrumentation Details

The instrumentation site is on the Kwinana Freeway, approximately 20 km south of the Perth CBD. The Kwinana Freeway is a major commuter route in and out of central Perth, with heavier traffic in the afternoon peak compared to the morning peak. Traffic data is available at this site (see Table 4.3), although it does not include a count of heavy vehicles. To estimate heavy vehicle numbers, a value of 12.1% heavy vehicles is drawn from a nearby site located further south along the Kwinana Freeway near Russell Road.

Table 4.3: 2017/18 traffic statistics at Kwinana Freeway southbound at bridge under Berrigan Drive (site 8437)

Count time	Morning peak – 7am (vehicles/hour)	Afternoon peak – 4pm (vehicles/hour)	Daily traffic (vehicles)	Heavy vehicles (%) *(nearby site)*
Weekdays	2999	3767	48366	12.1%
Full week	2822	3545	45512	N/A

Source: Main Roads Western Australia (2018)

The temperature sensors have been installed in the emergency stopping bay just south of the Berrigan Drive overpass (Figure 4.2). This location was considered suitable for the sensor installation for a number of key reasons, including:

- low traffic over emergency stopping bay means a low likelihood of vehicles parked over the sensors, which would block the sun and artificially reduce the pavement temperature at depth
- minimal pedestrian access, as it is on a freeway reservation, i.e. – low risk of vandalism
- clear area around site with minimal restrictions to sunlight (except for one streetlight)
- shoulder material is mostly sand, and easy to dig through
- enough space on the shoulder and roadside reserve for safe access for personnel during installation and periodic maintenance.

Figure 4.2: Map of instrumentation site

Source: Google (2018)

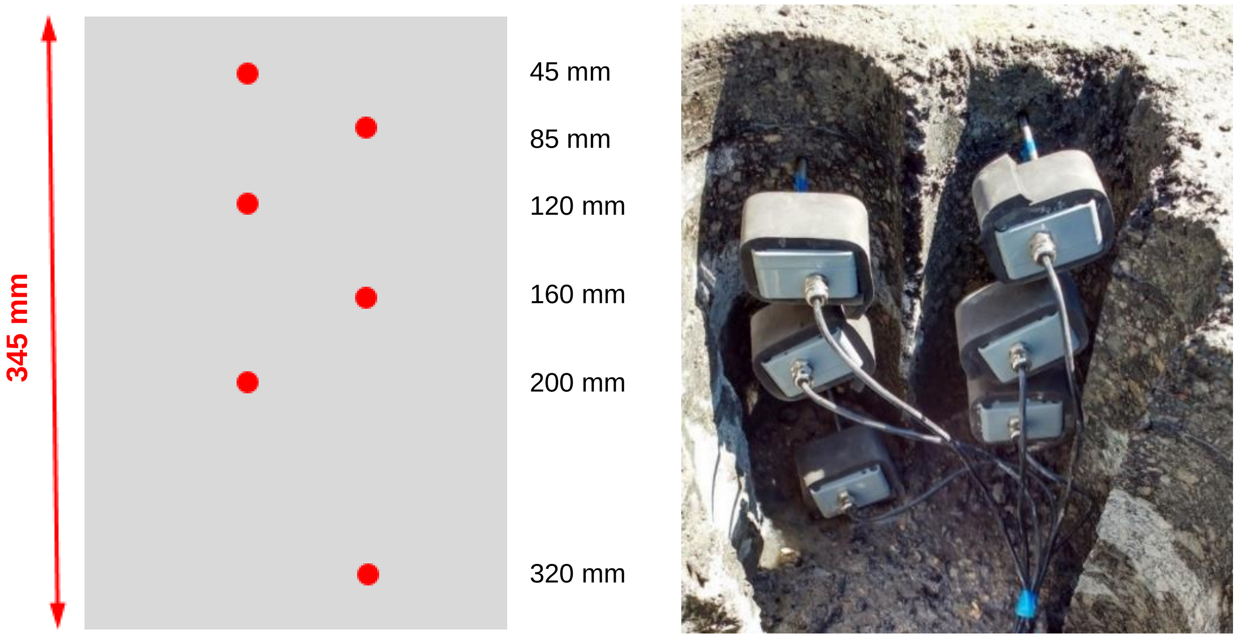
4.2.2 Temperature Sensor Depths

The depth of the temperature sensors was discussed during the planning stages, and it was agreed to avoid installing a sensor in the open-graded asphalt surfacing, and to place the first sensor at 45 mm depth. The other five sensors are spaced roughly evenly down to the bottom sensor which was placed 25 mm above the base of the lowest asphalt layer (Table 4.4 and Figure 4.3).

Table 4.4: Depth of temperature sensors within asphalt layers

Layer	Layer depth (mm)	Progressive depth (mm)	Sensor No.	Sensor depth from road surface (mm)	Notes
OGA	30	30	-	-	(OGA not suitable for installing sensors)
10 mm DGA	30	60	1	45	Sensor at middle of DGA10 layer
14 mm IC	50	110	2	85	Sensor at middle of IC14 layer
20 mm IC (A15E)	60	170	3	120	
			4	160	Sensor at approx. mid-depth of asphalt layer
20 mm IC (C320)	175	345	5	200	
			6	320	Sensor at ~25 mm above bottom of asphalt layer

Figure 4.3: Temperature sensor layout (left) and sensors after installation (right)



4.2.3 Procedure

The procedure for installation, as well as a series of photos relating to the various steps in this process, can be found in Appendix A.1.

4.2.4 Lessons Learnt

Fortunately, experiences through the installations in Brisbane and South Gippsland meant that there were few issues encountered.

The only major delay in timing was on the second day, due to some difficulties with the weather station installation and coring the asphalt. This meant that some of the tasks from day 2 were completed on the morning of day 3.

4.3 Karratha

4.3.1 Site and Instrumentation Details

A second site for monitoring asphalt pavement temperatures in WA was originally planned for installation in 2017 at the Northlink EME2 demonstration project in the northern suburbs of Perth. The weather station and various instrumentation for this second site were supported by the Australian Asphalt Pavement Association (AAPA), continuing their involvement across various research studies of asphalt temperatures in Australia.

In early 2018, it was decided to use the weather station and sensors purchased for this site at a location that could offer a significantly different data set from a different climate zone. A site in the northern part of the state (at the Main Roads Karratha depot) was subsequently secured. The site required the construction of a full-depth asphalt test pad in mid-June 2018, at which the temperature sensors and weather station were installed on the 26th and 27th of June 2018 (see Figure 4.4).

Figure 4.4: Completed installation in Karratha – June 2018

4.3.2 Temperature Sensor Depths

The depth of the temperature sensors was the same as the previous trial for the top five sensors, with the first sensor at 45 mm depth. The deepest sensor was placed roughly 25 mm above the base of the lowest asphalt layer, which equated to a depth of 260 mm as opposed to 320 mm for the bottom sensor at the Kwinana Freeway site.

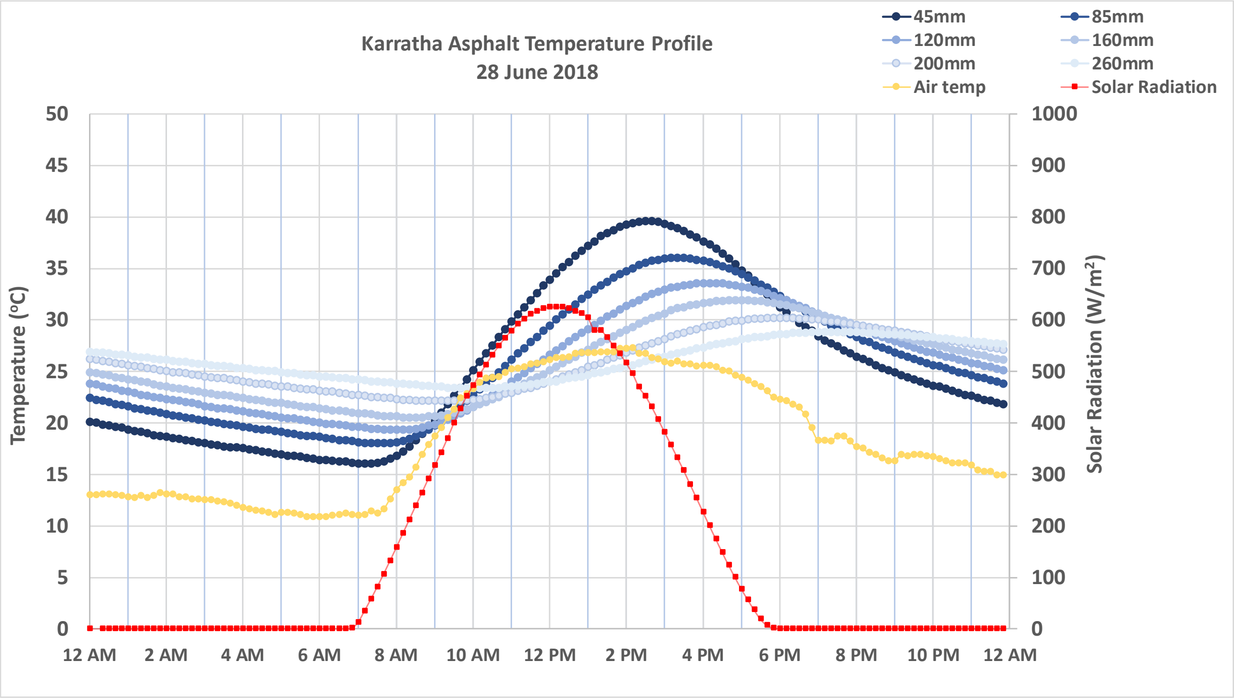
4.3.3 Procedure

The procedure for installation, as well as a series of photos relating to the various steps in this process, can be found in Appendix A.2.

4.3.4 Collected Data

Data collected on the first full day following installation (28/6/2018) for the Karratha installation are presented in Figure 4.5. The data reflect similar relationships between the temperature sensors at various depths, and climate factors (notably the solar radiation and air temperature) compared to the other installation sites. This suggests that no major errors have occurred during construction or installation. Over the first few days, the temperature profiles for each day were near identical, reflecting the very stable and predictable weather conditions in Karratha during the dry season. Additionally, it is reassuring that there are no sudden drops in the solar radiation data which may indicate an obstruction to the sensor. The surrounding area was checked for potential obstructions before installation.

Figure 4.5: Karratha site - asphalt temperature profile and weather over 24 hours (28 June 2018)



4.3.5 *Power Issues – December 2018*

In November 2018, some gaps in the data were appearing in the early hours of the morning (just before sunrise). It is likely that this was due to the battery not receiving enough charge from the solar panel during daylight hours in order to power the unit right through the night. A new higher capacity battery was installed however the issue continued, with almost all data unrecoverable between 9 December 2018 and 30 January 2019. One possibility is that this was due to the solar panels being aligned incorrectly, and not accounting for the fact that the site is north of the Tropic of Capricorn and hence needs a south facing solar panel during the peak of summer.

Small gaps in data in November 2018 have been reasonably approximated using the existing data. It was decided that due to the loss of most of two months of data, it was too large of a gap to interpolate or model results for the December-January period, so those months have been removed from the monthly analysis. Data is once again being reliably captured however a more permanent solution to these issues is to be implemented before the 2019/20 summer.

4.4 Comparison between the Perth and Karratha Sites

After two complete months of data capturing, the data from the two WA locations are compared to illustrate the significant differences in climate in the two locations, and how this impact on the asphalt temperature at various depths. For a single corresponding day of data, the contrast is clear (see Figure 4.6), with pavement temperatures and weather data presented in Table 4.5.

It is interesting to note that although the average air temperature at the Karratha site was only 6.4 °C higher than in Perth, the average asphalt temperature was more than 12 °C higher at each sensor depth, with maximum asphalt temperatures up to 17.6 °C higher. This is likely attributable to the significant difference in cumulative solar radiation received at each site, with Karratha averaging 16.0 MJ/m^2 per day and Perth averaging just 8.2 MJ/m^2 per day. The air is also much drier in Karratha, with average relative humidity at 51.6% compared to Perth's 76.8%.

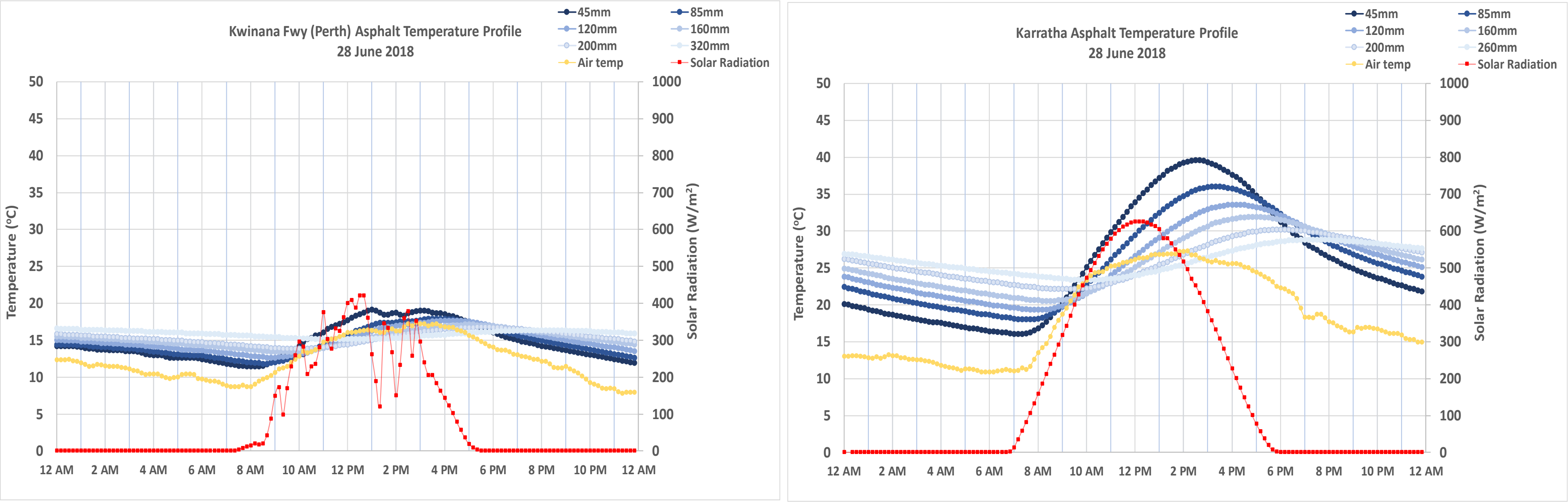
The air temperatures were also much more consistent at the Karratha site. The standard deviation of maximum and minimum air temperatures over this period were 1.7 °C and 2.2 °C respectively for Karratha, as compared to 2.2 °C and 3.1 °C respectively for the Perth site. This may mean that the Karratha site will be more likely to experience prolonged periods of very high temperatures, which have been identified as being critical to generating high temperatures deep in the pavement.

Also of note was the very high minimum temperature measured by the deepest sensor at the Karratha site. For the entire 62 days over July and August 2018, the temperature at 260 mm depth never dropped below 23.8 °C. The cooler nights were clearly not cool enough or long enough to make much impact deeper in the pavement. This also reduces the energy required to bring the deep-layer temperature back up to its maximum value.

Table 4.5: Comparison of pavement temperatures and weather factors in July/August 2018 at two WA sites

		Perth	Karratha
Air temperature (°C)	Max	25.2	30.7
	Avg	13.5	19.9
	Min	3.5	8.0
Avg. daily maximum air temp (°C)		18.3	27.1
Avg. daily minimum air temp (°C)		8.7	12.8
Avg. relative humidity (%)		76.8	51.6
Daily solar exposure (MJ/m²)	Max	14.3	19.3
	Avg	8.2	16.0
	Min	0.8	10.9
Total rainfall (mm)		341.0	0.2
Sensor 1 (°C) (nearest surface)	Max	27.8	45.4
	Avg	15.6	28.0
	Min	7.6	16.4
Sensor 2 (°C)	Max	25.5	41.0
	Avg	15.5	28.0
	Min	8.0	18.4
Sensor 3 (°C)	Max	24.0	38.3
	Avg	15.6	27.9
	Min	8.8	19.7
Sensor 4 (°C)	Max	22.2	36.2
	Avg	15.6	27.9
	Min	9.8	21.0
Sensor 5 (°C)	Max	21.2	34.0
	Avg	15.6	28.0
	Min	10.3	22.5
Sensor 6 (°C) (deepest sensor)	Max	19.0	32.2
	Avg	15.7	28.0
	Min	12.1	23.8

Figure 4.6: Comparison of pavement temperatures and weather on 28 June 2018



5 PAVEMENT TEMPERATURE ANALYSIS

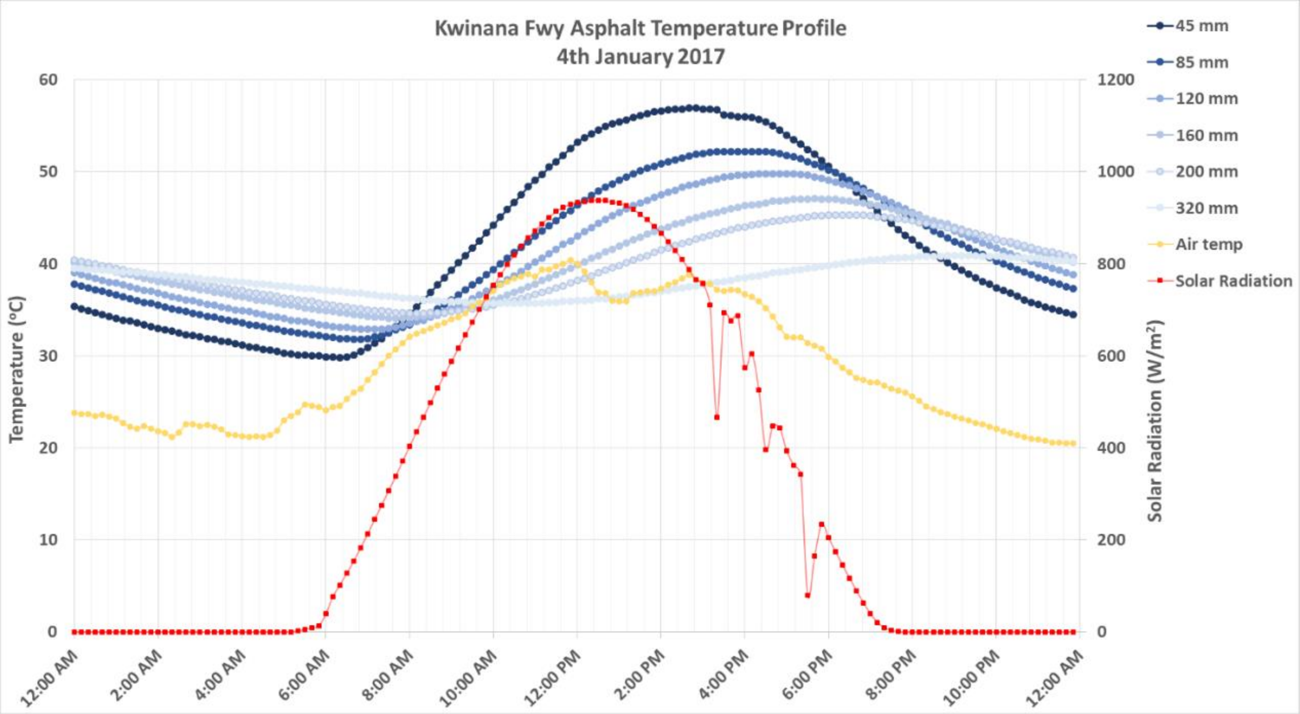
To acquire an early indication of the range of temperatures over the hot summer months, a preliminary analysis was completed at the end of March 2017. The hottest day of the 2016/17 summer, 4 January 2017, is analysed in Section 5.1. At update after a full 12 months of data is presented in Section 5.2, with a summary of the 2017/18 summer (i.e. the 2nd summer) in Section 5.3. The predicted general climate in 2018/19 is explored in Section 5.4

5.1 Initial Analysis

5.1.1 Hottest Summer Temperatures – 2016/17

Across the 2016/17 summer, the hottest day in terms of pavement temperatures near the surface was the 4th of January 2017, as shown in Figure 5.1. The maximum temperature at 45 mm depth of 56.9 °C was reached at around 3pm.

Figure 5.1: Temperature profile on hottest day of the 2016/17 summer



5.1.2 Comparison to Other Australian Sites – 2016/17 Summer

Climate and pavement temperature data, including extreme temperatures, over the first six months of the installation at the Kwinana Freeway, are included in Table 5.1. This table also includes data for the sites in Victoria and Queensland for comparison. It should be noted that due to failures with two sensors in early 2016, it was preferable to use 2015/16 data for the Brisbane site rather than 2016/17.

Table 5.1: Comparison of four ARRB instrumented sites over first summer (November to March)

		Perth	Brisbane[1]	South Gippsland
Air temperature (°C)	Max	41.9	36.8	36.4
	Avg	21.7	25.2	18.0
	Min	8.3	17.2	4.3
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)	Avg	22.1	16.9	15.6
Total rainfall (mm)		191.0	341.4	218.2
Sensor 1 (°C) (nearest surface)	Max	56.9	55.9	48.8
	Avg	33.3	36.6	26.0
	Min	14.9	23.6	12.0
Sensor 2 (°C)	Max	52.2	54.7	46.4
	Avg	33.1	36.5	26.0
	Min	17.2	24.0	12.7
Sensor 3 (°C)	Max	49.8	50.4	N/A (damaged during construction)
	Avg	33.0	36.3	
	Min	18.6	25.5	
Sensor 4 (°C)	Max	47.1	46.0	36.7
	Avg	32.9	36.1	25.6
	Min	20.1	27.6	16.1
Sensor 5 (°C)	Max	45.3	42.9	34.5
	Avg	32.7	35.8	25.4
	Min	20.8	29.1	16.8
Sensor 6 (°C) (deepest sensor)	Max	40.9	40.6	31.8
	Avg	32.2	35.1	25.2
	Min	23.3	29.5	17.8

Note 1: Brisbane data is from October 2015 to March 2016

Some notable observations over this period include:

- the overall average air temperatures at the Perth site was measured at 21.7 °C, which falls between the average temperature measured at the South Gippsland and Brisbane sites. Perth also had the widest range between average daily maximum and minimum air temperatures
- the Perth site receives significantly more average daily solar exposure than the other two locations
- the Perth site also had the lowest rainfall over this period, and more than half of the total for the six month period fell on the 9th and 10th of February 2017
- pavement temperatures exceeded 55 °C at the shallowest sensor in the Perth and Brisbane sites, with the temperature at the actual surface likely to be over 60 °C (see Section 6.3.4 for more detail)

  - — this is lower than the maximum pavement temperatures found in the Australian study by Dickinson (1981), with one factor potentially being that these road surfaces each included an open-graded wearing course, which may not have the same thermal properties as dense-graded layers, or because the albedo of the surface was slightly higher than for previous studies

- the thermal properties of each pavement seem to be fairly consistent, as evidenced by the relative maximum, minimum and average temperatures reached at each depth
- The Perth site appears to be the site with the most notable change in behaviour at the deepest sensor, with the maximum and minimum temperatures being quite different to the sensor directly above. This could potentially be due to the type of material in the underlying granular layer, moisture in the underlying granular layer, or the proximity of the sensor to the granular layer.

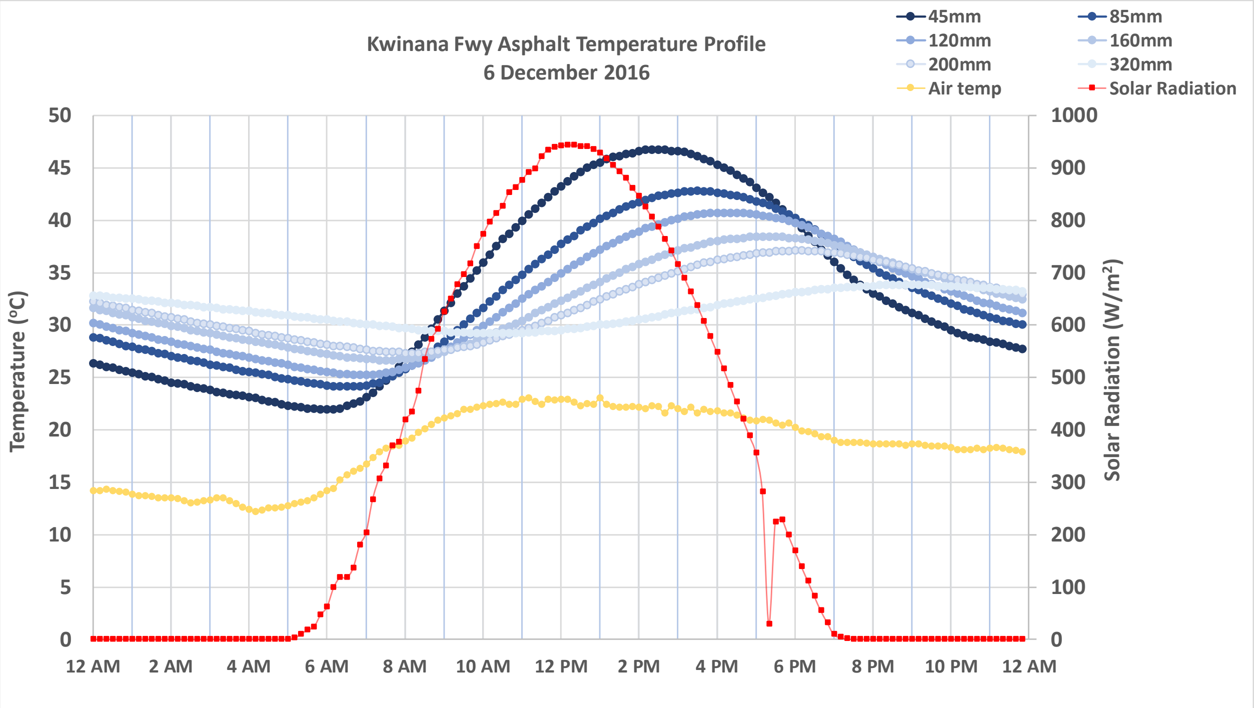
5.1.3 Other Initial Observations

Solar Radiation Irregularities

At the Eagle Farm site, there was a significant shading effect in the late afternoon from a tree just to the north-west of the solar radiation sensor on the weather station (although the shading did not impact on the pavement itself). As this was interfering with the solar radiation readings, the trees were removed with the permission from the local council.

The same effect appears to be present at the Kwinana Freeway site but to a much lesser extent (only around 20 minutes worth of interruption in the late afternoon). An example from an otherwise clear, sunny day is shown in Figure 5.2. A similar dip is evident in most clear and sunny days. The cause of this may be a light-pole or similar obstruction, but the issue is only in the late afternoon with already low solar radiation values and is not likely to greatly impact on any temperature predictions and modelling.

Figure 5.2: Solar radiation drop on sample day in December 2016



5.2 Updated Analysis in 2018

The summary of results in Table 5.1 was updated after a full 12 months of data was available and is presented in Table 5.2. The updated data provide for a better overall summary of the differences and similarities across the three sites as it accounts for the impact of the cooler winter months.

Table 5.2: Comparison of three ARRB instrumented sites over 12-month period

		Perth	Brisbane[1]	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	17.7	8.9
Daily solar exposure (MJ/m^2)	Max	28.1	25.1	25.8
	Avg	15.8	14.0	11.3
	Min	1.5	1.4	1.9
Total rainfall (mm)		796.0	739.2	700.8
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	*30.6*	19.3
	Min	7.4	*12.1*	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	30.1	19.3
	Min	11.6	18.5	9.4

Note: Brisbane data is from October 2015 to September 2016

Data in italics - Includes some interpolated data after errors in the original data file

Some notable observations include:

- the average air temperatures at the Perth site still falls between the temperatures measured at the Brisbane and South Gippsland sites. The Perth site also still has the largest range between the measured maximum air temperature and measured minimum air temperature

- the Perth site still receives the highest average daily solar exposure, but the difference between the Perth and Brisbane sites over the entire year is not as great as during summer (i.e. Brisbane has relatively more sunshine during winter)
- the total rainfall for the year was relatively similar between the three locations (all in the 700-800 mm range) but it was distributed differently throughout the year
- when comparing Perth and Brisbane pavement temperatures, the maximum temperature reached near the surface is very similar (56.9 °C vs 55.9 °C), however the overall minimum temperatures measured are significantly different at all depths, reflecting the milder winters in Brisbane
- during winter, the temperature behaviour of the asphalt at the Perth site more closely matches the temperatures measured at South Gippsland site rather than the site at Brisbane.

5.3 Updated Analysis for the 2017/18 Summer

After a cooler than average summer in 2016/17 (summer in this case defined as 1 December through until 28 February), the average daily maximum air temperature during the 2017/18 summer was higher than the previous year, but it was still 1-2 °C cooler on average than the 2012-16 summers (Table 5.3).

Table 5.3: Hottest days in Perth over previous six summers

Summer		Maximum temperature (°C)	Average daily maximum temperature across whole summer (°C)	Extreme heat days (daily maximum above 38 °C)
2012/13		41.3	32.1	13
2013/14		43.2	31.8	7
2014/15		43.7	31.4	6
2015/16		42.4	31.1	10
2016/17	BoM station	43.3	29.8	6
	Kwinana Fwy	41.9	28.7	6
2017/18	BoM station	38.6	30.2	1
	Kwinana Fwy	37.7	29.1	0

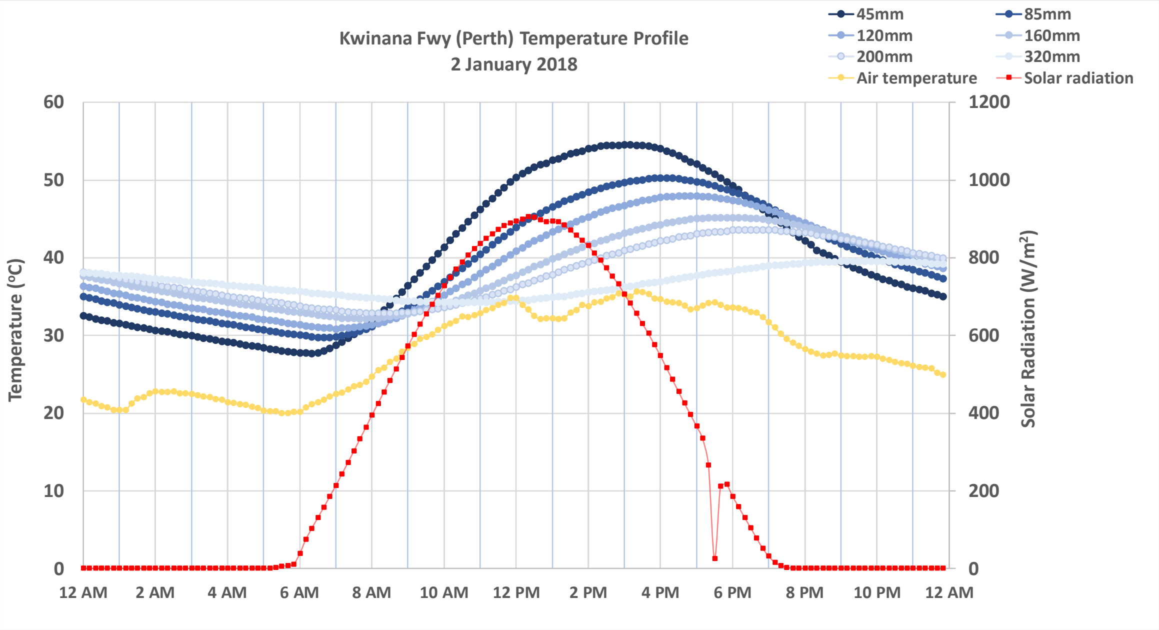
Source: Commonwealth of Australia (2018a)

There was a notable lack of ‘extreme’ heat days in 2017/18, which is when pavement surface temperatures could be expected to spike to 60 °C or higher. As measured by the Kwinana Freeway weather station, there were no days above 38 °C across the entire summer, while there were 6 days above 38 °C in 2016/17 and an average of 9 extreme heat days between 2012 and 2016.

The hottest day for the pavement was 2 January 2018, with the pavement temperature at the 45 mm sensor peaking at 54.5 °C at around 3pm (Figure 5.3).

It can also be seen that the temperatures taken from the weather station at the site are reporting values 1–1.5 °C below the values at Jandakot Aero. This is likely due to the slight difference in how temperatures are recorded. While most major BoM sites record temperatures with very high frequency (at least once a minute), the weather station on site records data every second but compiles this data in temporary on-board storage and logs a single average value every ten minutes. As such, the small fluctuations during that ten-minute interval are not considered when recording instantaneous maximum temperatures. This likely reduces the ‘extreme’ temperatures listed at this site by a small amount but should have a negligible impact on average values.

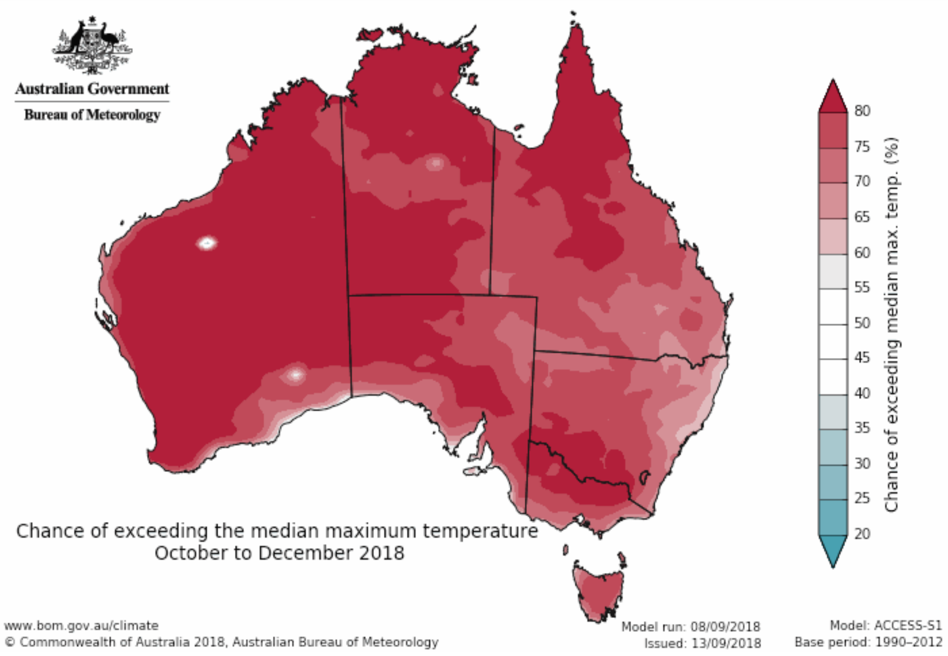
Figure 5.3: Temperature profile on hottest day of the 2017/18 summer



5.4 Updated Analysis for the 2018/19 Summer

The January 2019 Interim Report noted that the early part of the 2018/19 summer was predicted to be 80% chance or higher of having above average median maximum temperatures across nearly the entire landmass of WA, including Perth and Karratha (Figure 5.4). This indicated that there was a higher chance of extreme heat days and above average maximum pavement temperatures at the two sites for the upcoming summer, which would provide data for the most extreme of conditions.

Figure 5.4: Climate outlook maps - chance of exceeding the median maximum temperature Oct-Dec 2018



Source: Commonwealth of Australia (2018b)

In actuality for Perth, mean daily maximum temperatures were very similar to the previous two summers, and below the trend from 2012 through 2016 (Table 5.4).

Table 5.4: Hottest days in Perth over previous seven summers

Summer		Maximum air temperature (°C)	Average daily maximum temperature across whole summer (°C)	Extreme heat days (daily maximum above 38 °C)
2012/13		41.3	32.1	13
2013/14		43.2	31.8	7
2014/15		43.7	31.4	6
2015/16		42.4	31.1	10
2016/17	BoM station	43.3	29.8	6
	Kwinana Fwy	41.9	28.7	6
2017/18	BoM station	38.6	30.2	1
	Kwinana Fwy	37.7	29.1	0
2018/19	BoM station	42.0	30.2	5
	Kwinana Fwy	40.7	28.9	3

Source: Commonwealth of Australia (2018a)

Although it was not possible to use climate data from the weather station in Karratha due to the power supply issues, Karratha Aero BoM station did record average maximum air temperatures that were slightly above the long term averages for December to February, although October-November 2018 was actually slightly cooler than average (Table 5.5). The highest temperature at 45.5 °C was fairly typical for a maximum summer temperature.

Table 5.5: Hottest days in Karratha over previous seven summers

Summer	Maximum air temperature (°C)	Average daily maximum temperature across whole summer (°C)
2012/13	41.6	36.8
2013/14	44.0	36.6
2014/15	47.0	36.8
2015/16	46.1	36.3
2016/17	43.0	35.2
2017/18	42.1	35.5
2018/19	45.5	36.2

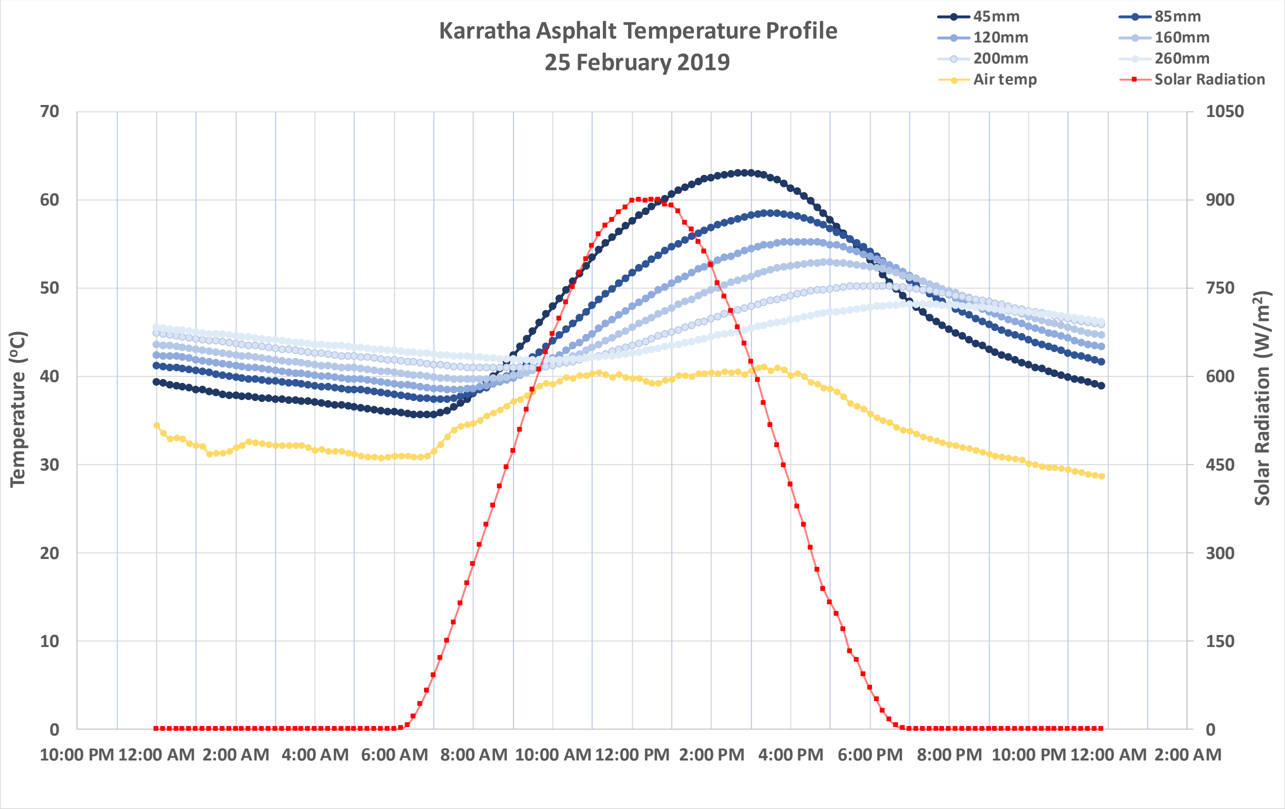
Source: Commonwealth of Australia (2018a)

5.4.1 Hottest Summer Temperatures in Karratha

As in Section 5.1.1, it is valuable to look at a single extreme heat day to better understand the maximum pavements temperatures likely to be encountered over the course of a year. On 25 February 2019, the air temperature reached a maximum of 40.4 °C and it was a totally cloudless day. At 2.40 pm the pavement temperature at 45 mm depth hit a peak of 63.0 °C, which likely means that the temperature right at the surface was close to 70 °C (see Figure 5.5).

It is also worth noting that on a hot day such as this, the minimum temperatures deep in the pavement will remain very high right through the night. On 26 February, the 200 mm sensor never dropped below 40 °C for the entire 24-hour period, despite the overnight low being around 24 °C.

Figure 5.5: Karratha temperature profile on 25 February 2019



5.5 Updated Analysis with Four Instrumented Locations

Although there were two months of data lost due to power issues, June 2019 marks a full 12 months since the instrumentation in Karratha, and thus is a good time to once again compare the ARRB instrumented sites around Australia. The temperature figures for Karratha may be slightly lower than would be expected if the December and January data had not been lost.

The data (presented in Table 5.6) for each site represents a 12 month period, although they do not necessarily line up across the same 12 months, it is useful for the purpose of identifying key similarities and differences. Adding to the earlier observations in Section 5.1.2 and Section 5.2, notable observations regarding the Karratha site include:

- average air temperature is more than 7 °C higher at Karratha compared to Perth, but extreme heat days are more closely matched. When comparing to Brisbane, the average air temperature is only 3.5 °C higher but extreme heat days are more than 8 °C higher
- solar radiation sits in a narrower range, with peaks in summer that are similar to the other sites but the average is much higher due to the high proportion of clear, sunny days
- only seven days across the entire year had rainfall in excess of 1 mm although rainfall totals are only 26% lower than the Perth site which had 78 days with over 1 mm rainfall over the previous 12 months
- pavement temperatures near the surface are higher than those in Perth even when accounting for a difference in air temperature and solar radiation on clear days, with at least two possible explanations, namely:

  - the consistency of hot sunny days and mild overnight temperatures means that the starting temperature in the morning is higher in Karratha compared to other locations, allowing for pavement temperatures to peak earlier in the day
  - there is no traffic at the Karratha site, which may be having a cooling effect on the Kwinana Freeway
- there is similar temperature gap between Perth and Karratha at each sensor depth, which may indicate that heat transfer and thermal properties of the two materials are similar.

Table 5.6: Comparison of four ARRB instrumented sites over 12-month period

		Perth	**Karratha**	**Brisbane**[1]	**South Gippsland**
Air temperature (°C)	Max	41.9	45.1	36.8	36.4
	Avg	18.1	25.4	21.9	14.1
	Min	2.8	8.0	7.2	-2.3
Avg. daily maximum air temp (°C)		23.8	32.1	26.9	19.3
Avg. daily minimum air temp (°C)		12.6	19.2	17.7	8.9
Daily solar exposure (MJ/m²)	Max	28.1	27.2	25.1	25.8
	Avg	15.8	18.3	14.0	11.3
	Min	1.5	1.1	1.4	1.9
Total rainfall (mm)		796.0	591.2	739.2	700.8
Sensor 1 (°C) (nearest surface)	Max	56.9	63.0	55.9	48.8
	Avg	25.4	35.2	*30.6*	19.3
	Min	6.0	15.8	*10.9*	2.8
Sensor 2 (°C)	Max	52.2	58.4	54.7	46.4
	Avg	25.4	35.1	*30.6*	19.3
	Min	7.4	18.0	*12.1*	3.5
Sensor 3 (°C)	Max	49.8	55.2	50.4	N/A (damaged during construction)
	Avg	25.4	35.0	*30.5*	
	Min	8.3	19.3	*13.0*	
Sensor 4 (°C)	Max	47.1	52.9	46.0	36.7
	Avg	25.3	35.0	*30.4*	19.3
	Min	9.3	20.5	*15.0*	7.2
Sensor 5 (°C)	Max	45.3	50.2	42.9	34.5
	Avg	25.2	34.9	30.4	19.2
	Min	9.9	22.1	17.0	8.0
Sensor 6 (°C) (deepest sensor)	Max	40.9	48.1	40.6	31.8
	Avg	25.0	34.8	30.1	19.3
	Min	11.6	23.4	18.5	9.4

Note 1: Karratha is from mid-June 2018 through mid-June 2019, excluding December 2018 and January 2019 where data was lost
Note 2: Brisbane data is from October 2015 to September 2016

Data in italics - Includes some interpolated data after errors in the original data file

6 NEW APPROACH TO ASPHALT PAVEMENT TEMPERATURE IN DESIGN

Some background to the method by which temperature is currently used for pavement design purposes in Australia was provided in Section 2. Research over recent years has highlighted that improvements to this methodology are very achievable, and some alternatives to the simplified WMAPT approach are presented in Section 6.1. Other methods of calculation and more complex and data-intensive models are documented in Section 6.2, with Section 6.3 detailing key factors that have been considered when developing the proposed model and design tool in this project.

6.1 Alternative Approach to WMAPT

Some relatively simple changes to how the WMAPT is calculated could result in smaller differences between observed and predicted pavement temperatures. Using the existing temperature data from Bureau of Meteorology sites in the Perth area as well as the weather data from the weather station installed for this project, an estimate for the WMAPT for the site can be calculated and compared to the assumed value for Perth of 29 °C.

Using a single year of data (2016/17) as input into the WMAPT formula (which is intended to capture multiple years of data) returns a WMAPT value of 28.2 °C for the Kwinana Freeway site, as compared to 29.0 °C for the Perth Airport BoM station and 28.3 °C for the Jandakot Airport BoM station over the same time period.

Some of the discrepancy is due to the method of measuring the temperature at the Kwinana Freeway site, which takes an average over a time interval (set at either 10 minutes or 1 hour). In the data set from the Bureau of Meteorology, that time interval is much shorter, so that maximum and minimum temperatures may be more extreme. The data supports this assumption, with average daily maximums 1.1 °C lower at the Kwinana Freeway site compared to Perth Airport, and average daily minimums 0.5 °C higher.

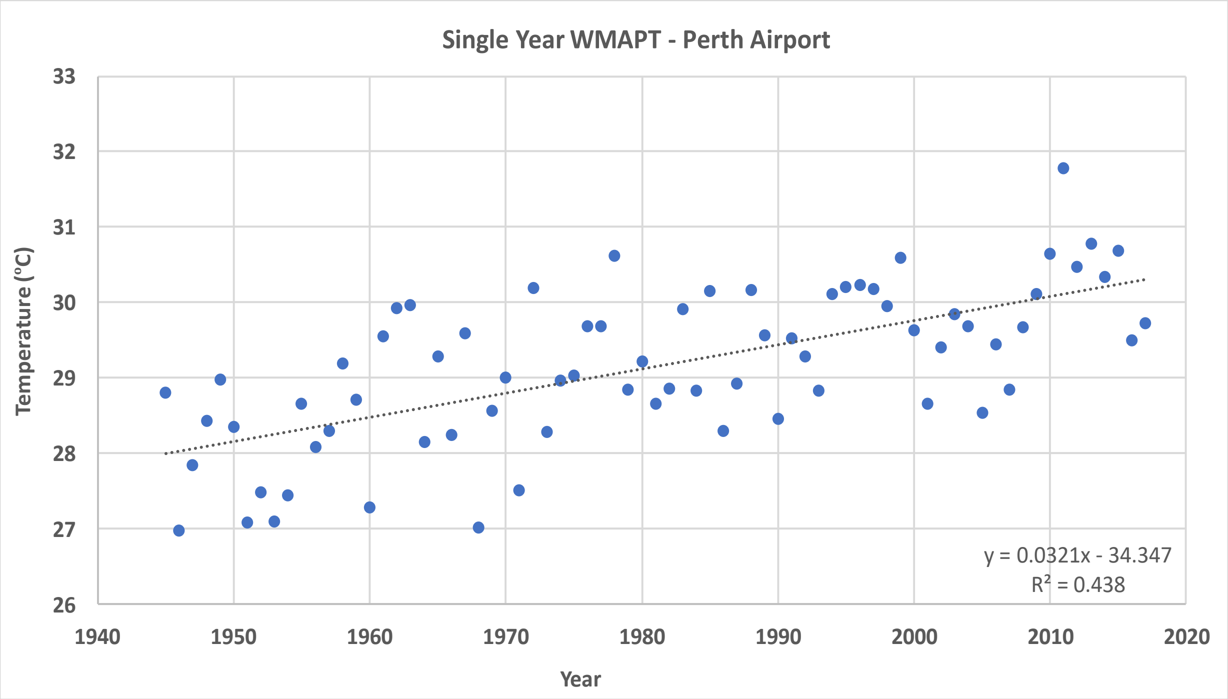
The Perth Airport Bureau of Meteorology station (Site 9021) has been used for the WMAPT comparison as it has a long and continuous record of data and is also less likely to be influenced by heat island effects which may be present closer to the Perth CBD. Table 6.1 shows the WMAPT for this location over the full history of this site (since 1945) as well as using the most recent 30 years of data (1987-2016).

Table 6.1: WMAPT at Perth Airport, Kwinana Fwy and Jandakot – averages and recent data

	Long term averages		Recent years	
	1945-2016 WMAPT (°C)	1987-2016 WMAPT (°C)	2016/17	2017/18
Perth Airport (BoM site 9021))	29.2	29.8	29.0	30.2
Jandakot Airport (BoM site 9172)	N/A	28.7	28.3	29.4
Kwinana Fwy (installation site)			28.2	28.9

Although the WMAPT of 29 °C for Perth (Austroads 2017a) may have been appropriate based on full data from 50+ years of measurements, there should ideally be some consideration of recent trends for higher temperatures in many parts of the country. Over the previous 30 years, the WMAPT at this site would be calculated at 29.8 °C, with the trend of temperature over time evident in Figure 6.1.

Figure 6.1: Single year WMAPT at Perth Airport by year



While there is a high degree of variance in the year-by-year data, assuming a linear trend and 40-year pavement design life (typical for Main Roads high-traffic pavements), the WMAPT could be expected to be 30.9 °C on average over the life of the pavement. This raises the question of whether pavements should be designed with higher WMAPT values considering the clear evidence of warming in many parts of Australia. A simple change would be to adjust the listed values upwards by 1–2 degrees, which in most cases would require a small increase in pavement thickness. However, in practice any changes to listed WMAPT values would ideally consider a range of factors, including location-specific weather, pavement depth, and temperature data from any nearby instrumented pavements.

The formulas used in the WMAPT calculation are intended to provide a reasonable estimate of the pavement temperature of a typical asphalt pavement with a thickness of 100 mm. This then feeds into a formula in Equation 1 which adjusts the design modulus from the value calculated at the laboratory test temperature (typically 25 °C).

$$\frac{\text{Modulus at WMAPT}}{\text{Modulus at test temperature}(T)} = \exp(-0.08[\text{WMAPT} - T]) \qquad 1$$

Source: Austroads (2017a)

As a result, an asphalt mix with a laboratory modulus of 4000 MPa at 25 °C (for example) would be adjusted down to approximately 2900 MPa at a WMAPT of 29 °C. This means that pavements constructed in higher temperature regions of the country are required to be built at increased pavement thicknesses as a result of lower asphalt moduli and associated higher tensile strains. This has been identified as being problematic when thick pavements are constructed in northern and central regions of Australia as there is very little evidence of asphalt fatigue in thick pavements designed under this methodology (Austroads 2013b).

With access to a full year of temperature data, it is therefore worth comparing the average measured temperature at 100 mm with the value listed in Appendix B of Austroads (2017a), as well as to some alternative methods of calculating the WMAPT.

The five analysis cases with different WMAPT, outlined in Table 6.2, are defined as:

1. actual pavement temperature data from the sensor closest to 100 mm, found through averaging and interpolating between the 85 mm and 120 mm hourly temperatures for the entire year (although as noted, the average annual pavement temperature is almost identical at all depths)
2. WMAPT referenced from the closest site listed in Appendix B in Austroads (2017a)
3. WMAPT value calculated from weather station data at the instrumented site (covers period Oct 2016 through end Sept 2017)
4. WMAPT calculated from Chart RT in the Shell Pavement Design Manual (Shell 1978), taking into account the five lines in the chart (Figure 2.1) representing different depths (and interpolating between lines when necessary)
5. as above in Case 4, except using a Weighted Mean Average Air Temperature (WMAAT) calculated using only the weather station data from Oct 2016 through end Sept 2017 (this will allow for better comparison with Case 1)

Table 6.2: Comparison of traditional and alternative WMAPT calculation methodologies

			Kwinana Fwy		**South Gippsland Hwy**		**Eagle Farm**		
		Closest WMAPT site	**Perth**		**Warragul**		**Brisbane**		
		Year	**2016/17**	**2017/18**	**2015/16**	**2016/17**	**2014/15**	**2015/16**	**2016/17**
1	Average annual pavement temperature at 100 mm (°C)		25.3	*25.5*	20.2	19.3	30.3	30.4	31.0
2	Austroads WMAPT (2017a)	WMAPT (°C)	29		22		32		
		Offset to actual (°C)	3.7	3.5	1.8	2.7	1.7	1.6	1.0
3	Calculate WMAPT from single-year weather station data	WMAPT (°C)	28.2	28.9	24.0	22.7	33.0	33.4	33.8
		Offset to actual (°C)	2.9	3.4	3.8	3.4	2.7	3.0	2.8
4	Shell PDM Chart RT (correcting for depth)	WMAPT (°C)	26.8		20.6		29.0		
		Offset to actual (°C)	1.5	1.3	0.4	1.3	-1.3	-1.4	-2
5	Shell PDM Chart RT (2016/17 weather station data)	WMAPT (°C)	26.0	26.6	22.4	21.3	29.8	30.2	30.6
		Offset to actual (°C)	0.7	1.1	2.2	2.0	- 0.5	- 0.2	- 0.4

At each site, the WMAPT from Austroads (2017a) 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, but in order to remove this as a factor, the WMAPT can be calculated for each site using the air temperature data from the roadside weather stations at each instrumented pavement. The offset to actual pavement temperatures across the three sites is ranging between 2.7 °C and 3.8 °C.

Each of these pavements is over 300 mm in depth. While it was shown in Table 5.2 that the average annual temperature is almost identical at any depth in a full-depth asphalt pavement (although it does vary by depth at certain times of the year), there may be some influence from the total thickness of the pavement on 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 more easily as latent heat is stored deeper in the pavement.

The net effect of this may be that thick pavements have a mean annual pavement temperature several degrees lower than what would be expected under the WMAPT assumptions. It should be remembered that the WMAPT formula was adopted based on work done for the Shell Pavement Design Manual, which is several decades old and focussed on mix designs and materials that may not bear much resemblance to those currently used for full-depth asphalt pavements in Australia.

Scenario 4 takes into account the multiple lines in Shell PDM Chart RT, and interpolates the WMAPT between lines where necessary. The net result of directly referencing Chart RT is that the WMAPT is up to 3 °C lower for these thick pavements. Adjusting this for the localised weather station data in Scenario 5 results in the closest average offset to actual recorded pavement temperatures (Table 6.3).

Table 6.3: Accuracy of four alternative 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

6.1.1 Demonstrated Examples

Using the three instrumented pavements, a theoretical pavement design was undertaken using the CIRCLY pavement design software and a presumptive modulus based on the WMAPT determined using the various methods discussed in Section 6.1. In each of these scenarios, a simplified methodology of using a single WMAPT across the whole year was adopted. A more sophisticated approach with temperature values for each hour is demonstrated in Section 7.

The same five cases outlined in Table 6.2 have been run through CIRCLY, using an asphalt thickness equal to that in each instrumented pavement design, a 150 MPa granular layer (as in Table 6.4 of Austroads 2017a) of 500 mm thickness, on a CBR5 subgrade. The presumptive asphalt modulus at laboratory conditions has been set at 5000 MPa to reflect a heavy duty asphalt for a highway environment. This results in a temperature-adjusted modulus value of 3824 MPa at the Perth WMAPT of 29 °C.

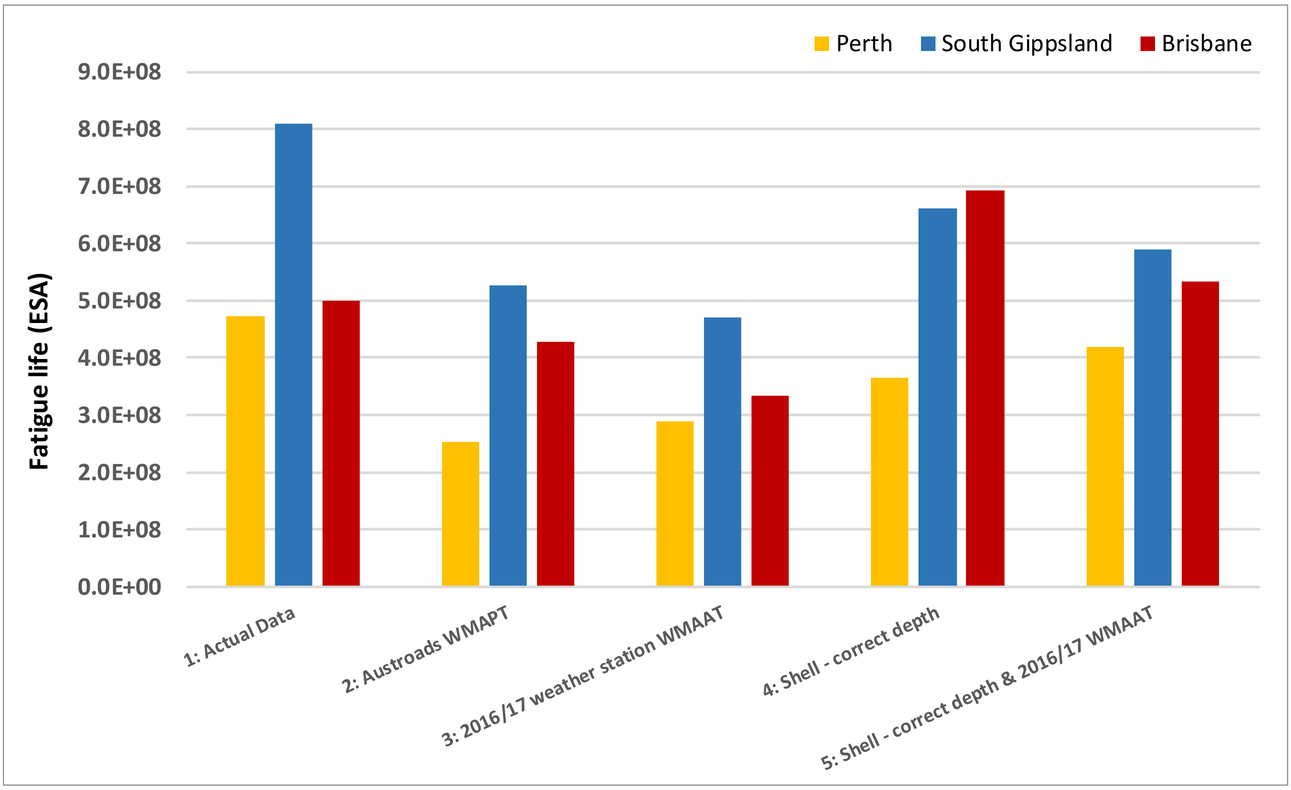
The results for Perth in Table 6.4 and Figure 6.2 show that the current methodology using the WMAPT in Austroads (2017a) leads to adopting a temperature-adjusted moduli that is lower than those estimated by means of the alternative methodologies, and as a result the design life (as measured in ESAs) is comparatively shorter.

Table 6.4: Comparison of design and pavement life changes for varying WMAPT values – Thick pavement

Site	Case	Depth (mm)	Modulus at 25 ºC (MPa)	WMAPT (ºC)	Temp. adjusted modulus (MPa)	CIRCLY design life (ESA)	Percentage difference	Change in fatigue life[1] (years)
Perth	1	350	5000	25.3	4876	4.73E+08	187%	34.9
	2	350	5000	29.0	3559	2.53E+08	100%	0.0
	3	350	5000	28.2	3811	2.89E+08	114%	5.7
	4	350	5000	26.8	4295	3.66E+08	145%	18.0
	5	350	5000	26.0	4597	4.20E+08	166%	26.5
South Gippsland	1	330	5000	19.3	7850	8.10E+08	154%	21.5
	2	330	5000	22.0	6383	5.27E+08	100%	0.0
	3	330	5000	22.7	6037	4.70E+08	89%	-4.3
	4	330	5000	20.6	7118	6.60E+08	125%	10.1
	5	330	5000	21.3	6743	5.91E+08	112%	4.8
Brisbane	1	400	5000	31.0	3012	5.00E+08	117%	6.7
	2	400	5000	32.0	2781	4.28E+08	100%	0.0
	3	400	5000	33.8	2439	3.33E+08	78%	-8.9
	4	400	5000	29.0	3559	6.93E+08	162%	24.7
	5	400	5000	30.6	3112	5.33E+08	124%	9.7

Note 1: Assuming a 40-year design life and zero traffic growth

Figure 6.2: Comparison of calculated fatigue life using various WMAPT methodologies – Thick pavement



In the case of a pavement in Perth, for example, the Case 5 methodology (i.e. WMAPT calculated for correct depth from Chart RT in the Shell PDM, except using WMAAT calculated using actual weather station data) would lead to a theoretical extension of 26.5 years to the pavement life. This example is not factoring in the increases in estimated average pavement temperatures over time as documented in Section 6.1. This would have the effect of partially offsetting the large discrepancy between the observed pavement temperature and the WMAPT for Perth.

The same exercise can be conducted on a thin asphalt pavement. This time, a 100 mm asphalt layer, with the same material properties as for the thick pavement, is placed on top a 500 mm granular layer at 250 MPa (again calculated from Table 6.4 in Austroads 2017a) and a CBR5 subgrade. The results of the CIRCLY analysis are presented in Table 6.5 and Figure 6.3.

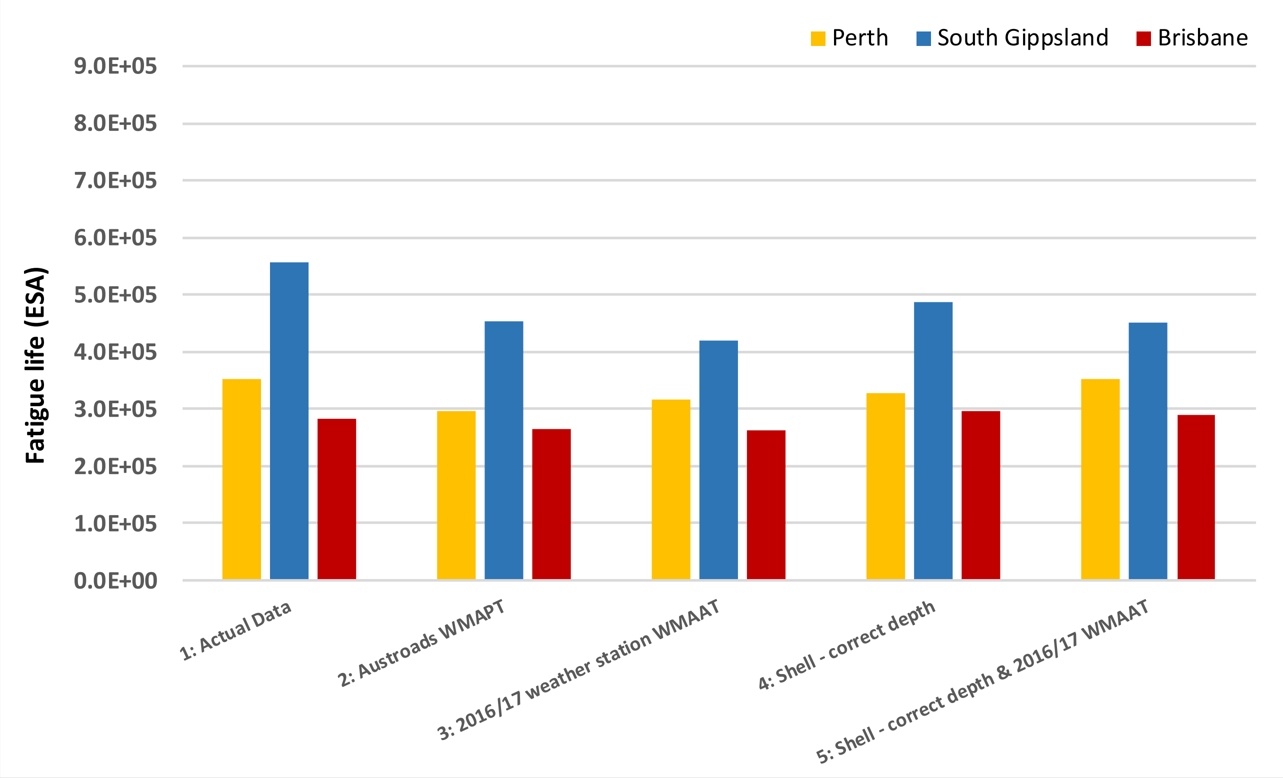
When looking at thin asphalt pavements, the discrepancies between the current Austroads WMAPT model and the more sophisticated methodologies are much less significant. A shift of several degrees in either direction does not dramatically impact on the calculated fatigue life, with the relative changes across the three locations also being much smaller than with the thick asphalt pavement example.

Table 6.5: Comparison of design and pavement life changes for varying WMAPT values – Thin pavement

Site	Case	Depth (mm)	Modulus at 25 ºC (MPa)	WMAPT (ºC)	Temp adjusted modulus (MPa)	CIRCLY design life (ESA)	Percentage difference	Change in fatigue life[1] (years)
Perth	1	100	5000	25.3	4876	3.52E+05	119%	7.5
	2	100	5000	29.0	3559	2.96E+05	100%	0.0
	3	100	5000	28.2	3811	3.16E+05	107%	2.7
	4	100	5000	26.8	4295	3.27E+05	110%	4.1
	5	100	5000	26.0	4597	3.52E+05	119%	7.5
South Gippsland	1	100	5000	19.3	7850	5.57E+05	123%	9.1
	2	100	5000	22.0	6383	4.54E+05	100%	0.0
	3	100	5000	22.7	6037	4.21E+05	93%	-2.9
	4	100	5000	20.6	7118	4.87E+05	107%	2.9
	5	100	5000	21.3	6743	4.52E+05	100%	-0.2
Brisbane	1	100	5000	31.0	3012	2.82E+05	106%	2.5
	2	100	5000	32.0	2781	2.65E+05	100%	0.0
	3	100	5000	33.8	2439	2.63E+05	99%	-0.3
	4	100	5000	29.0	3559	2.96E+05	112%	4.7
	5	100	5000	30.6	3112	2.89E+05	109%	3.7

Note 1: Assuming a 40-year design life and flat traffic growth

Figure 6.3: Comparison of calculated fatigue life with five WMAPT methodologies – Thin pavement

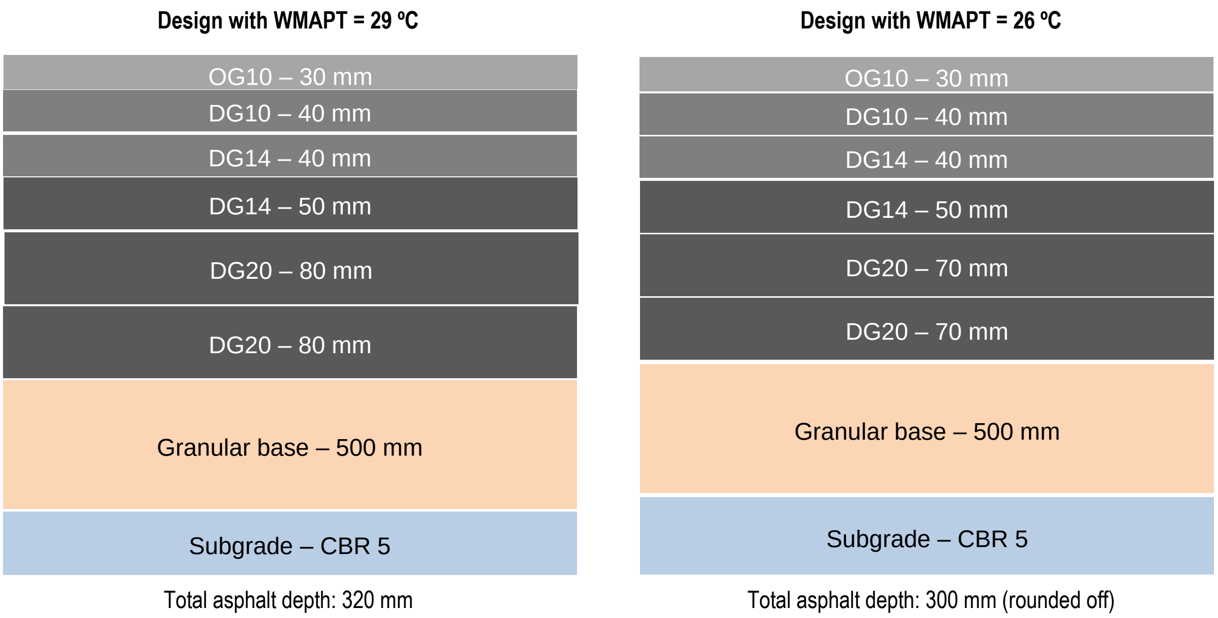


Another way to consider this is from a pavement design perspective. Should a thick asphalt pavement be designed to achieve a set number of ESAs over its design life, a pavement design can be completed for a range of WMAPT values to compare the asphalt thickness required for each scenario. A generic pavement design has been used, with WMAPT values in this exercise up to 4 °C higher and lower than the Perth WMAPT of 29 °C. Even allowing for the below-average temperatures in the previous two summers, the analysis earlier in this section shows that the true WMAPT for thick pavements in Perth may be better estimated at 26-27 °C.

A 320 mm thick pavement with design traffic of $5*10^8$ ESAs is modelled under this approach, keeping all variables constant except for the assumed moduli changing depending on the WMAPT used. Shifting from a Perth-area WMAPT of 29 °C down to 26 °C results in a required asphalt thickness of 298 mm, 22 mm less than the original pavement design (as shown in Figure 6.4). Again, this does not account for the partially offsetting impacts of gradually increasing pavement temperatures due to the effects of climate change. A shift of 3 °C in the opposite direction (i.e. from 29 °C up to 32 °C) would result in a required increase in asphalt thickness of 19 mm to achieve the same design life.

Following a similar approach for a thin asphalt pavement design (~100 mm) shows that a shift of 3 ºC in either direction makes very little difference in required thickness to reach an equivalent fatigue life. In the hypothetical pavement design used, the required thickness was within 2 mm of the original design for the whole range of temperatures, a difference that would be even less than typical construction tolerances. Different assumptions on design inputs may lead to varied outcomes, but in most cases a shift in design temperature at a given location is going to have minimal impact on the eventual design thickness for a thin asphalt pavement (i.e. notionally thickness < 150 mm).

Figure 6.4: Comparison of theoretical thick asphalt pavement design at WMAPT of 29 °C and 26 °C



6.2 Other Approaches and Models

Several alternative approaches have been adopted in other countries for calculating the asphalt surface temperature or layer temperature at a given depth.

Austroads (2013b) reviewed the various methods employed for calculating the surface temperature through the use of the energy balance concept, the most widely used of which is the integrated climate model (ICM) (Lytton et al. 1993) which drew upon earlier work in the United States. The ICM can be used to calculate maximum and minimum surface temperatures in order to aid in the selection of an appropriate performance grade binder. A version of the ICM was adopted for use in the mechanistic empirical pavement design guide (MEPDG), which is used across various jurisdictions in the United States. The energy balance approach has some clear advantages, in that it uses real climatic, material and physical characteristics to predict performance, however it can potentially be complex for widespread use and requires a range of assumptions regarding the various parameters used.

The methodology in these models involves calculating the pavement performance for multiple scenarios rather than using single values for an entire year, and although this adds a layer of complexity to the analysis, they have been shown to be effective at predicting fatigue response in asphalt pavements on a combination of accelerated pavement testing projects, test tracks and long-term monitoring sites.

While there are various methods for calculating the surface temperature, there has been less research into the subsequent calculation of temperature at various depths in the pavement. ASTM have approved a method for predicting the asphalt pavement temperature at depth from infrared surface temperature measurements (ASTM 2015). The surface temperature, time of day, air temperature over the previous 24 hours and pavement depth for measuring are entered into the BELLS Method (Stubstad et al. 1994), which uses a formula derived from long-term monitoring sites to output a pavement temperature at any designated depth. This method can be used to calculate pavement temperatures at other sites, and particularly when testing deflection of pavements.

Similarly, a paper presented at the 2015 AAPA Conference proposed a three-season model for calculating pavement temperatures at up to 450 mm depth, which ultimately found pavement thickness savings in the order of 10-15% using the proposed approach (Gray et al. 2015).

One of the most directly applicable research projects was conducted through instrumenting pavements at the Virginia Smart Roads facility by Diefenderfer et al. (2002). The research project resulted in the development of two models: a simple version and a more complex version. The general form of the more complex version of the model incorporates maximum and minimum daily ambient air temperature, the depth within the pavement and the calculated daily solar radiation.

The model was calibrated against data from an instrumented section of 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 subsequently evaluated against a range of other data sets including additional temperature data from the Virginia Smart Roads facility and two long-term pavement monitoring sites elsewhere in the United States, with generally good fit of the model to independent data. The general form of this model only requires easily accessible weather data, so could be more readily adopted in Australia.

6.3 Key Considerations for Proposed Model

When developing a pavement temperature model to predict pavement temperatures at depth over the course of a year, significant effort was required to identify the key factors underpinning this model and determine the data requirements. Observing pavement temperature behaviour over the first 18 months at the Kwinana Freeway site and first few months at the Karratha site, and combining these observations with the knowledge of the behaviour of the pavements in Brisbane and South Gippsland, has enabled the following to be identified as being important considerations behind the development of this model:

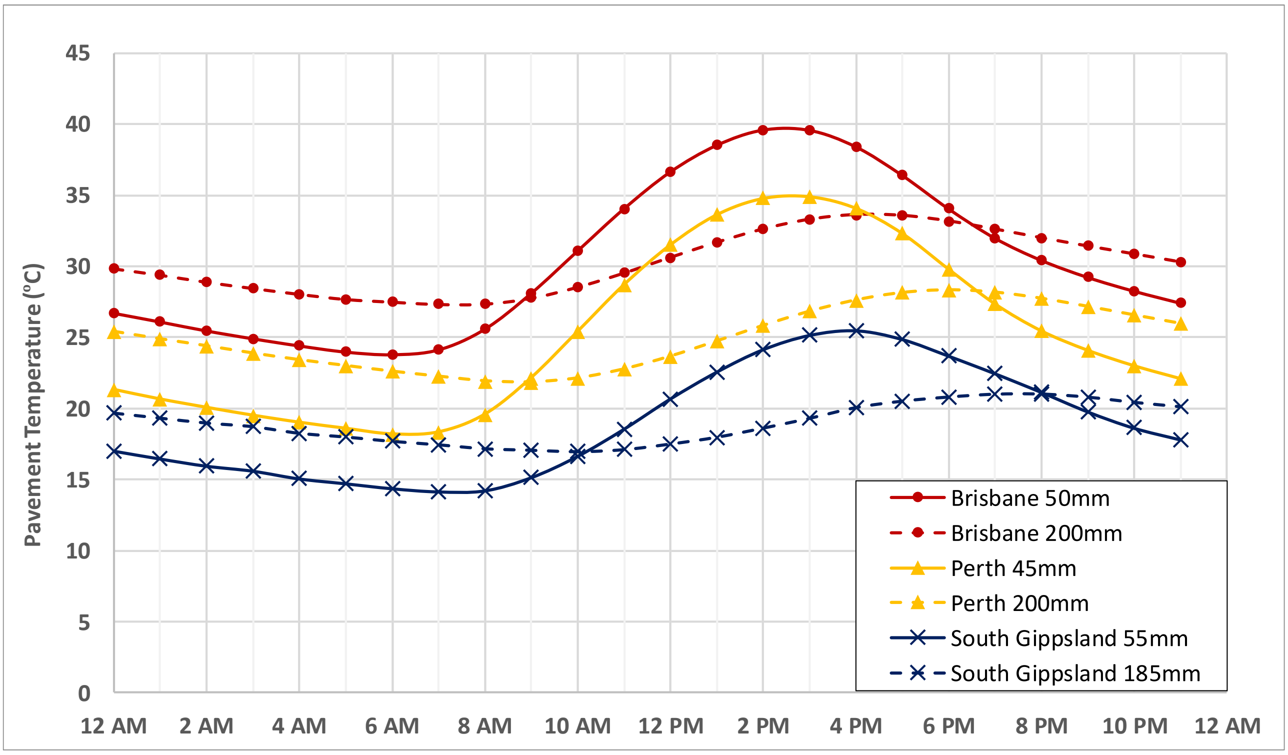
- the daily distribution (by hour) of temperatures near the surface and at depth
  - what impact does the depth have on maximum and minimum temperatures?
  - when are the maximum and minimum temperatures reached, and how does it change for various depths?
  - what ‘shape’ does the temperature function take over the course of day?
- the impact of solar radiation, independent of the air temperature
  - what is the practical difference between a warm but overcast day and a day with the same temperature but full sunlight?
  - how does shading from trees and buildings etc. impact on pavement temperature and is it practical to include in modelling?
- moderate-to-heavy rainfall can cause a rapid drop in temperature at the surface
  - is the impact significant enough to factor this in for all locations, or just in locations with more regular rainfall, or ignore it completely?
- surface temperature calculations and the relationship between the actual surface temperature and the near-surface temperature (e.g. at around 50 mm)
- the effect of vehicle movements in terms of shading and/or wind draught as vehicles pass
  - can we differentiate between the shading/wind effect of trucks and light vehicles?
- the impact of the material type - different types of asphalt and other (e.g. foamed bitumen)

- climate trends show increasing air temperatures over time
    - can it be incorporated into our proposed model and design tools, and is there benefit in accounting for this in design for long-life pavements?
- specific data must be readily available for use in the proposed model

6.3.1 Daily Distribution of Temperatures at Various Depths

Figure 6.5 shows the distribution of temperatures across the day for the shallowest sensor (close to 50 mm in each case) and the sensor closest to 200 mm. The relationship between the temperature at the two sensors is similar at each site, with about a 5-6 °C difference between the maximum temperature near the surface and at ~200 mm depth, and a 3-4 hour delay in peak temperatures at depth owing to the time taken for heat to transfer through the asphalt layers.

Figure 6.5: Temperature distribution at two depths at three sites



The typical daily shape of pavement temperatures near the surface appears to be comprised of two distinct periods, from around 6-7am through to around 7-8pm (i.e. from sunrise to just after sunset) where the profile follows what looks to be a sinusoidal curve centred around a maximum at about 2-3pm, and another period from 7-8pm through to 6am the next day where the temperature profile is decreasing more linearly to a minimum value at 6-7am.

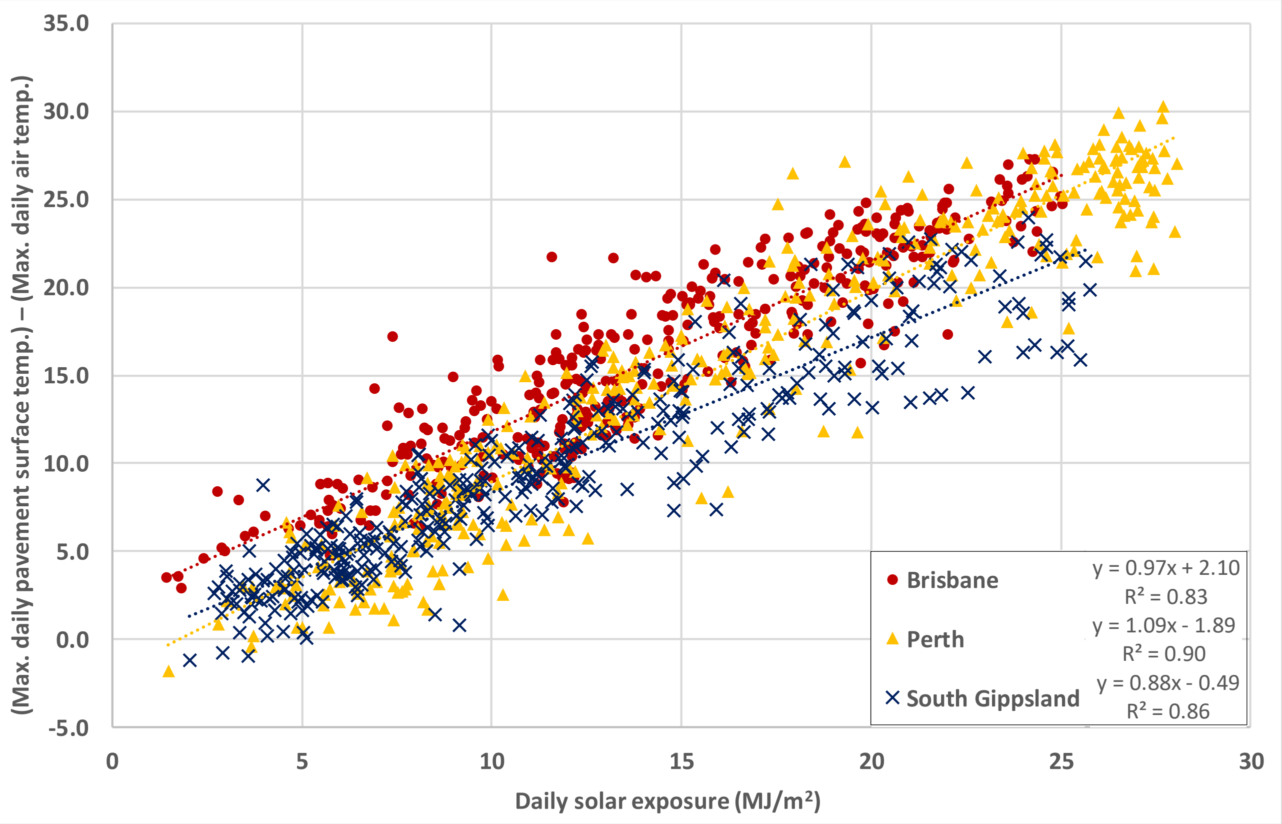
Any hourly pavement temperature model may therefore best fit the data by combining two separate models, one for daylight hours and another for night-time. The model will also be required to ‘delay’ the impact of weather deeper into the pavement so that the temperature distribution over the day deeper into the pavement fits the observed behaviour.

6.3.2 *Solar Radiation*

Demonstrating the impact of solar radiation and rainfall on pavement temperature was covered in previous research (Beecroft, Denneman & Petho 2015), with the data at that time suggesting that solar radiation was a major contributor to the maximum pavement temperature, with clear sunny days leading to maximum pavement temperatures in some cases of up to 25 °C higher than the maximum air temperature.

To determine the impact, the daily solar exposure from the three sites over at least one year each was plotted against the difference between the maximum daily air temperature and the maximum daily pavement temperature at the surface (estimated based on near-surface temperatures) (Figure 6.6).

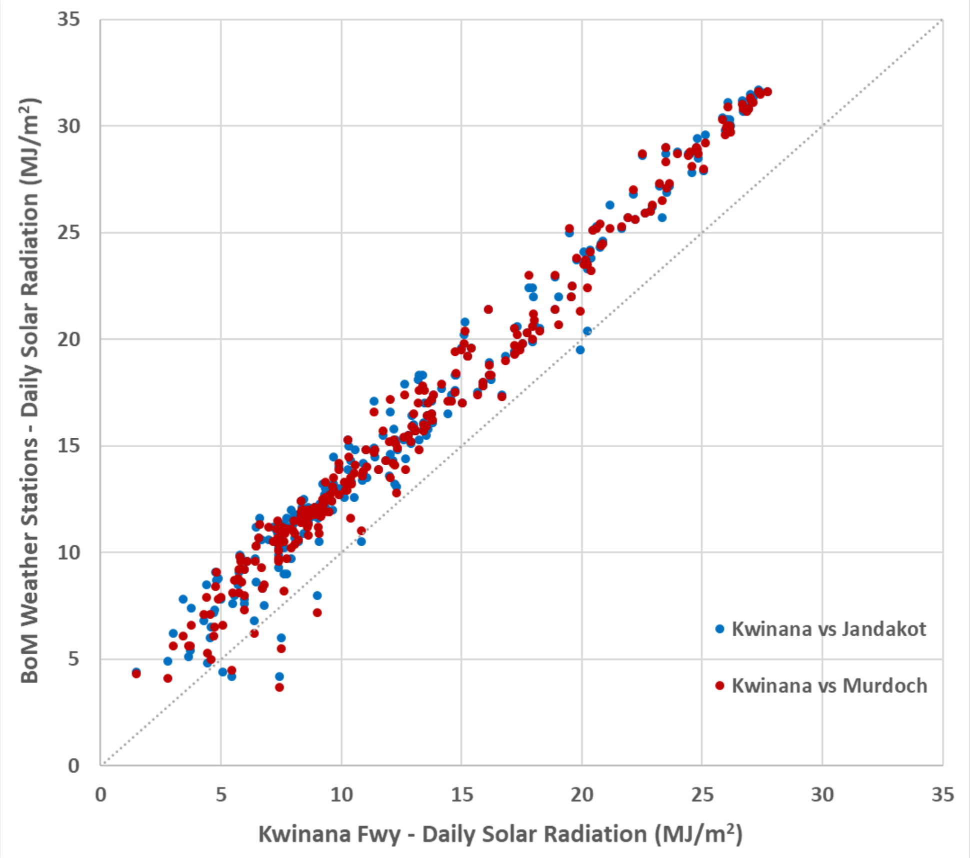
Figure 6.6: Influence of solar radiation on offset between max pavement surface and air temp.



The strong correlation (R^2 of between 0.83 and 0.90 for each site) suggests that outside of ambient air temperature itself, solar radiation is a dominating factor in determining pavement temperature, particularly near the surface. This does not account for any other factors, such as rainfall, time of year, latent heat in the pavement and of solar radiation distribution through the day.

When comparing the solar radiation recorded at the Kwinana Freeway site to the cumulative solar radiation at the two nearest Bureau of Meteorology sites, it can be seen that the readings at the Kwinana Freeway site are consistently 2-4 °C lower (Figure 6.7). The reasons for this discrepancy are not clear, however the implications for this are explored further in Section 7.2.

Figure 6.7: Solar radiation at Kwinana Fwy site and closest weather stations



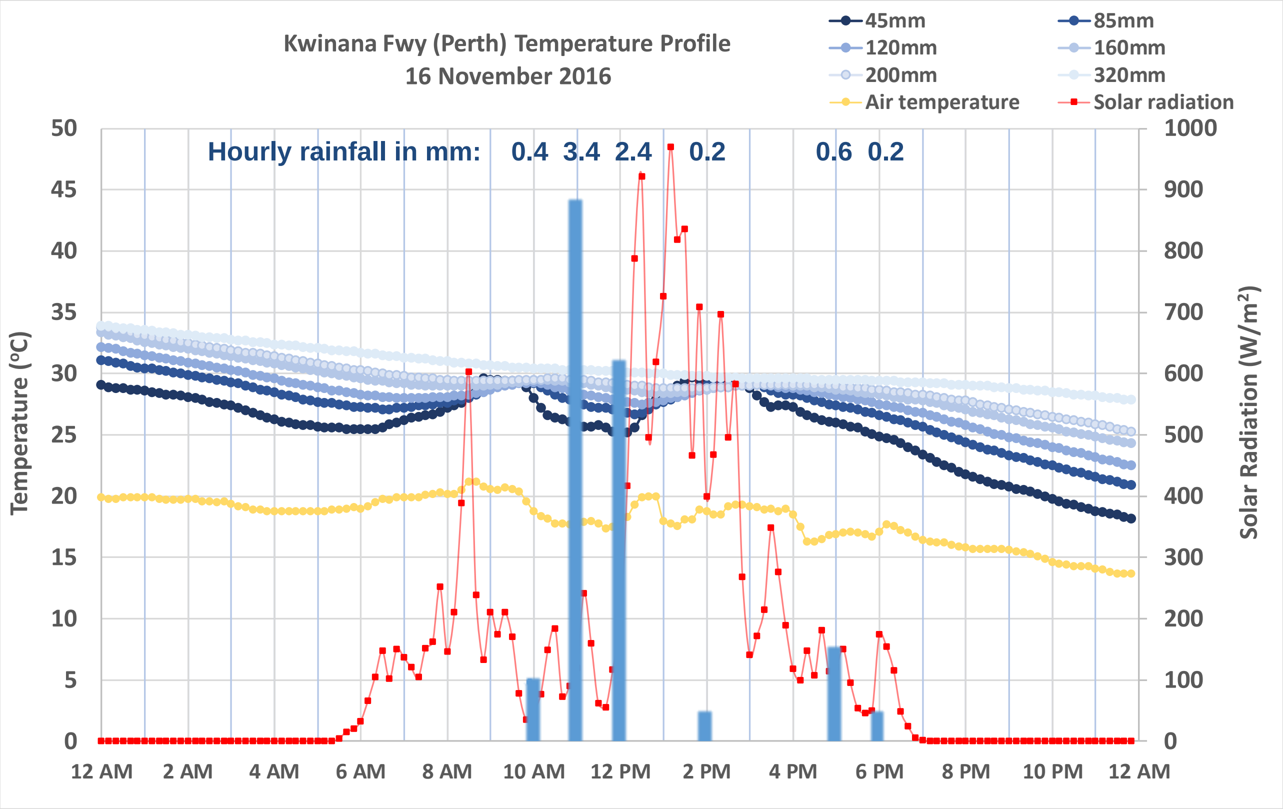
6.3.3 *Rainfall*

Very light rainfall is seen to have minimal effect on the pavement temperature, even near the surface, as the cloud cover itself is already having an effect on temperatures and should the sun reappear, moisture on the road surface will dry quickly. However, heavier rainfall has been observed to have a significant impact on the surface temperature, and subsequently on the temperature at depth should that rain continue for several hours.

This can be seen in Figure 6.8 for 16 November 2016, where a partly sunny morning was followed by two hours of steady rainfall, then another 3-4 hours of mostly sunny conditions. At the surface, the morning sun had brought the temperature 45 mm below the surface up to approximately 30 °C, before the rain resulted in the temperature dropping to just under 25 °C. As the rain cleared, the near surface temperature returned to a peak of around 30 °C. Deeper in the pavement, the temperature was more consistent as the periods of sun and rain were too short to make a significant impact.

The model may benefit from incorporating some consideration of hourly or daily rainfall, however the effects can be very short-lived and are already accounted for to some extent by considering the solar radiation for that day (i.e. if it is raining, it is also cloudy and hence reduced solar radiation). Due to uncertainty in how this will impact the overall accuracy of the model, rainfall will not be part of the initial pavement temperature model developed for this project.

Figure 6.8: Impact of rainfall on pavement temperature on a sample day at Kwinana Fwy



The most significant impact of rainfall on pavement temperatures may be during the wet season in tropical or sub-tropical locations where otherwise sunny days may have short bursts of heavy rain (particularly in the afternoon). This would have the effect of rapidly reducing the pavement temperature during what is otherwise one of the hottest periods of the day for the pavement, and as a result, vehicles would have a lessened impact on pavement fatigue under current assumptions of asphalt fatigue equations. The site at Karratha will be closely observed through the wet season to determine the impact of these events.

6.3.4 Surface Temperatures

Several surface temperature readings were taken during December 2016 at the Kwinana Freeway (Jandakot) site as well as at a foamed bitumen trial section, also on the Kwinana Freeway but further south near Baldivis (Table 6.6).

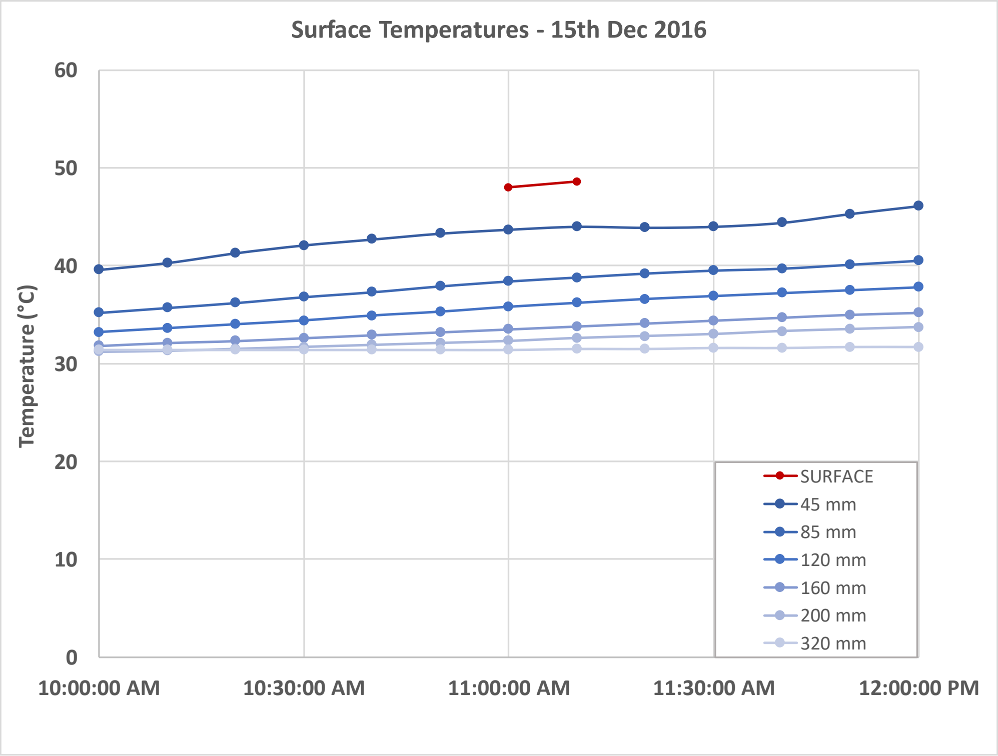
It should be noted that despite the base layers being different materials (asphalt vs foamed bitumen), the wearing courses are both a combination of open-grade and dense-graded asphalt, so any conclusions drawn from the Baldivis site can reasonably be applied to the Jandakot site and vice-versa.

One advantage of this data is that an offset between surface temperature readings and the 45 mm deep sensor could be determined to develop a formula for calculating the surface temperature at any time of day based on the temperature at depth. An example from 15 December 2015 is provided in Figure 6.9.

Table 6.6: Surface temperature readings at FBS and FDA trial sites, December 2016

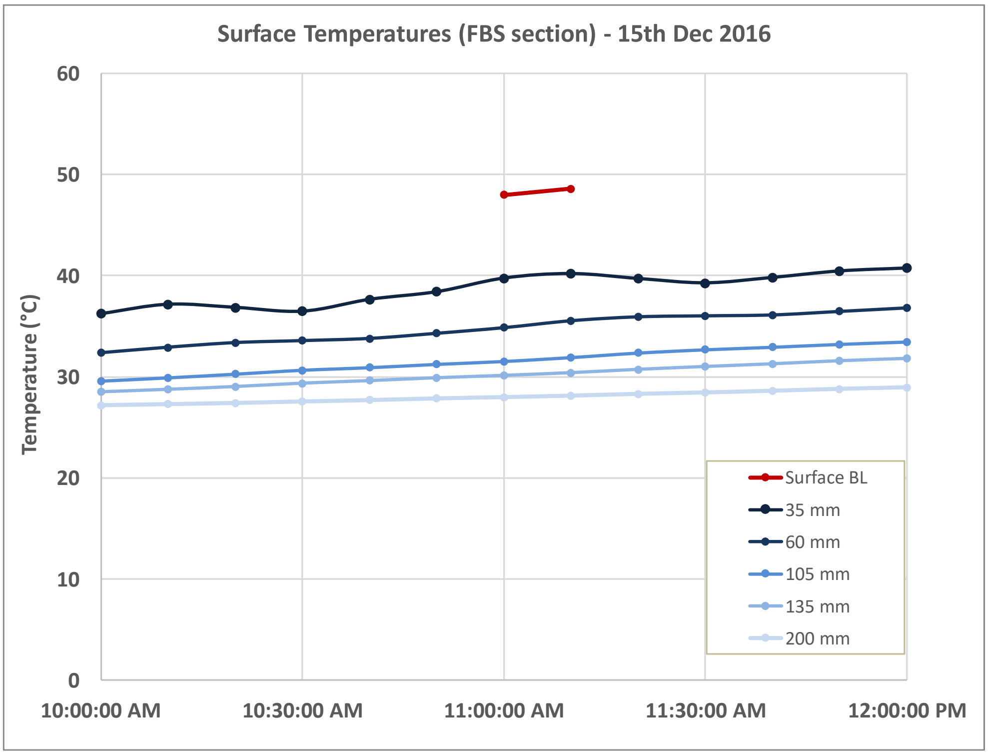
	Kwinana Fwy weather station		Foamed bitumen trial sections (Kwinana Fwy, Baldivis)		
	15th Dec, 11.00am & 11.10am		Chainage 175 6th Dec, 11.30am	Chainage 225 6th Dec, 11.40am	Chainage 225 15th Dec, 12.40pm
Approx. temp at highest sensor (°C)	43.7	44.0	38.7	38.8	41.1
Surface temp. – breakdown lane (°C)	48.0	48.6	45.4	47.4	45.8
	+ 4.3 °C	+ 4.6 °C	+ 6.7 °C	+ 8.6 °C	+ 4.7 °C
Surface temp. – edge line (°C)	47.2	47.4	42.2	43.0	42.4
	+ 3.5 °C	+ 3.4 °C	+ 3.5 °C	+ 4.2 °C	+ 1.3 °C
Surface temp. – left lane/slow lane (°C)	39.8	40.6	38.2	38.8	41.4
	- 3.9 °C	- 3.4 °C	- 0.5 °C	+ 0.0 °C	+ 0.3 °C
Surface temp. – middle lane (°C)	37.8	38.4			
	- 5.9 °C	- 5.6 °C			

Figure 6.9: Surface temperatures vs temperature at depth on 15 December 2016 at Kwinana Fwy Jandakot



The same exercise for the foamed bitumen section is presented in Figure 6.10. A reasonable starting assumption that the surface temperature can be linearly interpolated from the temperatures at the top two sensors. In the examples presented here, the actual measured surface temperature is higher that what a linear interpolation would predict, while in the other case it is lower than predicted. Factors that effect this could include wind, the incident solar radiation within the very precise measurement window, any vehicle effects and some recording errors (i.e. ‘spot’ measurements at surface vs 10 minute intervals at depth). The relative heat conduction properties of the two pavements may also be having some effect on the difference in temperature between the surface temperature and the temperature at the first in-pavement sensor (35-45 mm depth).

Figure 6.10: Surface temperatures vs temperature at depth on 15 December 2016 at FBS section (Baldivis)

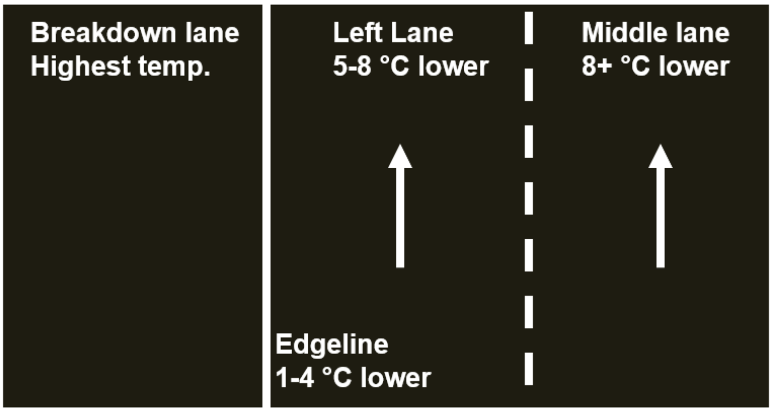


From this limited data, it appears as though the relationship is close to linear and that the starting assumption is reasonable for the purposes of this project. This means that we can have a moderate-high level of confidence in predicting extreme surface temperatures based purely on a linear interpolation from the temperatures recorded at the top two sensors. The analysis is however more complicated when looking at sites with vehicle traffic (see Section 6.3.5).

6.3.5 Effect of Vehicle Movements

When comparing the data from non-trafficked and trafficked lanes (Table 6.6), there was a notable difference in surface temperature, with trafficked sections having lower surface temperatures than non-trafficked lanes. Again, utilising the data from the foamed bitumen section at Baldivis (Table 6.6), the impact of traffic and surface albedo can be assessed and visualised (Figure 6.11).

Figure 6.11: Comparison of surface temperatures by lane (Kwinana Fwy, Baldivis)

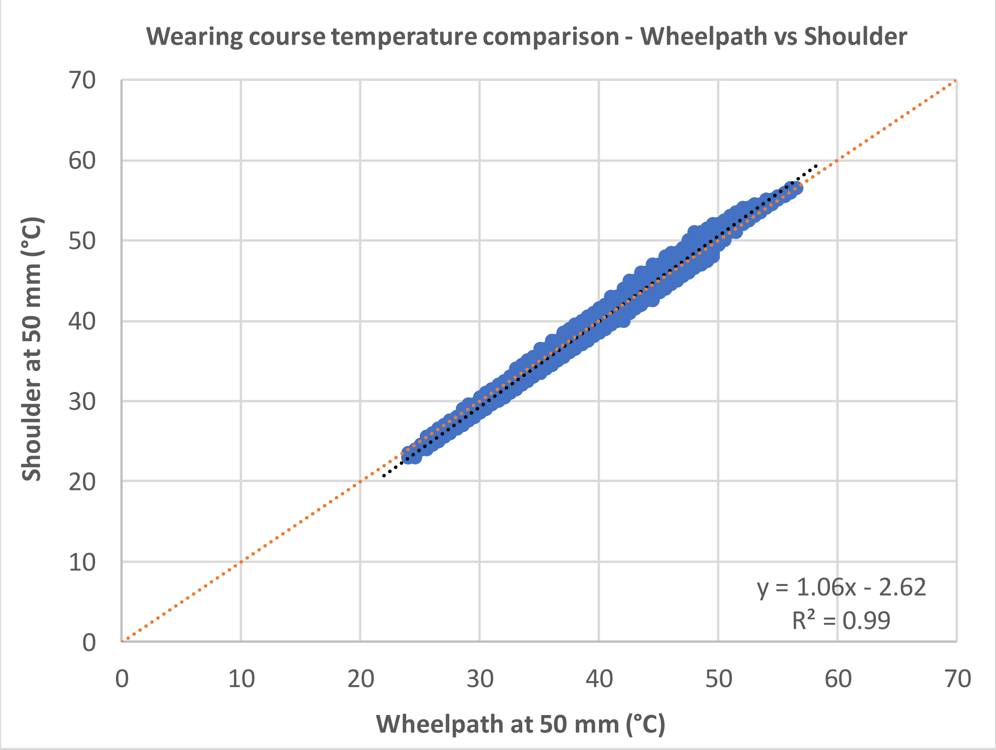


The highest surface temperatures were measured in the breakdown lane, whereas the edgeline produced temperatures only slightly lower than the breakdown lane, likely because of albedo and material effects of the line marking material itself and not so much due to traffic effects. The left (slow) lane) was comparatively much cooler than the breakdown lane, but hotter than the middle (fast) lane. In this location, the middle lane was trafficked by a large volume of trucks that move to away from the left lane which exits at the next intersection. The temperature differential is thought to be related to a combination of vehicle draught and shading while cars and trucks pass by. The fact that more trucks leads to lower temperatures fits with this theory.

It should be noted that these readings were taken around midday on a relatively sunny day. It would be anticipated that the differences would not be as extreme at night, on overcast days or closer to sunrise/sunset when the impact of solar radiation is lessened.

Through data supplied by DIPL from a site south of Darwin, the impact of near-surface temperature on trafficked and non-trafficked surfaces was further assessed. This site included sensors at 50 mm depth in both the shoulder and near the wheelpath. The relationship between the two sensors shows that there is relatively little difference between the two locations (Figure 6.12). At high temperatures, the shoulder was up to 2 °C hotter than the wheelpath. It would be anticipated that the offset at the surface may be slightly greater, but there is no data to confirm this.

Figure 6.12: Comparison of wearing course temperatures – trafficked vs non-trafficked lanes



One reason for the smaller offset would be the respective traffic volumes at the two sites. The instrumented section of the Stuart Highway is estimated to have AADT of around 6000 vehicles (based on closest count stations as documented in Northern Territory Government (2016), as compared to over 45,000 vehicles per day on the Kwinana Freeway. Longer periods of time in between vehicle movements allows for the wheel path surface to have a similar solar exposure compared to the shoulder. It is also possible that there is some influence on temperature from the friction of vehicle tyres in the wheelpath.

Although based on very limited data, it appears as though there are factors significantly lowering the surface temperature in traffic lanes compared to the shoulder or non-trafficked lanes. This cooling effect is likely due to some combination of shading from vehicles and the wind draught from passing vehicles, and potentially some differences in albedo (‘dirty’ surface in the traffic lanes). Any effect of heat from the vehicles themselves or tyres may offset this somewhat, but it would appear to be negligible at highway speeds. Further study on this effect would be valuable in order to quantify the difference with greater confidence.

Should the data in Table 6.6 prove to be broadly representative of the typical temperature behaviour of an urban highway or urban arterial road, there may be the potential to assume within the model that the traffic lane surface temperature is less than the calculated value based on weather station data alone. The traffic volume (preferably broken down by lane) would be a factor to consider in making this adjustment.

6.3.6 Pavement Materials - Comparison to Foamed Bitumen Trial Section

The day after installing pavement temperature sensors in the Kwinana Freeway near Jandakot, a series of temperature sensors were also installed in two sections of the Kwinana Freeway a further 20 km south, near Baldivis. This site was a trial of a foamed bitumen stabilised (FBS) pavement, and was constructed in February 2010 (Austroads 2013a). The FBS base layer varies from 150 mm to 290 mm thick, with a 30 mm dense-graded plus 30 mm open-graded asphalt wearing course. The FBS consists of 3.5% Class 170 bitumen, and the aggregate materials are mostly hydrated cement treated crushed rock base (HCTCRB) with some crushed limestone in the deeper layers.

The sensors at this site are not connected to a weather station nor do they have remote connectivity, but data can be retrieved by accessing the sensor terminals which are stored in a roadside box in the shoulder of the pavement. Due to their relatively close proximity, a comparison of the pavement temperatures at this site may be able to provide information on the impact of pavement configuration and material thermal properties on pavement temperatures and behaviour at depth.

The temperature sensors return profiles that appear very similar to those for the full-depth asphalt section (Figure 6.13), but are consistently offset downwards by around 4 °C, with the greatest average differential at around midday at 6.5 °C and lowest at around 3am at just 2.2 °C (Figure 6.14). This offset also holds true for the deeper layers (see Figure 6.15).

It is possible to draw some conclusions on the behaviour of the two pavement materials based on the temperature differential between top and bottom sensors at various times of the day. In reference to Figure 6.16, a pavement that transfers heat more rapidly throughout the layer would be expected to show a smaller differential and a flatter gradient of the curve during daylight hours, as the bottom of the layer heats up more quickly than in a pavement which does not transfer heat as effectively. During the night and early morning, a pavement that transfers heat more rapidly would also show a smaller differential and a flatter gradient as the hot lower layers transfer heat back towards the surface. This is reflected in Figure 6.16, with the full-depth asphalt pavement exhibiting a flatter curve across the day.

This difference in behaviour limits the ability to utilise the proposed model for materials other than asphalt, with foamed bitumen or other granular pavements appearing to be sufficiently different in properties such that it would be difficult to adopt the model to characterise their behaviour. For the purposes of comparing different dense-graded asphalt pavements (e.g. DG14, DG20, EME2) the offset at peak temperatures and throughout the day is likely to be significantly less even with slightly different bitumen contents, aggregate types or aggregate sizes. There may be less alignment should the albedo or another surfacing property be significantly different.

Figure 6.13: Sample of temperature in FDA and FBS pavements at 45 mm (interpolated for FBS)

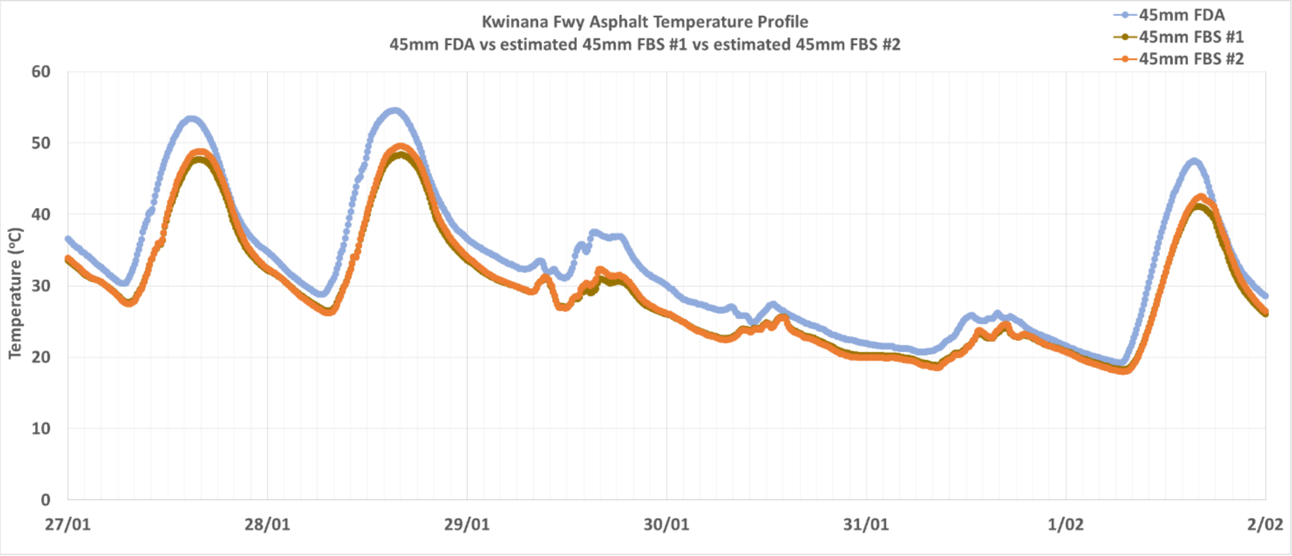


Figure 6.14: Temperature offset between FDA and FBS at 45 mm (interpolated for FBS)

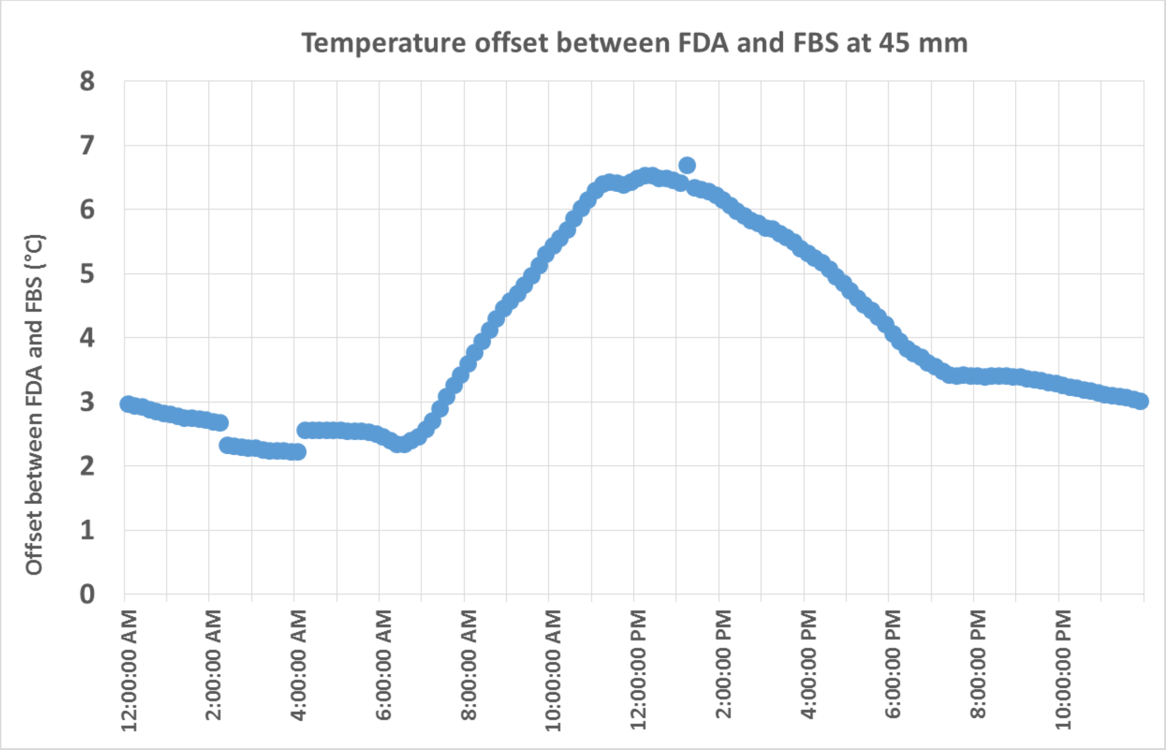


Figure 6.15: Sample of temperature plots between FDA and FBS pavements at 160 mm and 150 mm

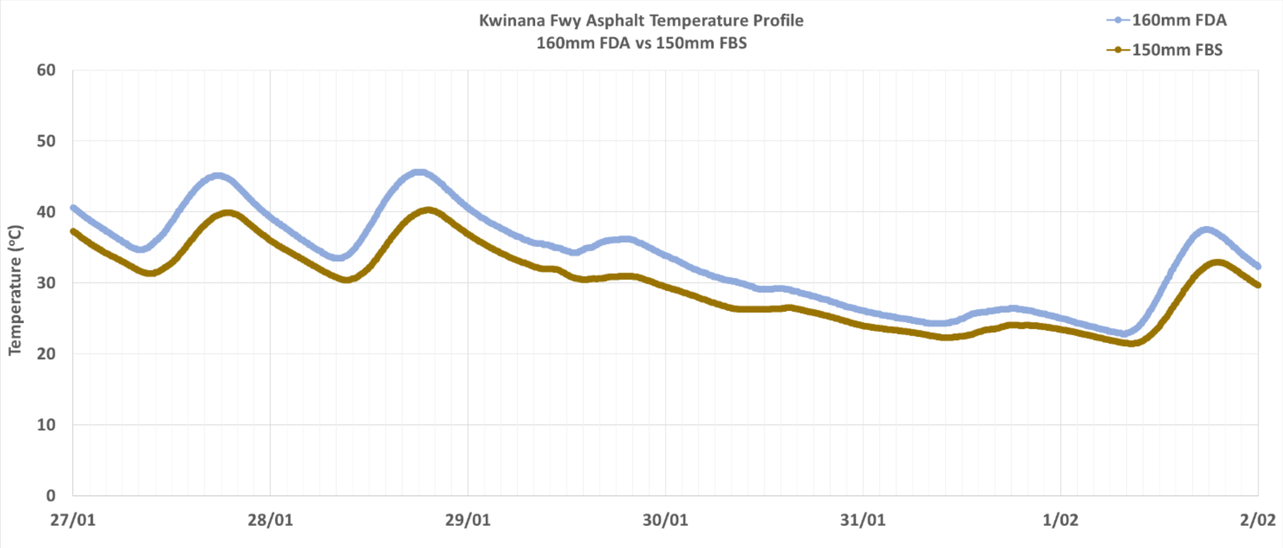
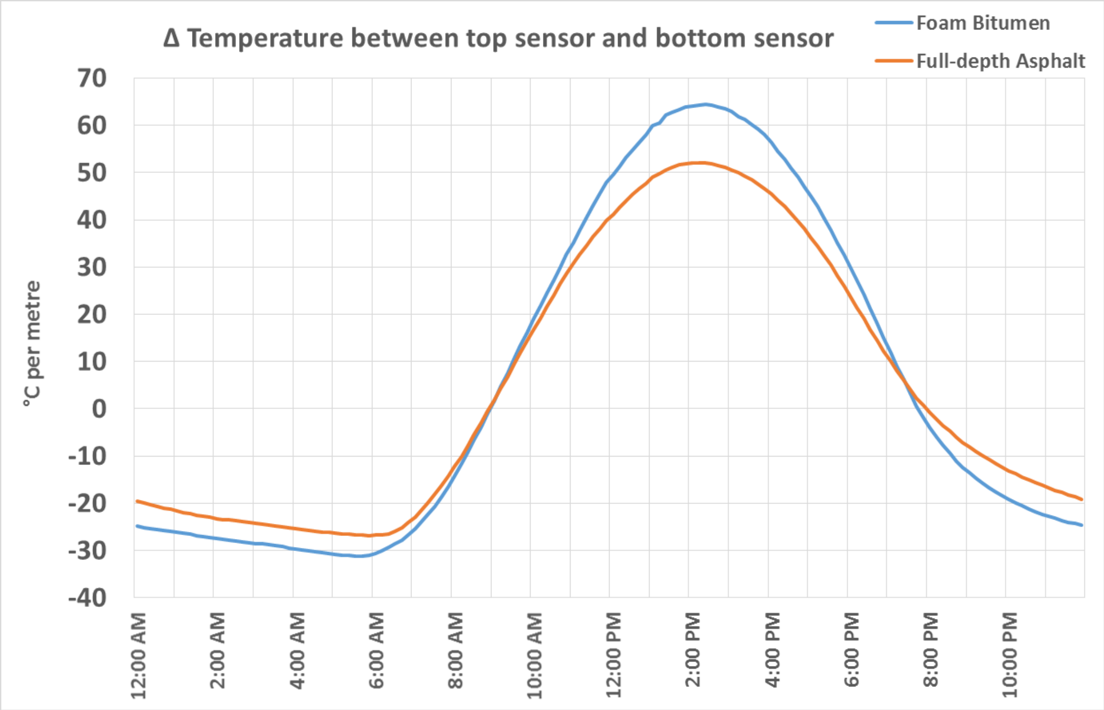


Figure 6.16: Difference in temperature between top and bottom sensors in FDA and FBS

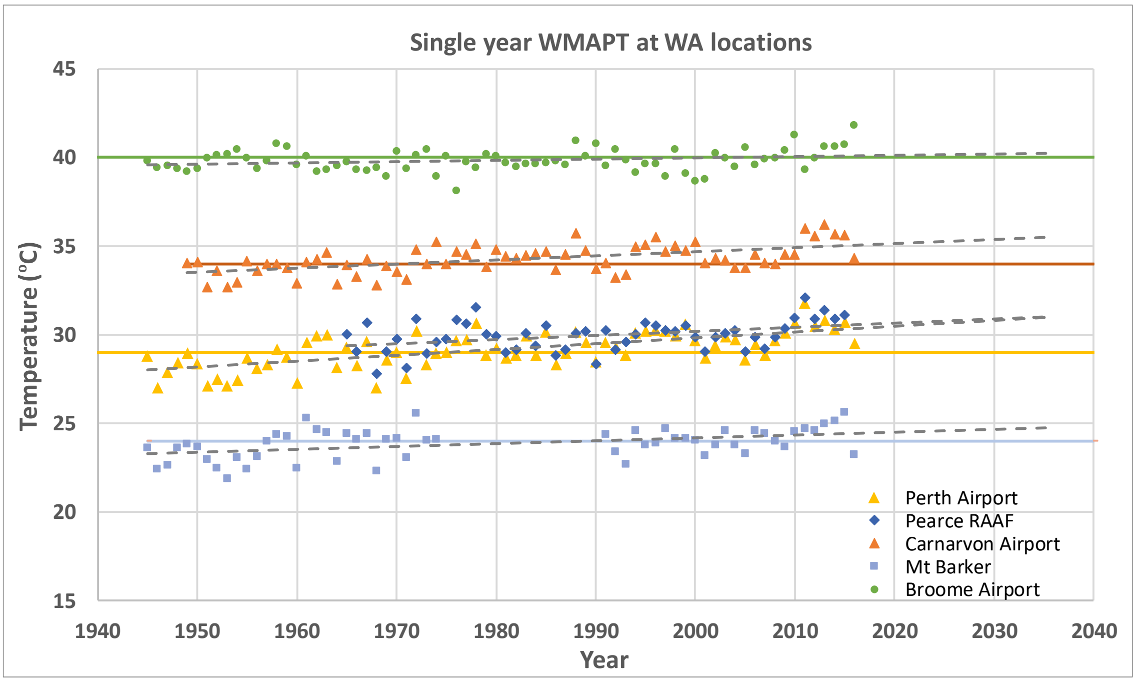


6.3.7 Climate Change Impact

WMAPT values listed in Appendix B of Austroads (2017a) are based on temperature records from the mid-to-late 20th century and are not routinely updated based on recent temperature data. This may be satisfactory under the assumption that there is no short-term change in climatic factors, but evidence around the globe indicates that average temperatures are rising measurably, and this will have an impact on WMAPT calculations and pavement design. This is particularly relevant in Western Australia where heavy-duty asphalt pavements have relatively long design lives of 40 years.

The WMAPT values at five WA locations have been calculated on a single-year basis, which are shown in Figure 6.17. Apart from the far north of the state, weighted average air temperatures do seem to be rising by 1 °C every 20-30 years. In most locations, the presumptive WMAPT values may already be 1-2 °C lower than recent temperature data would indicate, meaning that by the end of a 40 year design life of a pavement constructed in 2018, the presumptive WMAPT in Austroads (2017a) may be understating pavement temperatures by up to 4 or 5 °C.

Figure 6.17: Single year WMAPT at West Australian locations with trendlines



Source: Commonwealth of Australia (2018a)

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 theoretical 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 a more 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. Of course, this is just one effect, and it does appear that at least for thick asphalt pavements, the net effect is not nearly as great. The solution is not as simple as raising the WMAPT values, as any changes should consider all the factors influencing this calculation, which was discussed earlier in Section 6.1.

6.3.8 Data Availability

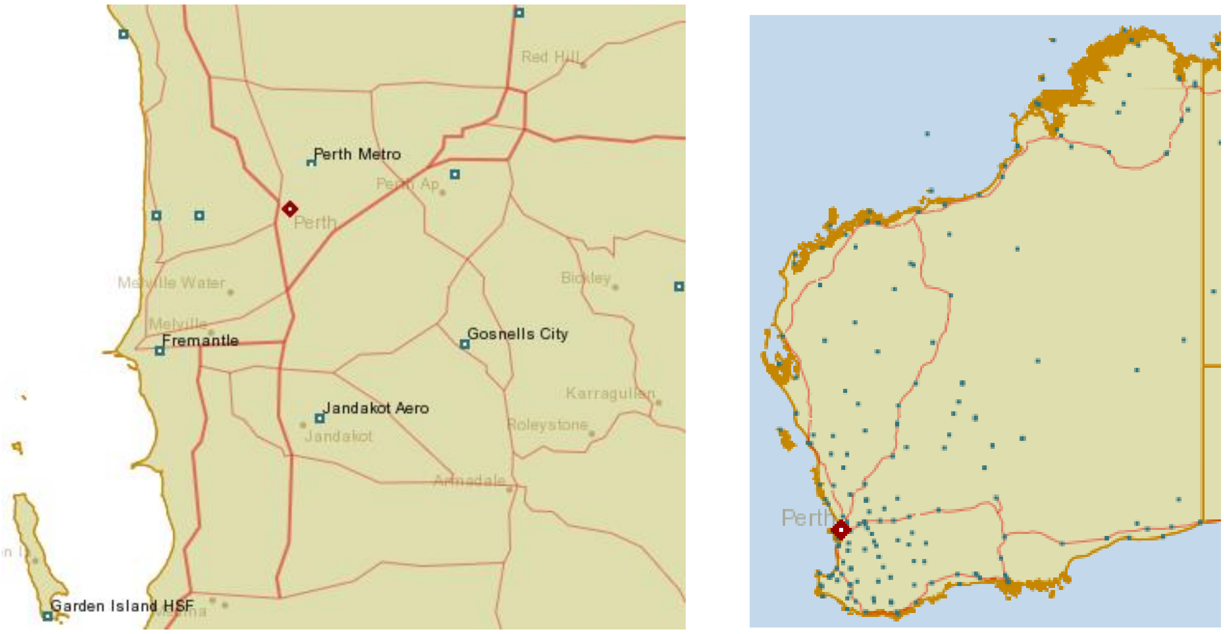
Whatever model that is adopted, it will not be practical or economical to install expensive pavement temperature sensors at any proposed site of a new pavement and record 12+ months of data, as was done through this project. Future use of the model must be able to make use of readily available climate and location data. Australia's Bureau of Meteorology maintains thousands of locations across Australia with basic temperature and rainfall data for each day, with many of these also providing more detailed data such as solar radiation, humidity and wind.

The literature suggests that the bare minimum to produce a reasonably insightful pavement temperature model would be maximum and minimum air temperatures. Additionally, due to the high importance of solar radiation as outlined in Section 6.3.2, cumulative solar radiation data would also be desirable. Rainfall may also provide some added benefit to the model, although some of the cooling effect of rainfall is already accounted for through the presence of heavy rain clouds (i.e. minimal solar radiation).

There are many sites around WA that have (currently active) daily maximum and minimum air temperature and solar radiation data, as shown in Figure 6.18 .

Figure 6.18: Sites in WA with max/min air temp and solar radiation

Perth **Entire state**



South-west WA

Source: Commonwealth of Australia (2018a)

Location data (longitude and latitude) is readily accessible through online mapping applications, which can help to identify the closest Bureau station. The data is downloadable in .csv files which can then be copied directly into the data input section of the model. It is envisaged that in future versions of the tool that the data is centrally stored and accessible through a user interface which only requires users to specify the location of the site (similar to the approach used for CalME[2] and MEPDG[3] in the US).

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[2] CalME (i.e. California Mechanistic-Empirical) is a software program developed for design and analysis of asphalt pavements in California (Ullidtz et al. 2010) and utilises a number of climate zones, with the software including a database of surface temperatures for a range of pavement types in each climate zone that can be used to more accurately predict accumulated damage for design purposes.

[3] The Mechanistic-Empirical Pavement Design Guide (MEPDG) is used across a number of states in the US, and also includes detailed climate data (AASHTO 2008). Data from at least 851 weather stations are embedded in the software, with latitude and longitude used to automatically select the closest weather station.

7 DEVELOPMENT OF A PAVEMENT TEMPERATURE PREDICTION MODEL

This WARRIP project included a task for the development of a pavement temperature prediction model for asphalt pavements of any depth at any location in Western Australia, along with a simple design tool to assist in providing location-specific guidance on expected pavement temperatures, both in terms of extreme temperatures and the hourly distribution of temperatures over the year.

As discussed in Section 2.1, efforts to develop a robust and comprehensive asphalt pavement temperature model for Australia have been hampered by a lack of local pavement temperature data. With at least 18 months of data at three sites, there are now sufficient data to develop of pavement temperature prediction model.

A general form of the proposed model is presented in Section 7.1, with the process for calibration of the model outlined in Section 7.2. The output of the general model can then be used to produce an hourly distribution of temperatures (see Section 7.3) across each day of a given year. This can then be combined with traffic data and pavement characteristics to estimate the pavement fatigue life using a mechanistic pavement design tool (CIRCLY in this case) in Section 7.4.

7.1 Components of the Proposed General Model

The proposed general form of the model is based on work by Diefenderfer et al. (2002). Their model had two approaches, one simple approach and a more complex approach which included inputs of maximum and minimum daily air temperature, daily cumulative solar radiation, and the pavement depth at which the temperature is required. This model has been calibrated against data from several sites within the United States of America.

The key considerations for the model, outlined in Section 6.3, have assisted to inform the adaptation and development of a model suitable for Australian conditions. This input data is readily available at many Bureau of Meteorology weather stations around Australia. The equations can therefore be represented as in Equation 2:

$$T_{p\,max\,(at\ depth\ D)} = \alpha + \beta * (T_a \max) + \gamma * \frac{SR}{1000} + \delta * (D) \qquad 2$$

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

where

$T_p \max$ = daily maximum pavement temperature in °C at depth D

$T_p \min$ = daily minimum pavement temperature in °C at depth D

$T_a \max$ = daily maximum air temperature in °C

$T_a \min$ = daily minimum air temperature in °C

SR = daily total solar exposure in kJ/m^2/day

α = intercept coefficient

β = ambient temperature coefficient

γ = solar radiation coefficient

δ = pavement depth coefficient to adjust for temperature at depth

The following input variables have been used in calibration of the preliminary model:

- daily maximum air temperature
- daily minimum air temperature
- daily total solar exposure
- four constants for calculating maximum and minimum pavement temperatures from climate data (set of four values for each of maximum and minimum calculations)
  - 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

The model has been built in an Excel spreadsheet, which allows for calibration and analysis of the output. A separate (linked) version of the spreadsheet is used for calculating the hourly pavement temperatures and performing CIRCLY pavement design iterations for each hour of the year (see Section 7.3).

7.2 Calibration

The methodology for calibrating the proposed maximum and minimum pavement temperature models follows the key steps as below, with this process replicated for each monitoring location:

1. download the roadside weather station data for the relevant location and extract daily maximum and minimum air temperature and cumulative daily solar radiation as inputs for the model
2. with random seed values for each coefficient, calculate the maximum and minimum pavement temperature at each depth for each day of the year
3. download the pavement temperature data for the relevant location and extract daily maximum and minimum pavement temperature values at each sensor
4. calculate the difference between the model's predicted temperatures at depth and the actual pavement temperatures (maximum and minimum temperatures)
5. using the Excel Solver add-in, solve for four coefficients to return lowest cumulative errors across all depths and all days, for both maximum and minimum temperatures
6. compile coefficients for the site for maximum and minimum temperature calculation
7. after repeating single-site calibration for all three sites, sum the errors for each site and solve for a single combined set of coefficients for the entire dataset

After completing this process, it was apparent that the model could be simplified by setting values for the intercept coefficient (α) and the ambient temperature coefficient (β). With the intercept coefficient set at zero and the ambient temperature coefficient set at 1, the model is effectively suggesting that in a situation with no solar radiation (i.e. nighttime), in a simplistic sense the road surface temperature will be equal to the air temperature according to the concept of thermal equilibrium. In a practical sense this scenario is unlikely to occur, as with a thick asphalt pavement, the latent heat in the pavement will usually keep the surface temperature higher than the air temperature during the roughly 12 hours of full darkness. However, this assumption will allow for the model to be greatly simplified with only a negligible change to the average error at both the top sensor and the average across all sensors (see Table 7.1).

Across the five sites, the error at the top sensor and averaged across all sensors are only marginally higher when looking at maximum temperatures, and almost identical with both models for minimum daily temperatures.

The coefficient values listed below for all sites have been updated based on data through June 2019 from Perth and Karratha, in addition to the existing data from Queensland and Victoria.

Table 7.1: Average errors for max and min temperature at sensors - four component & two component model (June 2019)

		Daily maximum temperature		Daily minimum temperature	
		Four component model	Two component model	Four component model	Two component model
Perth	Error at top sensor (°C)	3.74	3.34	2.61	2.61
	Average error all sensors[1] (°C)	3.39	3.35	2.31	2.30
Karratha	Error at top sensor (°C)	3.71	4.34	1.67	1.67
	Average error all sensors[1] (°C)	2.89	3.24	1.89	1.89
QLD	Error at top sensor (°C)	3.33	3.85	1.65	1.66
	Average error all sensors[1] (°C)	3.02	3.22	1.85	1.85
VIC	Error at top sensor (°C)	2.98	2.68	1.80	1.81
	Average error all sensors[1] (°C)	3.94	4.04	2.10	2.10
NT	Error at top sensor (°C)	2.30	2.18	2.30	2.31
	Average error all sensors[1] (°C)	2.79	3.08	2.10	2.10
ALL SITES	Error at top sensor (°C)	3.44	3.55	1.93	1.94
	Average error all sensors[1] (°C)	3.31	3.46	2.04	2.04

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

The only two coefficients that require calibration are therefore the solar radiation coefficient (γ) and pavement depth coefficient (δ). The solar radiation coefficient, which determines the offset between air temperature and pavement surface temperature (see Section 6.3.2 for evidence of this relationship), is presumably influenced by surface albedo. A darker pavement is likely to have a higher coefficient (each kilojoule of energy from the sun results in more energy absorbed into the pavement rather than reflected) while a lighter coloured pavement would reflect more solar energy and therefore have lesser influence from solar radiation on eventual pavement temperature.

The pavement depth coefficient allows for daily maximum temperatures being lower at greater pavement depth, while daily minimums remain higher at greater pavement depth. This factor would be affected by the heat transfer properties of the pavement, such as the material properties, binder content, moisture content (especially after rainfall), the density and air voids. Some observations regarding how material properties can influence the models is shown in Section 6.3.6 when comparing asphalt pavement temperatures to foamed bitumen pavement temperatures. The difference between various full-depth asphalt pavements should however be relatively minor.

Graphs of the actual vs predicted maximum and minimum pavement temperatures, for the final model with α and β set as 0 and 1 respectively, are shown in Appendix B.3 for the highest sensor in each of the Perth, Brisbane and South Gippsland monitoring sites.

7.2.1 Blind Checks Against Other Locations

Since 2018, a dataset for an instrumented pavement south of Darwin has been supplied by the Northern Territory DIPL. This site includes sensors at 50 mm, 150 mm and 250 mm depth, with an additional sensor at 50 mm depth in the shoulder (i.e. not trafficked). This data set covers August 2017 through May 2019, with some small gaps in data due to power issues or erroneous results.

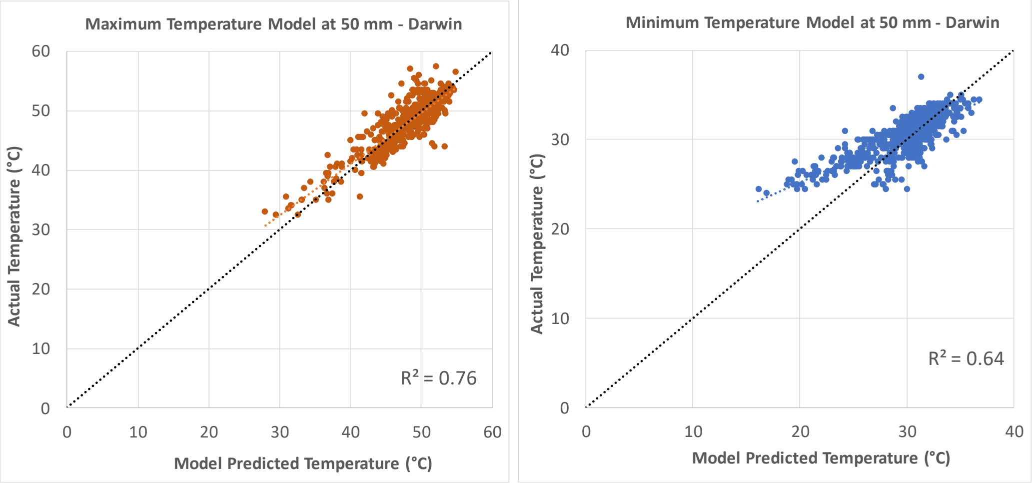
This data set provided an opportunity to test the coefficients developed from the three sites on a completely different site. A small change needed to be made to the model, due to a difference in how the Environdata and Bureau of Meteorology weather stations record data on solar radiation. Solar radiation recorded at the three roadside weather stations was compared to solar radiation data from the nearest respective Bureau weather station, and the data was very strongly correlated but consistently lower by around 20%. Thus, where Bureau data is to be used on a new site, a factor of 0.82 is applied to the solar radiation coefficient (γ) to account for the higher solar radiation recorded at these sites. The exact reasons for this are unknown, but may be due to a different alignment or height of the sensors, or different assumptions in the way the data is processed.

When the calibrated coefficients (with 0.82 solar radiation adjustment) are applied to the Darwin data set, the average error for daily maximum and minimum temperatures are just 2.18 °C and 2.31 °C at the top sensor respectively (the results are summarised in Table 7.2). The measured temperatures against predicted temperatures are shown graphically in Figure 7.1.

Table 7.2: Average errors at Darwin site (blind check)

Average error at depth	Daily maximum temperature error (°C)	Daily minimum temperature error (°C)
50 mm	2.18	2.31
150 mm	3.26	3.24
250 mm	3.80	2.61
All depths combined	3.08	2.73

Figure 7.1: Temperature model – fit against actuals – blind check for Darwin



The Bureau site in Darwin at which the ambient air and solar data is sourced is nearly 10 km from the instrumented pavement, and does not appear to be a high-quality Bureau site as evidenced by missing several days of data. The minimum air temperatures in particular seem to have several errors. Also, this site is in a tropical climate that is quite drastically different to the other three sites. Given this, the overall good fit of the model output to the actual data is provides confidence that this model can be used at various locations in other parts of WA and Australia. The only notable departure from the relationship is at the coolest minimums, where the model is consistently lower than actual data.

7.2.2 Update in June 2019

The calibration factors have been revised with 10 months of data from the Karratha site, which has added more data from hot climates into the calibration of the model. The data from the Perth location has also been updated for the first half of 2019 to further enhance model calibration.

The addition of data from hot and sunny Karratha has meant that solar radiation now has a greater influence on predicted maximum temperatures near the surface, with this being a critical factor at the Karratha location.

7.3 Hourly Pavement Temperature Model

For sites without instrumented data, daily maximum and minimum air temperatures and daily cumulative solar radiation are required from the closest Bureau of Meteorology weather station. From there, as for the example in Darwin, the model can predict daily maximum and minimum pavement temperatures for any depth within a full depth asphalt pavements.

Once the daily maximum and minimum temperatures are calculated, a separate model has been developed to predict the pavement temperature for each hour of the day. This model consists of two parts, a day model and a night model, with a formula to recognise when to shift between the two models based on the sunrise and sunset times, and the pavement depth at which the hourly distribution is required. The day time function consists of a sinusoidal curve, which starts just after sunrise and runs through to just after sunset, with its peak aligned with the maximum pavement temperature for the day, calculated earlier in the general model (Section 7.1). The night function consists of a proportionate drop-off in temperature from the current temperature down to the daily minimum temperature at a particular depth.

The day model can be represented as in Equation 3:

$$T_{p\,(at\ depth\ D)} = \frac{(T_p\max + T_p\min)}{2} + \frac{(T_p\max - T_p\min)}{2} * \sin[x_1 * t + x_2 - (D * x_3)] \qquad 3$$

where

T_p = temperature at the given depth, calculated for each hour for 1 year

$T_p\max$ = daily maximum pavement temperature in °C at depth D from Equation 2

$T_p\min$ = daily minimum pavement temperature in °C at depth D from Equation 2

D = depth at which pavement temperature is required (in metres)

x_1 = sine curve shift coefficient 1

x_2 = sine curve shift coefficient 2

x_3 = sine curve depth delay coefficient for depth = D

The following input data is required for the hourly temperature model:

- latitude and longitude for the location
- time zone for the location, entered as the offset from Coordinated Universal Time (UTC)
- sunrise and sunset times, as determined through a US National Oceanic and Atmospheric Administration (NOAA) solar calculation spreadsheet
- layer depths for calculation (generally mid-depth of the asphalt layer of interest)
- model coefficients to produce curves and shift between day/night mode
    - two curve shift coefficients as a part of the day function
    - a depth delay coefficient to shift the time of maximum temperature based on the calculation depth
    - a time delay coefficient to delay shifting the mode between day and night based on sunrise and sunset times
    - a drop-off coefficient for proportional temperature loss at night

The night model calculates the pavement temperature, with a starting point as the temperature for the previous hour. The minimum pavement temperature for that day, as calculated by the general model in Equation 2, is then multiplied by a coefficient and subtracted from the calculated temperature for the previous hour. This effectively means that when the pavement temperature is significantly higher than the predicted overnight minimum, there will be a larger and more rapid temperature drop. This reflects the temperature behaviour of pavements monitored through this study, where hot pavements cool rapidly once the sun sets.

The output of these models is a predicted pavement temperature at a specified depth for each hour of a given year. This can be used in conjunction with a traffic distribution and pavement material properties to produce an hourly mechanistic pavement design.

The night model can be represented as in Equation 4:

$$T_{p\,(at\ depth\ D)} = T_{p\,(\,t-1)} - x_4 * T_p \min \tag{4}$$

where

T_p = pavement temperature at depth = D and time = t

$T_{p\,(\,t-1)}$ = pavement temperature at depth = D and time = t – 1 (i.e. 1 hour previous)

x_4 = drop-off coefficient for proportional temperature loss at night

$T_p \min$ = daily minimum pavement temperature in °C at depth D from Equation 2

The day model is applicable when the time of day is greater than the sunrise time plus a constant multiplied by the calculation layer depth, and also less than the sunset time plus a constant multiplied by the calculation layer depth. The transition function can be represented as in Equation 5:

$$Day\ model\ active\ IF{:}\ \ t > (t_{sunrise} + x_5 * D)\ AND\ \ t < (t_{sunset} + x_5 * D) \tag{5}$$

where

t = time (hourly increments, measured in days and fractions of days)

$t_{sunrise}$ = time of sunrise at location

t_{sunset} = time of sunset at location

x_5 = depth delay coefficient for shifting mode between day and night

D = depth at which pavement temperature is required (in metres)

7.4 Pavement Life Analysis

The hourly predicted pavement temperatures can be used to generate temperature distributions throughout the year, or can provide insight into the occurrence of extreme temperatures. An advanced application of this data is to run a mechanistic pavement design calculation for every hour of a sample 12-month period. The current methodology of performing a mechanistic pavement design on a single configuration at just one temperature is overly simplistic and ignores daily fluctuations in asphalt characteristics, as well as the varied traffic levels throughout a day.

This analysis is made possible by utilising an customisable automated CIRCLY spreadsheet, which can perform a series of pavement designs very rapidly with data drawn from the results of the models introduced in Section 7.1 and Section 7.3.

For the purposes of the analysis, a generic pavement design has been used which has the same total asphalt thickness as the Kwinana Freeway site but simplified to just two asphalt layers for the purposes of this analysis (see Figure 7.2). The two layers use moduli values calculated at 85 mm and 200 mm respectively. It would be possible to interpolate the temperature at the second layer mid-depth of 257.5 mm to produce a more realistic estimate. For the purposes of this analysis, the 200 mm depth value provides a conservative estimate.

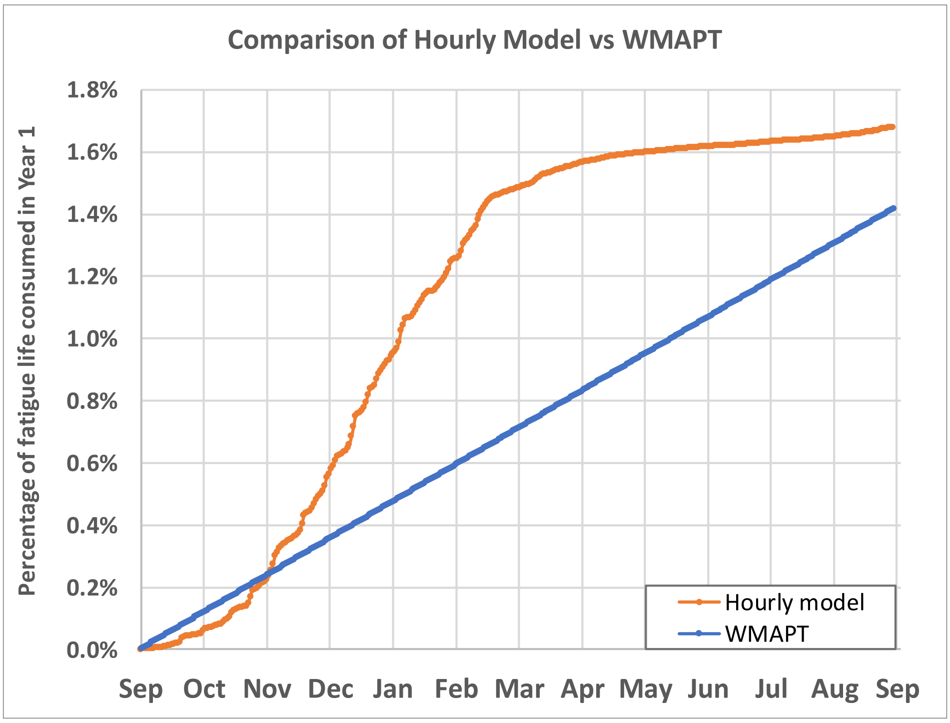
The hourly layer temperatures are obtained from the model, and are used in the CIRCLY analysis for each hour of the day through an Excel VBA macro. The resultant critical strains for each hour of the day are logged and then combined with a generic traffic distribution (using assumptions based on the ‘Kwinana Freeway at Berrigan Drive SB’ traffic count) and assumed material properties to produce an estimated damage increment for each hour of a full year. This can subsequently be projected forward through the 40-year pavement design life with an assumed traffic growth of 2.5% p.a. to determine the percentage of the fatigue life consumed. In this analysis, some assumptions were changed slightly to allow for the WMAPT scenario to reflect close to a 100% fatigue life after 40 years.

Figure 7.2: Generic pavement design used in CIRCLY analysis of hourly model (based on Kwinana Freeway)

Hourly model	WMAPT
LAYER 1 – 170 mm Modulus based on temperature for each hour at depth = 85 mm	LAYER 1 – 170 mm 3651 MPa (at WMAPT 29 °C)
LAYER 2 – 175 mm Modulus based on temperature for each hour at depth = 200 mm	LAYER 2 – 175 mm 3651 MPa (at WMAPT 29 °C)
Granular base – 500 mm at 210 MPa	Granular base – 500 mm at 210 MPa
Subgrade – CBR 7 (~70 MPa)	Subgrade – CBR 7 (~70 MPa)

In the initial scenario, the modulus of the layers in the hourly model was not constrained, leading to asphalt moduli values as low as 300 MPa and consequently predicted very rapid fatigue damage on very hot days. For example, during a 3 hour period between 4pm and 7pm on 4 January 2017, each ESA was predicted to have done 19 times more damage than the average three hour period across the year. The effect of this can be seen in Figure 7.3 – with very rapid damage accumulation during the hot summer months and minimal damage accumulating from around May through September.

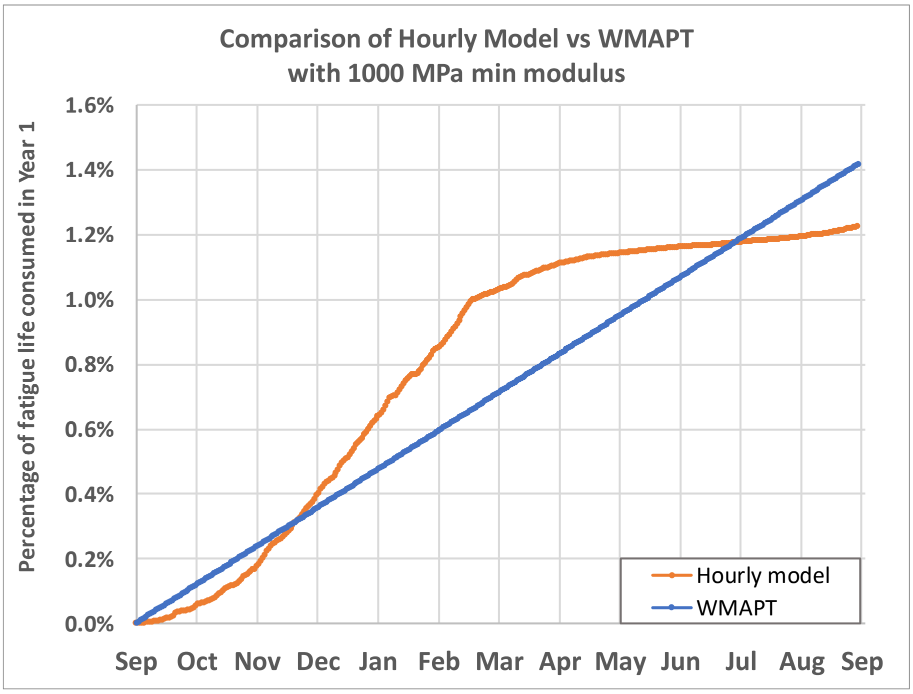
Figure 7.3: Comparison of two approaches to calculating fatigue damage



The result is that the hourly model theoretically accumulates 18% more fatigue damage each year, leading to a design life that is around 4 years shorter than under the existing WMAPT assumptions. This may not be representative of actual fatigue damage occurring in service. The cumulative damage may not be as severe as the model would predict, with observed behaviour suggesting minimal fatigue at higher temperatures (Austroads 2013b).

Main Roads Engineering Road Note 9 recommends that where an asphalt design modulus is less than 1000 MPa, a modulus of 1000 MPa should be used instead. The CIRCLY analysis was therefore also run with the hourly moduli limited to a minimum value of 1000 MPa. With this minimum limit set, the damage predicted through summer is no longer as critical, which is considered to better reflect reality (see Figure 7.4).

Figure 7.4: Comparison of two approaches to calculating fatigue damage – with 1000 MPa minimum modulus



The same 3 hour period on 4 January now only contributes roughly double the damage per ESA than the average over the year. As a result, the analysis now predicts around 14% *less* accumulated fatigue each year under the hourly approach compared to using a single WMAPT. This results in a predicted fatigue life approximately five years longer than the WMAPT approach (i.e. 45 years as opposed to 40).

The consequences of this is that significant pavement rehabilitation/reconstruction could be deferred for another five years, or the pavement could be designed at slightly lesser total asphalt depth to achieve the 40-year fatigue life – which in this case equates to around a 10 mm saving in total depth.

The process of running a full year of analysis and fatigue life prediction for a pavement takes approximately 45 minutes of processing and computation time, with an approximately similar length of time for inputting site data and pavement characteristics. This analysis process can likely be streamlined with some relatively simple programming, however the approach described here is considered appropriate for the purposes of this initial research work and in order to provide a relatively simple design tool for Main Roads.

7.5 Permanent Deformation Prediction

While fatigue is typically the critical factor in determining the asphalt depth during the design of thick asphalt pavements, permanent deformation through mechanisms such as rutting and shoving when the material has insufficient stability, can lead to premature failure well before the predicted fatigue life has been reached (Austroads 2017a). The following relevant paragraph from the Austroads Guide to Pavement Technology (2017a) provides context on why this is a critical issue for pavement design and why it has traditionally been a difficult risk to quantify:

> While permanent deformation is well acknowledged as a distress mode of primary importance for asphalt, it is not included in the design procedures because no model is available which will reliably predict the development of rutting with the passage of traffic/time. The reason for this may be readily understood. During the service life of an asphalt layer in a road pavement, a very significant proportion of the accumulated permanent deformation in the asphalt layer will have occurred during the very rare times when the asphalt is at a highly elevated temperature. For asphalt layers to reach such elevated temperatures (throughout the layer) requires a succession of very hot, clear days and accompanying hot nights. Prediction of the occurrences of such weather patterns during the service life of the asphalt can be extremely difficult. Likely problem areas are those associated with heavy vehicles travelling at low speed or accelerating or braking (climbing lanes, intersections, etc.).

Factors that influence the stability of a mix include the aggregate properties, binder properties, volumetric properties of the mix, binder content, rate of loading, and environmental conditions – of which temperature is a critical factor. Wheel tracking of samples at various temperatures may provide some insight into the sensitivity of a mix to high temperatures, but without knowledge of the likelihood of reaching those temperatures, it is difficult to quantify the risk and make informed decisions regarding the use of materials and binders that are less susceptible to permanent deformation at high temperatures.

Knowing the number of times that a pavement exceeds a certain ‘extreme’ temperature may allow us to better understand these risks and design pavements accordingly. For example, at the Kwinana Freeway site for the 12 months following 22 September 2016, the temperature at 45 mm depth exceeded 55 °C (i.e. likely 60 °C+ at the surface) during a total of 55 one-hour periods; with 10 of these hours in November, 14 in December, 28 in January and 3 in February. It should be noted that 2016/17 was one of the coolest summers in recent times, so this likely understates the number of extreme heat days in a typical summer. In terms of the time of day, the most common time for extreme heat was between 3pm and 5pm, which tends to coincide with afternoon/evening peak traffic in many locations.

This data can be combined with a local traffic distribution to estimate the number of ESAs at a particular location while the temperature exceeds a critical value. For example, using the Kwinana Freeway traffic count at Berrigan Drive southbound, approximately 39,000 ESAs per year are experienced at this location while the pavement temperature at 45 mm is above 55 °C. This may allow for a better understanding of the relative risk of permanent deformation across different locations and traffic profiles. Although it may be difficult to do much to minimise this risk, it could provide some direction on where to use deformation-resistant binders and materials. This is an area for further investigation and could be a valuable inclusion into future asphalt pavement design procedures.

This would not only be relevant in locations such as Perth with relatively hot pavements in summer, but would also be a useful tool for climates such as those in Victoria or Tasmania with lower average temperatures, but has a smaller number of extremely hot days each summer that may be responsible for a very high proportion of total pavement damage due to permanent deformation.

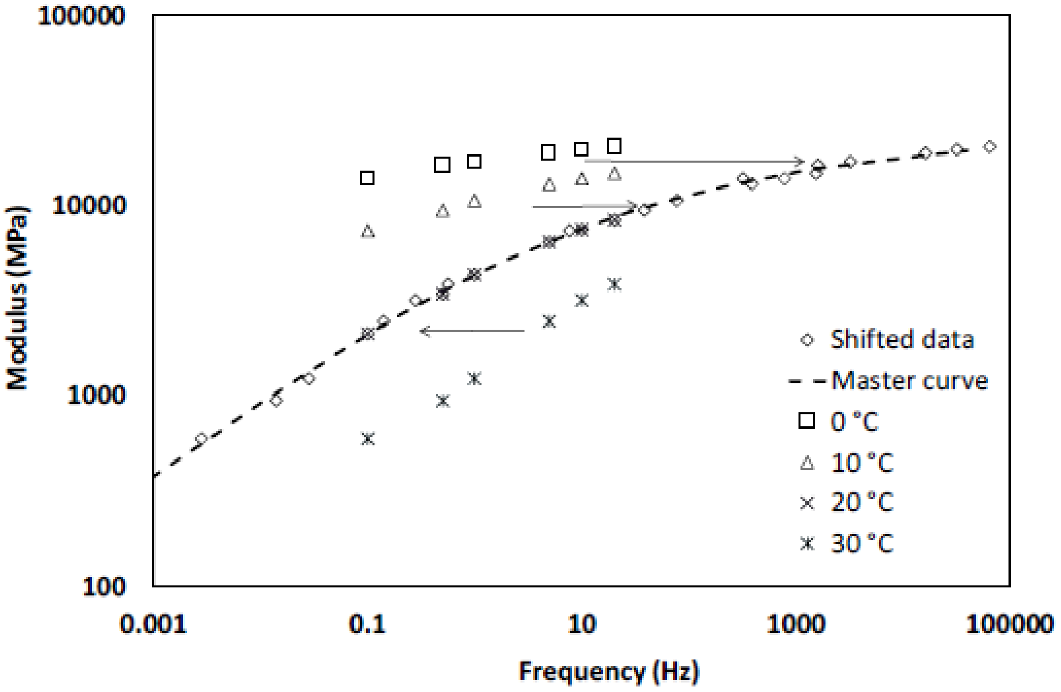
7.6 Rate of Loading

As a viscoelastic material, the modulus of asphalt is dependent on both the temperature and the rate of loading. While this study was primarily focused on the discussion around temperature, a stronger understanding of asphalt and binder behaviour under traffic will not be possible without further study into the relationship between modulus and loading time at different temperatures, and ultimately how this may impact upon pavement life.

The relationship is shown below in Figure 7.5, with the effect of altering loading time clearly evident. For example, this mix has undergone flexural modulus testing at six frequencies at each of four temperatures. At 30 °C, the laboratory flexural modulus at 1 Hz (equivalent to a heavy vehicle speed of approx. 6 km/h) is around 1200 MPa while at 10 Hz (63 km/h) it is over 3000 MPa. Two pavements, both at 30 °C, would behave very differently if most of the traffic they experience was at low speeds (for example at an intersection approach or roundabout) versus at high speed (free flow highway environment).

The relative effect of loading time increases as temperature increases, which can be seen in Figure 7.5. At 30 °C the modulus shows a 150% increase at 10 Hz compared to 1 Hz, while the same shift at 10 °C equates to only a 30% increase in modulus. This means that any changes that we make to how we calculate and account for pavement temperature in design will also need to consider loading time. If we were to adopt a two-layer approach with hourly temperatures for the design of thick asphalt pavements, it may be that the loading time also needs to be considered in a more sophisticated manner.

Figure 7.5: Variation in laboratory measured modulus at various temperatures and load frequencies



Source: Austroads (2017a)

8 CONCLUSIONS AND RECOMMENDATIONS

Main Roads has recognised that the current temperature inputs used in the design of asphalt pavements in WA have led to very thick asphalt pavement designs, and there is limited evidence of comparable thick asphalt pavements in hot climates showing significant fatigue damage. A potential reason for this is the simplified WMAPT approach adopted, which represents a single design temperature value for a given location, and does not take into account asphalt thickness, underlying substrate properties, localised weather, the hourly distribution of traffic and other location-specific factors.

There have been previous efforts to enhance this process with more sophisticated modelling and mix-specific design measures, however it was necessary to gather real pavement temperature data from a range of representative locations.

This project has built on the investment through NACOE and Austroads, and supported by AAPA, to instrument a series of pavements and use that data to better understand the range and extremes of pavement temperatures in WA and more widely, and to harness this data in a pavement temperature model calibrated for local conditions and materials.

Sourcing data from Curtin University’s instrumented pavement at the Great Eastern Highway provided some early guidance for the project, although the sensors were only active for a few months and the applications of this data were limited. It did provide some early indications of the expected temperatures of pavements in the Perth area.

The two sets of sensors with accompanying weather stations were successfully installed at the Kwinana Freeway in Jandakot (south of Perth) and in Karratha in the north of WA. With more than two years worth of data from the first site and one year at the Karratha site, it was possible to analyse this data and make observations regarding the likely extreme temperatures that may be experienced and link the observed pavement temperatures to key climatic factors. Despite relatively mild summers in both 2016/17 and 2017/18, the Kwinana Freeway section still experienced a maximum surface temperature of approximately 60 ºC, and in February 2019 the Karratha site had a reading of 63 °C at the 45 mm sensor (likely close to 70 °C at the surface).

When measured as average mid-depth temperatures in the asphalt pavement over the course of the year, at 25.3 ºC and 25.5 ºC for the two years, this is significantly lower than the WMAPT value for Perth of 29 ºC. While this design value is weighted, the offset between the actual temperature and assumed WMAPT was greater in Perth than for any year in the other two instrumented locations in Brisbane and South Gippsland. Some potential amendments to how the WMAPT is calculated have been explored through this work, which have the potential to reduce required asphalt thicknesses in some locations.

A number of potential approaches to calculating asphalt pavement temperatures were investigated, resulting in the proposal of a pavement temperature model for thick asphalt pavements. The proposed model can estimate the hourly pavement temperature at any depth for any location in Australia with only very simple and readily accessible input data. This information can then be combined with some basic material characteristics and traffic data to predict the fatigue life for a asphalt layer at a particular location. Some implications of this model have been explored, and an example of its application provided.

Ultimately, it is expected that this model will enable designers to make better informed decisions regarding the design choices they make, and in many cases will potentially lead to thickness reductions and eventual cost savings when designing thick asphalt pavements.

8.1 Recommendations

A series of recommendations are provided below, including considerations for future research through WARRIP or otherwise:

1. Continue monitoring the two sites and providing monthly updates, along with any notable observations, through June 2021. The December and January data from Karratha are particularly important due to the power supply issues over that period in the first year of operation.
2. Pavement temperatures at depth were shown to be relatively predictable across a number of locations, however the surface temperature appeared to be influenced by a wide range of factors. This project only analysed very limited surface temperature data, so it may be necessary to capture a prolonged period of surface temperature data. Some of the key factors appear to be:
   (a) Albedo
   (b) Lane effects (shoulder vs left lane vs middle/right lanes)
   (c) Wind draught from cars and particularly trucks
   (d) Shading from passing vehicles and roadside objects
3. The impact of permanent deformation at extreme pavement temperatures, particularly near the surface, is difficult to quantify. Some efforts have been made in this report to introduce potential solutions, however this may require additional investigation including laboratory testing and further analysis.
4. Linked to the issue of extreme surface temperatures, in addition to reducing the risk of permanent deformation, there are several reasons why reduced surface temperatures would be beneficial, including to reduce the urban heat island effect and to increase road user comfort (for stationary vehicles in particular). This has been a topic of research previously, with lighter coloured aggregates being one option. The use of high standard granular pavements with thin asphalt surfacings may be another option. Main Roads may benefit from a focussed study into minimising surface temperatures to deliver benefits both in terms of pavement performance and improved road user and community outcomes.
5. Introduce options for incorporating climate change variables into the model, based on recent trends in air temperature and solar radiation, both in terms of scaling up the average temperatures over the year as well as the regularity of extreme conditions (e.g. more days each year with 60 °C+ pavement temperatures). This may be developed as an optional component for a given location.
6. The pavement temperature model, and the design tools in Excel spreadsheet format, are valuable for occasional use for upcoming major projects and where Main Roads has a particular interest in assessing the impact of pavement temperatures. In order to use these tools more widely, and to facilitate their use on a wider range of projects and potentially applied Australia-wide, it is necessary to develop this tool further. This is currently being developed through a concurrent NACOE project, but may require further support and funding.
7. This work has the potential to feed into the wider research efforts regarding improvements to the current Austroads design methodology, to which several other WARRIP projects are also contributing. Improving the characterisation of temperature in asphalt pavements is a major link in this overall process, but the full benefits of each research element can only be realised when they are combined. The close linkage between temperature and loading time would suggest that this would be valuable for further research to enhance the outcomes of this project.

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APPENDIX A INSTALLATION PROCEDURE AND PHOTOS

A.1 Installation Procedure and Photos – Kwinana Freeway, Perth

Table A 1: Procedure for installation of temperature sensors and weather station at Kwinana Freeway

	Step	Details	Equipment required
Day 1	Site layout	▪ Layout conduit, measure location for weather station ▪ Final check for obstructions (buried services, objects that might restrict sunlight to the solar radiation sensor)	▪ Electrical conduit (50 mm diameter)
	Digging and trenching	▪ Dig hole 1m deep for weather station mast ▪ Using wooden frame for guidance, dig base for weather station plinth (approx. 1m by 0.6m and 200 mm deep) ▪ Dig trench from edge of shoulder to edge of plinth, minimising number of elbow joints (i.e. one only) ▪ Sawcut or jackhammer through asphalt to 1.5–2 m into shoulder, to ensure a solid diameter of asphaltic material around sensors	▪ Shovels ▪ Jackhammer or concrete saw
	Concreting	▪ Lay conduit in trenches with temporary cord at each end (to later pull cables through) ▪ Fit conduit and joints at weather station ▪ Place mast support in deep hole ▪ Backfill mast-hole and plinth with concrete (preferably rapid-set) ▪ Apply surface finish at plinth and allow to cure overnight ▪ Lay concrete over conduit in trench to minimise risk of vehicle damage, cover with sand/dirt when partially cured	▪ Cord/rope (at least 20 m) ▪ Weather station components and parts ▪ Concrete (recommend use of ‘concrete taxi’ for fast and flexible service) ▪ Concreting tools
	Place cold-mix asphalt	▪ Secure and water-proof conduit in asphalt (using tape or plastic bag) ▪ Apply and moderately compact cold-mix asphalt on top of conduit to allow re-opening of road overnight	▪ Cold-mix asphalt in bags ▪ Asphalt whacker compactor
Day 2	Install weather station	▪ Secure cabinet needs to be bolted down to concrete plinth ▪ Assemble weather station mast and attach instruments (solar panel, air temperature sensor, solar radiation sensor, rain gauge, wind sensor) ▪ Attach mast to mast support, winch/lift and secure in position ▪ Tie up instrument cables and attach to cord to pull through to weather station terminal	▪ Weather station components and parts
	Core out asphalt	▪ Take a series of cores to form a rectangular shape that will allow access to drill holes for the sensor tips, ensure depth is at least 30 mm deeper than lowest proposed sensor depth ▪ Jackhammer out temporary cold-mix backfill to expose conduit ▪ Remove all water and material for a dry and clear working area	▪ Asphalt coring rig ▪ Jackhammer ▪ Suction hose or other device to remove water
	Install sensors	▪ Drill 100 mm into face of cored section, parallel to road surface, drill-bit with diameter equal to sensor tip diameter ▪ Apply thermo-conductive gel to sensor tip and seal in holes ▪ Mark ends of sensor leads with coloured/numbered tape and tie securely to cord in conduit ▪ Connector ends removed to prevent blockage in conduit ▪ Pull cord through from weather station and re-wire connector ends	▪ Drill ▪ Sensors and leads

	Step	Details	Equipment required
	Complete weather station install	▪ Connect weather station power source (solar panels) ▪ Connect all temperature sensor cables to terminal ▪ Run cables through from weather station instruments to terminal and connect ▪ Link to modem for wireless, real-time access to data ▪ Test all connections and readings with online portal	▪ Weather station components and parts
	Back-fill cored section	▪ Mix up small batch of ready-mix rapid-set concrete ▪ Carefully place around sensor boxes to minimise damage from compaction ▪ Backfill hole with remaining concrete to cover sensor boxes ▪ Allow to cure for at least 1 hour ▪ Add cold-mix asphalt to provide good surface finish, compact	▪ Rapid-set concrete (in bags) ▪ Concreting tools ▪ Cold-mix asphalt ▪ Asphalt whacker compactor
	Clean site	▪ Clean asphalt pavement from dust/debris ▪ Clean shoulder area and remove all rubbish etc. ▪ (At later stage, add markers to signify location of sensors in case of further works in the area)	▪ Brooms, shovels etc.

Figure A 1: Extracted core showing layers in asphalt

Figure A 1: Weather station after install

A.2 Installation Procedure and Photos – Karratha

Table A 2: Karratha weather station installation

	Step	Details	Equipment required
Day 1	Site layout (as per Kwinana Freeway)	▪ Layout conduit, measure location for weather station ▪ Final check for obstructions that might restrict sunlight to the solar radiation sensor	▪ Electrical conduit (50 mm diameter)
	Digging and trenching	▪ Dig hole 500 mm deep for weather station mast inside the 250 mm box out area (750 mm total depth) ▪ Dig trench from edge of shoulder to edge of plinth, minimising number of elbow joints (i.e. one only)	▪ Shovels ▪ Jackhammer
	Core out asphalt	▪ Take a series of cores to form a rectangular shape that will allow access to drill holes for the sensor tips, ensure depth is at least 30 mm deeper than lowest proposed sensor depth ▪ Remove all water and material for a dry and clear working area	▪ Asphalt coring rig ▪ Jackhammer ▪ Preferably suction hose or other device to remove water
	Install sensors	▪ Drill 100 mm into face of cored section, parallel to road surface, drill-bit with diameter equal to sensor tip diameter ▪ Insert sensor tips into holes ▪ Mark ends of sensor leads with coloured/numbered tape and tie securely to cord in conduit ▪ Connector ends removed to prevent blockage in conduit ▪ Pull cord through from weather station and re-wire connector ends	▪ Drill ▪ Sensors and leads
	Concreting ($4\ m^3$)	▪ Lay conduit in trenches with temporary cord at each end (to later pull cables through) ▪ Fit conduit and joints at weather station ▪ Install formwork approx. 150 mm above boxed out area ▪ Place mast support in deep hole (total depth from concrete surface approx. 900 mm) ▪ Backfill mast-hole and plinth with concrete (preferably rapid-set) ▪ Apply surface finish at plinth and allow to cure overnight ▪ Lay concrete over conduit in trench to minimise risk of vehicle damage, cover with sand/dirt when partially cured	▪ Cord/rope (at least 20 m) ▪ Weather station components and parts ▪ Concrete (recommend use of ‘concrete taxi’ for fast and flexible service where possible) ▪ Concreting tools
	Back-fill cored section with concrete	▪ Carefully place around sensor boxes to minimise damage from compaction ▪ Backfill hole with remaining concrete to cover sensor boxes ▪ Allow to cure overnight	▪ Concrete (preferable rapid set) ▪ Concreting tools ▪ Cold-mix asphalt
Day 2	Backfill cored section with cold-mix asphalt	▪ Apply and moderately compact cold-mix asphalt on top of asphalt hole filled with concrete	▪ Cold-mix asphalt in bags ▪ Asphalt hand compactor

	Step	Details	Equipment required
	Install weather station (as per Kwinana Freeway)	▪ Secure cabinet needs to be bolted down to concrete plinth ▪ Assemble weather station mast and attach instruments (solar panel, air temperature sensor, solar radiation sensor, rain gauge, wind sensor) ▪ Attach mast to mast support, winch/lift and secure in position ▪ Tie up instrument cables and attach to cord to pull through to weather station terminal	▪ Weather station components and parts
	Complete weather station install (as per Kwinana Freeway)	▪ Connect weather station power source (solar panels) ▪ Connect all temperature sensor cables to terminal ▪ Run cables through from weather station instruments to terminal and connect ▪ Link to modem for wireless, real-time access to data ▪ Test all connections and readings with online portal	▪ Weather station components and parts
	Clean site (as per Kwinana Freeway)	▪ Clean asphalt pavement from dust/debris ▪ Clean shoulder area and remove all rubbish etc.	▪ Brooms, shovels etc.

Figure A 2: Approximate sensor and concrete base location

Figure A 3: Coring

Figure A 4: Core depth

Figure A 5: Cored section of pavement

Figure A 6: Sensor 1 (50 mm)

Figure A 7: Sensor 2 (85 mm)

Figure A 8: Sensor 3 (120 mm)

Figure A 9: Sensor 4 (160 mm)

Figure A 10: Sensor 5 (205 mm)

Figure A 11: Sensor 6 (260 mm)

Figure A 12: Sensors

Figure A 13: Cold-mix backfill

Figure A 14: Pre-concrete pour

Figure A 15: Concrete base and back fill

Figure A 16: West view

Figure A 17: East view

Figure A 18: North view

APPENDIX B MODEL CALIBRATION

B.1 Four component model (excluding Karratha)

From Equation 2:

Maximum pavement temperature

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

Minimum pavement temperature

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

Table B 1: Coefficients for daily maximum temperature with different calibration data

	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
α	5.919	-2.903	6.508	1.482	5.284	1.475	2.542
β	0.791	1.346	0.721	1.090	0.777	1.103	1.004
γ	0.843	0.534	0.662	0.668	0.778	0.567	0.669
δ	-47.197	-36.942	-30.536	-38.428	-35.612	-31.540	-34.234

Table B 2: Errors for daily maximum temperature with different calibration data

Site	Average error for...	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
WA	Top sensor	2.83	3.75	5.36	3.12	3.65	3.69	3.28
	All sensors[1]	3.06	4.11	3.87	3.54	3.14	3.55	3.32
QLD	Top sensor	4.05	2.56	6.82	2.91	5.16	3.47	3.59
	All sensors[1]	4.55	2.77	5.89	2.96	4.76	2.99	3.25
VIC	Top sensor	2.86	3.76	2.33	3.21	2.27	2.95	2.78
	All sensors[1]	3.80	4.82	2.95	4.21	3.31	3.93	3.82
All	**Top sensor**	**3.25**	**3.36**	**4.84**	**3.08**	**3.69**	**3.37**	**3.22**
	All sensors[1]	**3.80**	**3.90**	**4.24**	**3.57**	**3.74**	**3.49**	**3.46**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

Table B 3: Coefficients for daily minimum temperature with different calibration data

	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
α	-1.488	0.067	1.106	-0.720	0.099	0.239	-0.196
β	1.015	1.110	0.925	1.083	0.973	1.066	1.055
γ	0.344	0.225	0.309	0.285	0.331	0.267	0.292
δ	27.375	19.615	16.700	21.844	19.156	17.889	19.416

Table B 4: Errors for daily minimum temperature with different calibration data

Site	Average error for...	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
WA	Top sensor	1.92	2.05	1.96	2.00	1.99	2.09	2.04
	All sensors[1]	2.17	2.36	2.37	2.23	2.23	2.29	2.24
QLD	Top sensor	1.79	1.42	1.86	1.46	1.70	1.45	1.47
	All sensors[1]	2.02	1.74	2.37	1.78	2.06	1.77	1.80
VIC	Top sensor	1.94	1.85	1.79	1.85	1.82	1.83	1.83
	All sensors[1]	2.20	2.20	2.08	2.16	2.08	2.14	2.12
All	**Top sensor**	**1.88**	**1.78**	**1.87**	**1.77**	**1.83**	**1.79**	**1.78**
	All sensors[1]	**2.13**	**2.10**	**2.27**	**2.06**	**2.12**	**2.07**	**2.05**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

B.2 Two component model (excluding Karratha)

Simplified version of Equation 2:

Maximum pavement temperature

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

Minimum pavement temperature

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

Table B 5: Coefficients for daily maximum temperature with different calibration data

	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
α	Assumed to be 0						
β	Assumed to be 1						
γ	0.832	0.897	0.626	0.834	0.734	0.753	0.772
δ	-39.692	-30.086	-20.359	-30.534	-28.414	-23.328	-26.817

Table B 6: Errors for daily maximum temperature with different calibration data

Site	Average error for...	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
WA	Top sensor	2.86	2.61	4.93	2.72	3.64	3.29	3.16
	All sensors[1]	3.33	4.14	3.61	3.57	3.33	3.47	3.41
QLD	Top sensor	3.73	2.87	5.58	3.41	4.48	4.05	3.95
	All sensors[1]	3.93	3.24	4.11	3.31	3.78	3.38	3.42
VIC	Top sensor	2.76	3.35	2.68	2.87	2.54	2.57	2.61
	All sensors[1]	4.20	4.78	3.56	4.26	3.77	3.97	3.97
All	**Top sensor**	**3.12**	**2.95**	**4.39**	**3.00**	**3.55**	**3.30**	**3.24**
	All sensors[1]	**3.82**	**4.05**	**3.76**	**3.72**	**3.63**	**3.61**	**3.60**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

Table B 7: Coefficients for daily minimum temperature with different calibration data

	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
α	Assumed to be 0						
β	Assumed to be 1						
γ	0.303	0.331	0.316	0.316	0.318	0.333	0.324
δ	22.994	21.997	18.028	22.623	18.927	19.302	20.042

Table B 8: Errors for daily minimum temperature with different calibration data

Site	Average error for...	WA only	QLD only	VIC only	WA + QLD	WA + VIC	QLD + VIC	WA + QLD + VIC
WA	Top sensor	1.96	2.14	1.96	2.03	1.99	2.10	2.05
	All sensors[1]	2.21	2.22	2.26	2.21	2.23	2.21	2.21
QLD	Top sensor	1.59	1.56	1.62	1.57	1.60	1.57	1.58
	All sensors[1]	1.89	1.85	2.03	1.86	1.97	1.89	1.90
VIC	Top sensor	1.79	1.87	1.81	1.82	1.81	1.85	1.83
	All sensors[1]	2.11	2.15	2.11	2.12	2.09	2.10	2.09
All	**Top sensor**	**1.78**	**1.86**	**1.80**	**1.81**	**1.80**	**1.84**	**1.82**
	All sensors[1]	**2.07**	**2.07**	**2.13**	**2.07**	**2.10**	**2.07**	**2.07**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

B.3 Two component model (including Karratha)

Simplified version of Equation 2:

Maximum pavement temperature

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

Minimum pavement temperature

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

Table B 9: Coefficients for daily maximum temperature with different calibration data

	Perth only	Karratha only	QLD only	VIC only	Perth and Karratha	All four sites
α	Assumed to be 0					
β	Assumed to be 1					
γ	0.809	0.956	0.885	0.626	0.874	0.796
δ	-37.635	-52.460	-30.218	-20.359	-43.604	-30.054

Table B 10: Errors for daily maximum temperature with different calibration data

Site	Average error for...	Perth only	Karratha only	QLD only	VIC only	Perth and Karratha	All four sites
Perth	Top sensor	3.34	3.19	3.22	4.84	3.13	3.35
	All sensors[1]	3.25	3.66	3.98	3.49	3.37	3.35
Karratha	Top sensor	4.42	2.97	3.09	6.84	3.67	4.34
	All sensors[1]	3.20	3.17	3.62	3.81	3.13	3.25
QLD	Top sensor	3.97	2.97	2.95	5.73	3.45	3.85
	All sensors[1]	3.74	4.21	3.12	3.68	3.85	3.22
VIC	Top sensor	2.69	3.36	3.25	2.68	2.94	2.68
	All sensors[1]	4.09	4.98	4.67	3.56	4.43	4.04
All	**Top sensor**	**3.61**	**3.12**	**3.13**	**5.02**	**3.30**	**3.55**
	All sensors[1]	**3.57**	**4.01**	**3.85**	**3.64**	**3.70**	**3.46**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

Table B 11: Coefficients for daily minimum temperature with different calibration data

	Perth only	Karratha only	QLD only	VIC only	Perth and Karratha	All four sites
α	Assumed to be 0					
β	Assumed to be 1					
γ	0.302	0.233	0.344	0.316	0.265	0.313
δ	22.133	37.793	20.650	18.028	30.564	21.968

Table B 12: Errors for daily minimum temperature with different calibration data

Site	Average error for...	Perth only	Karratha only	QLD only	VIC only	Perth and Karratha	All four sites
Perth	Top sensor	2.54	2.45	2.84	2.56	2.47	2.61
	All sensors[1]	2.31	2.64	2.33	2.33	2.42	2.30
Karratha	Top sensor	1.58	1.37	1.99	1.64	1.43	1.67
	All sensors[1]	1.92	1.61	1.91	2.11	1.67	1.89
QLD	Top sensor	1.70	1.80	1.65	1.70	1.74	1.66
	All sensors[1]	1.89	2.54	1.81	2.02	2.09	1.85
VIC	Top sensor	1.79	1.76	1.91	1.81	1.76	1.81
	All sensors[1]	2.09	2.75	2.15	2.11	2.34	2.10
All	**Top sensor**	**1.90**	**1.85**	**2.10**	**1.93**	**1.85**	**1.94**
	All sensors[1]	**2.05**	**2.38**	**2.05**	**2.14**	**2.13**	**2.04**

Note 1: excludes bottom sensor due to high variability being close to the granular pavement below

B.4 Fit with actuals

Graphs of the actual vs predicted maximum and minimum pavement temperatures, for the final model with α and β set as 0 and 1 respectively, and inclusive of the 2018/19 Karratha data, are shown below.

Figure B 1: Max and min temperature model – fit against actuals - Perth

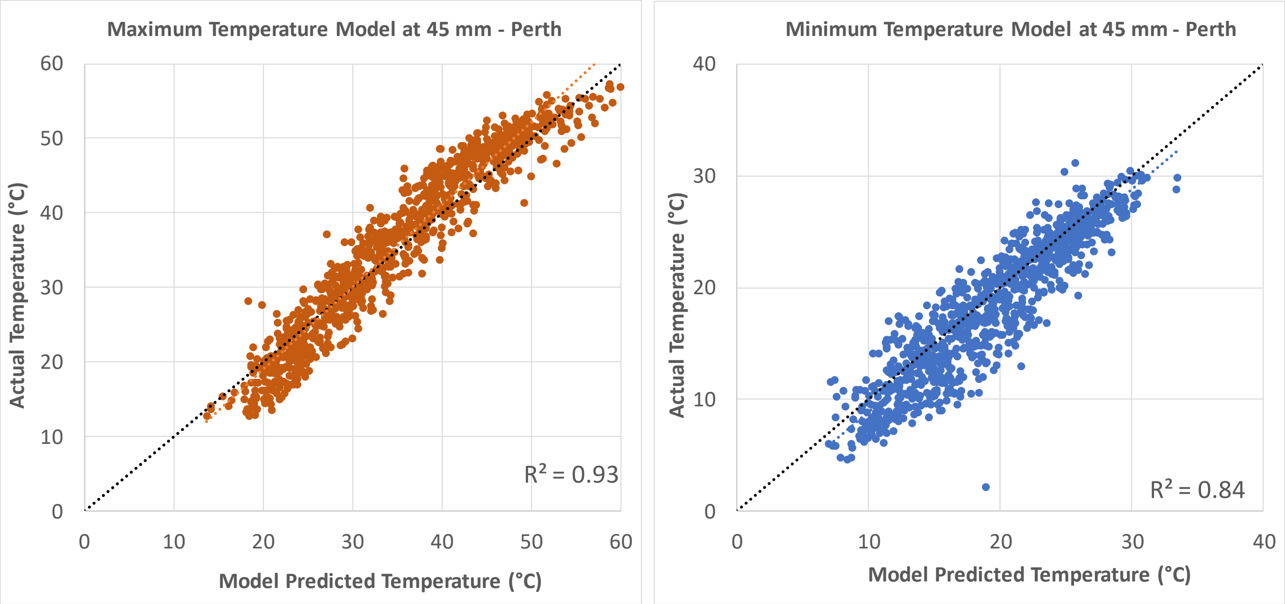

Figure B 2: Max and min temperature model – fit against actuals – Karratha

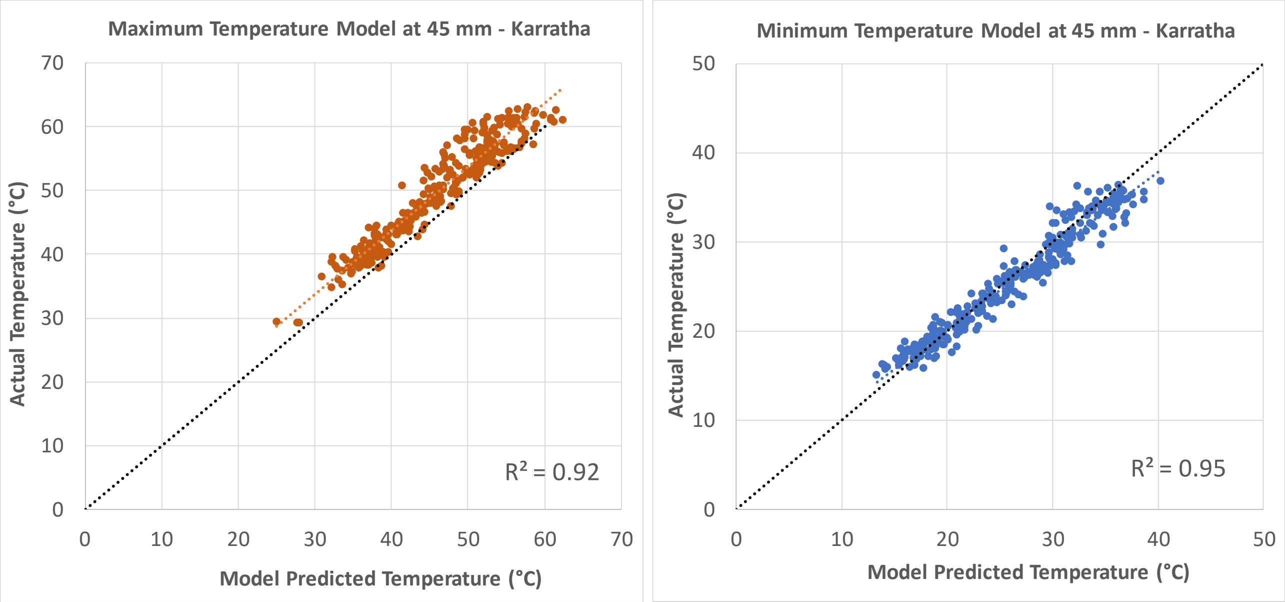

Figure B 3: Max and min temperature model – fit against actuals - Brisbane

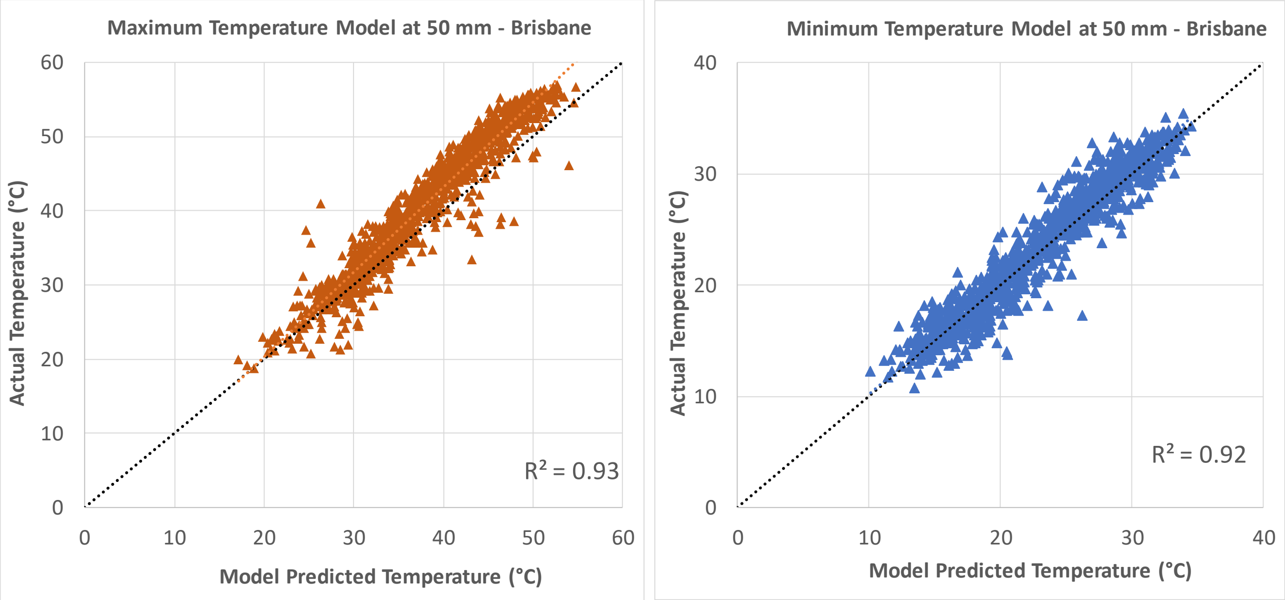

Figure B 4: Max and min temperature model – fit against actuals – South Gippsland