THE APPLICATION OF LOCALLY DEVELOPED PAVEMENT TEMPERATURE PREDICTION ALGORITHMS IN PERFORMANCE GRADE (PG) BINDER SELECTION

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ABSTRACT

The stiffness and rutting performance of Hot-mix asphalt (HMA) is highly temperature dependent due to the visco-elastic nature of bituminous binders. Hence, design temperature is an important parameter in the selection of the binder grade. In this paper, locally developed algorithms for asphalt pavement temperature prediction are validated against new field data. The algorithms provide acceptable estimates of the actual pavement temperatures at the monitored sites. The algorithms were translated into software that, using air temperature data from weather stations, calculates the temperature regimes under which HMA performs. The software can be used in Performance Grade (PG) binder selection as per the Superpave HMA design methodology. With both the pavement temperature prediction software and the PG binder classification for South African binders available, the validation of the PG binder selection methodology for local use can commence.

1. INTRODUCTION

The sensitivity of bitumen for temperature variation plays a mayor role in the stiffness and rutting performance of Hot-Mix Aasphalt (HMA). Illustration 1 shows the influence of temperature on the resistance against permanent deformation for a standard continuously graded medium mix widely used in South Africa. The Hamburg wheel tracking test results in the illustration provide an indication of the extent of behavioural change of HMA material at rising temperatures.

The temperature regime to which HMA pavement layers are subjected in South Africa has been the topic of several studies in the past. In the early 1970s Williamson performed some extensive investigations into pavement temperature measurement and the prediction thereof. His studies are documented in Williamson and Kirby (1970), Williamson (1971a, 1971b, 1971c, 1972a, 1972b, 1972c, 1972d), and Williamson and Marias (1975). Internationally, the Strategic Highway Research Program (SHRP) in the USA introduced temperature models as part of a standardized HMA design method known as Superpave. Everitt et al (1999) made a first attempt to calibrate the Superpave algorithms for use in South Africa, based on pavement temperature data recorded in Durban, Newcastle and Pretoria. They found the Superpave algorithms to provide a reasonable indication of maximum surface temperatures, but also stated that new local algorithms should preferably be developed. Viljoen (2001), used the datasets from the Everitt study, as well as the data gathered by Williamson and in several other local studies to develop temperature prediction equations for asphalt pavements in South Africa

This paper presents the validation of the Viljoen (2001) model against new pavement temperature data, in other words, data from outside the datasets against which the model was developed. The Viljoen algorithms form the basis of newly developed pavement temperature prediction software, called CSIR ThermalPADS. The use of this software in HMA design and in particular in Performance Grade (PG) binder selection is discussed in the last section of the paper.

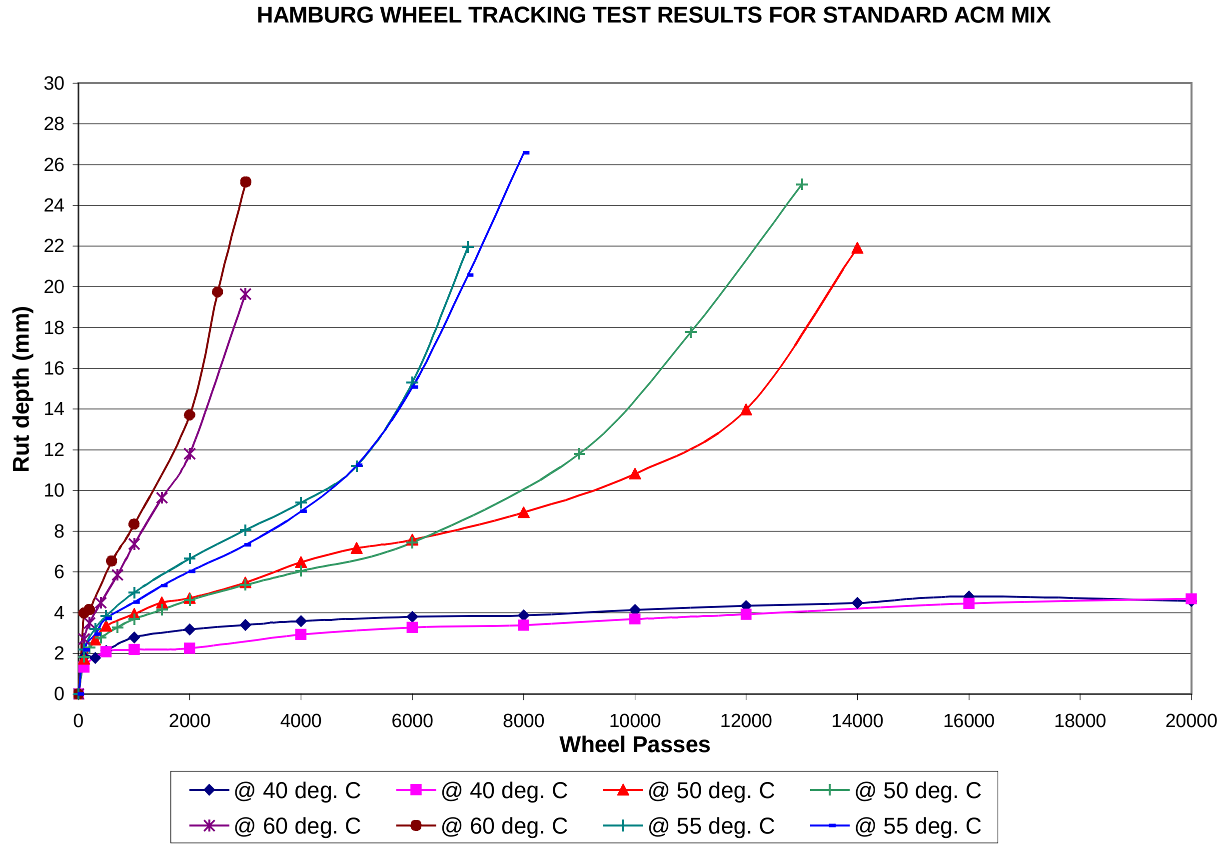

Illustration 1: Hamburg wheel tracking test results at various temperatures

2. TEMPERATURE PREDICTION ALGORITHMS

In this section the Superpave pavement temperature predictions algorithms, as contained in Kennedy et al (1994), and the algorithms developed for temperature prediction in the South African climate by Viljoen (2001), are presented and compared. The algorithms by Viljoen have, as far as could be established, never been made public before and will therefore be discussed to some detail.

2.1 Maximum surface temperature prediction

The maximum asphalt surface temperature predictions equations in Superpave (Kennedy et al., 1994) and by Viljoen (2001), are quite uncomplicated in their final form. They are based however, on the energy balance concept, and calibration of the equations involves identifying the best fit of values for the asphalt surface absorptivity, the transmission coefficient of air, the emissivity of air, the emissivity of the asphalt surface, the asphalt surface heat transfer coefficient and the conductivity of the asphalt material.

A difference in the final form of the equation, between Viljoen (2001), shown as Equation 1 and Superpave, shown as Equation 4, is the inclusion of the zenith angle, instead of the latitude only. The Superpave equation is valid only for the position of the sun in the summer sky. Inclusion of the zenith angle allows for seasonal, and in fact daily, variation in solar energy potential.

$$T_{s(max)} = T_{air(max)} + 24.5(\cos Z_n)^2 \cdot C \qquad (1)$$

where:

$T_{s(max)}$	= the daily maximum asphalt surface temperature in ºC
$T_{air(max))}$	= the daily maximum air temperature in ºC
Z_n	= Zenith angle at midday
C	= Cloud cover index

with:

C =	1.1	if $T_{air(max)}$ > 30 ºC
C =	1.0	if monthly mean air temperature < $T_{air(max)}$ < 30 ºC
C =	0.25	if $T_{air(max)}$ < monthly mean air temperature

The zenith angle is a function of the solar declination as shown in Equation 2 below:

$$\cos(Z_n) = \sin(latitude)\sin(declination) + \cos(latitude)\cos(declination) \qquad (2)$$

For the purpose of this paper, an approximation of the solar declination is provided as Equation 3. The ThermalPADS software contains a more accurate approximation of the daily solar declination.

$$Declination = -23.45^{o} \cdot \cos\left[\frac{360^{o}}{365} \cdot (N+10)\right] \qquad (3)$$

where:

N = day of the year (with 1st of January = 1)

The equation for maximum asphalt surface temperatures recommended in Superpave:

$$T_{s(max)} = T_{air(max)} - 0.00618 \cdot latitude^2 + 0.2289 \cdot latitude + 24.4 \qquad (4)$$

2.2 Minimum surface temperature prediction

The background of the minimum asphalt surface temperature prediction is less complex. The algorithm found to by Viljoen (2001) to provide the best fit to the available local data is shown as Equation 5. The recommended equation in Superpave is shown as Equation 6.

$$T_{s(min)} = 0.89\, T_{air(min)} + 5.2 \qquad (5)$$

$$T_{s(min)} = 0.859\, T_{air(min)} + 1.7 \qquad (6)$$

where:

$T_{s(min)}$	= the daily minimum surface temperature in ºC
$T_{air(min)}$	= the daily minimum air temperature in ºC

2.3 Asphalt temperature at depth

The prediction algorithm for maximum pavement temperature at depth, shown as Equation (7), was validated by Viljoen (2001) against some 600 temperature gradients.

$$T_{d(max)} = T_{s(max)}\,(1 - 4.237\times10^{-3}d + 2.95\times10^{-5}d^2 - 8.53\times10^{-8}d^3) \tag{7}$$

where

$T_{d(max)}$	= Maximum daily asphalt temperature at depth d in ºC
$T_{s(max)}$	= Maximum daily asphalt surface temperature in ºC from Equation 1
d	= depth in mm

The prediction algorithm for minimum pavement temperature at depth developed by Viljoen (2001) is shown as Equation (8)

$$T_{d(min)} = T_{s(min)} + 3.7\times10^{-2}d - 6.29\times10^{-5}d^2 \tag{8}$$

where

$T_{d(min)}$	= Minumum daily asphalt temperature at depth d in ºC
$T_{s(min)}$	= Minimum daily asphalt surface temperature in ºC from Equation 5

The Superpave algorithm for minimum and maximum pavement temperatures at depth are shown as Equations 9 and 10.

$$T_{d(max)} = (T_{s(max)} + 17.8)(1 - 2.48\times10^{-3}d + 1.085\times10^{-5}d^2 - 2.441\times10^{-8}d^3) - 17.8 \tag{9}$$

$$T_{d(min)} = T_{s(min)} + 5.1\times10^{-2}d - 6.3\times10^{-5}d^2 \tag{10}$$

2.4 Prediction of diurnal temperature profiles

The model by Viljoen (2001) can be used to predict the pavement temperature at depth at any time of day using Equation 11 at daytime and Equation 12 at nighttime.

$$T_{d(t)} = T_{d(min)} + [T_{d(max)} - T_{d(min)}]\sin\left[\pi\frac{(t - t_r - \beta)}{DL + 2(\alpha - \beta)}\right] \tag{11}$$

where

DL	= Day length (refer Equation 13)
t	= hour t
d	= depth in mm
$T_{d(t)}$	= asphalt temperature at depth d at hour t
$T_{d(max)}$	= Maximum temperature at depth from Equation 7
$T_{d(min)}$	= Minimum temperature at depth from Equation 8
t_r	= time of sunrise
α	= time lag between 12 noon and occurrence of maximum pavement temperature (refer Equation 14)
β	= time lag between sunrise and occurrence of minimum asphalt temperature, the best fit found for β is 1.5 hours

$$T_{d(t)} = T^n_{d(min)} + [T_{d(t_s)} - T^n_{d(min)}]^{\left[\frac{\gamma(t-t_s)}{24-DL+\beta}\right]} \quad (12)$$

where

t_s = time of sunset

$T^n_{d(min)}$ = minimum temperature at depth d on the next day

$T_{d(ts)}$ = is temperature at sunset calculated using Equation 2.11

γ = a decay parameter, assumed to be 3.9

$$DL = \frac{2}{15} \times \cos^{-1}[-\tan(latitude) \times \tan(solar\ declination)] \quad (13)$$

$$\alpha = 2 + \frac{d}{50} \quad (14)$$

With these equations the temperature prediction model is complete. It is now possible to plot the predicted diurnal temperature profile over the depth of the asphalt layer, as shown in Illustration 2.

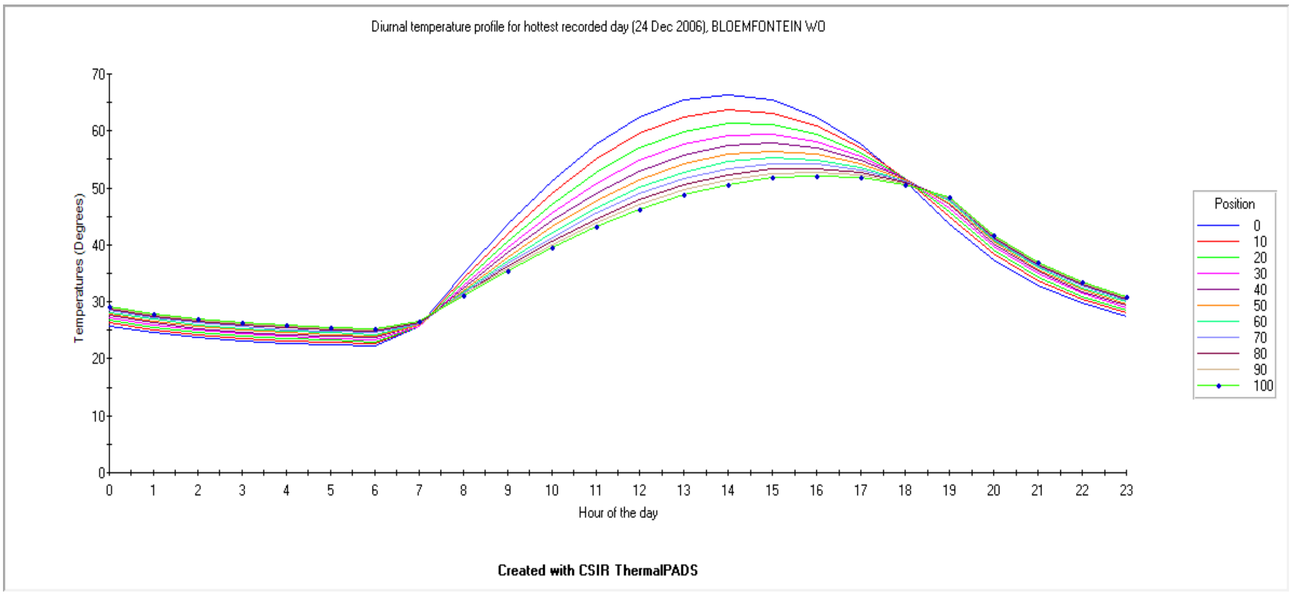

Illustration 2: Diurnal pavement temperature profile for hottest recorded day @ Bloemfontein weather office

3. VALIDATION OF THE PREDICTION ALGORITHMS

As mentioned in the introduction, Viljoen (2001) developed his algorithms using the data from previous pavement temperature studies in South Africa. To verify the reliability of the model for data from outside this original dataset, additional pavement temperature measurements were performed. Temperature readings were taken at Long Term Pavement Performance (LTPP) sections in Gauteng and the Western Cape. Data gathering took place with the use of i-buttons installed in a recess of approximately 18 mm in diameter, and 8 mm deep, at the top of the bituminous surfacing. The buttons were covered with bituthene tape. The use of i-buttons has several advantages over the use of thermocouples employed in previous studies. The buttons do not need separate costly data loggers, and are hard to spot and therefore less likely to get vandalized. The memory allows i-buttons to take hourly temperature readings for six months, with an accuracy of ± 0.5 ˚C.

Temperature data is usually reported in hourly values. The readings taken at two Western Cape LTPP were taken at two hour intervals, because the sites are monitored annually. Taking readings at two hour intervals instead of hourly may have reduced the recorded diurnal temperature amplitude by a maximum of 1˚C on a hot day.

Tables 1 and 2 show the results of the model validation for the LTPP sections. When taking into account that the models do not correct for cloud cover and the albedo of the pavement, both the Viljoen and the Superpave model provide surprisingly accurate predictions of the maximum surface temperature. The Viljoen model, in general, has less scatter, and therefore a lower standard deviation, for the error of the maximum surface temperature prediction. Figure 2 shows a plot of the predicted vs the actual maximum surface temperature, this plot makes the difference between the two models, found in all datasets, visible. The Viljoen model is more consistent, while the Superpave results show a trend from an overestimate of the surface temperature at low air temperatures to an underestimate of the surface temperature at high air temperatures. This difference in consistency can be attributed to the inclusion of the zenith angle in the Viljoen model.
The Viljoen model is in a majority of cases more accurate in the prediction of the minimum temperature as can be seen from Table 2. Both the Viljoen and Superpave algorithms show an inconsistent trend in the prediction of minimum temperatures, most likely due to lack of correction for seasonal variations in the environment.

The Viljoen model provides a pavement temperature prediction with acceptable accuracy to be used in HMA design. It is important however to select a nearby weather station for which the climate closely resembles that of the road of interest. For instance, the mean error in for the prediction of the maximum surface temperature at the N7 in Cape Town can be reduced to 0.31 ˚C if data from the Astron weather station is used, unfortunately the data for that station has considerable gaps. Currently the CSIR ThermalPADS software contains weather data from 65 stations, if this could be increased the prediction for many roads could be improved. Air temperature data is available at the weather service for over 400 South African weather stations.

Table 1: Accuracy maximum pavement temperature predictions (actual - predicted)

Location	Number of days data	Viljoen equation		Superpave	
		Mean error [ºC]	Standard deviation of error [ºC]	Mean error [ºC]	Standard deviation of error [ºC]
Cullinan (R238)	93	1.72	2.59	-4.32	-3.29
Vereniging (P234/1)	92	0.31	2.48	-2.03	2.83
Cape Town (N7)	332	-3.40	2.92	1.82	6.66
Lamberts Bay (R365)	320	-2.05	3.68	3.46	7.11

Table 2: Accuracy minimum pavement temperature predictions (actual - predicted)

Location	Number of days data	Viljoen equation		Superpave	
		Mean error [ºC]	Standard deviation of error [ºC]	Mean error [ºC]	Standard deviation of error [ºC]
Cullinan (R238)	93	-2.73	2.23	2.67	2.13
Vereniging (P234/1)	92	1.01	2.44	5.39	2.20
Cape Town (N7)	332	-2.80	2.85	3.23	2.28
Lamberts Bay (R365)	320	0.19	3.17	6.17	3.37

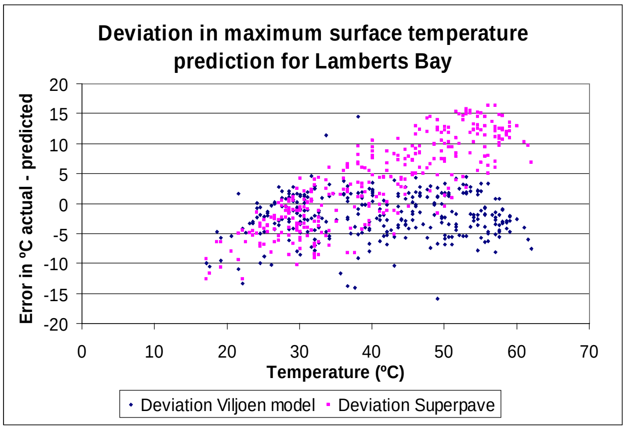

Figure 2: Deviation of prediction models for maximum surface temperature Lamberts Bay

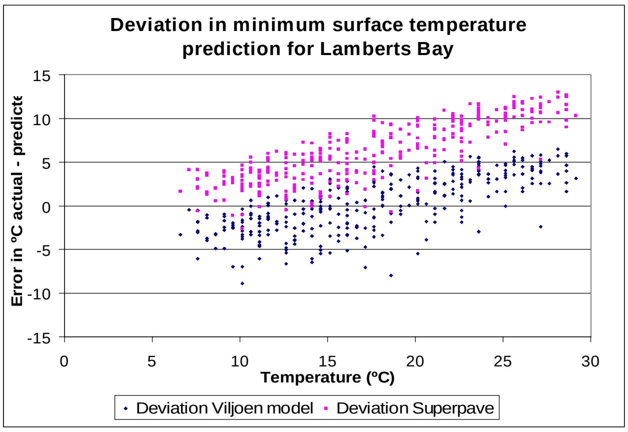

Figure 3: Deviation of prediction models for minimum surface temperature Lamberts Bay

4. PERFORMANCE GRADE BINDER SELECTION

Bitmumen in South Africa is classified by penetration index. Penetration values determined at 25ºC provide limited information about the performance of the binder at elevated or low temperatures. The same holds true for other parameters determined at standard temperatures. To better cater for the effect of temperature, the Superpave methodology employs a standard set of requirements that need to be met. The extreme temperatures at which the requirements are passed by a bitumen determines the Performance Grade (PG) for that bitumen. For instance, the climatological conditions under which a PG 58-22 is deemed to perform, range from 58ºC to -22ºC, as that binder satisfied the high temperature criteria for 58ºC and the low temperature criteria for -22ºC.

The performance grade temperatures refer to the 7-day maximum average temperature at a depth of 20 mm in the asphalt and the minimum surface temperature at a site. CSIR ThermalPADS can be used to determine these design temperatures. The software provides the mean value, the standard deviation and the 98th percentile value for the design temperatures. Client should specify the required reliability based on the importance of the road.

The PG system was calibrated for standard highway traffic conditions, the binder tests are deemed to imitate loads traveling at 90 km/h. In situations with slow or even standing traffic, such as intersections and uphill sections, a binder should be selected of one grade step higher, e.g. a PG 64 instead of a PG 58. For standing loads increasing the grade by two steps should even be considered. Selection of a higher PG grade is also recommended in situations where high traffic loads are projected over the design life of the surfacing. If more than 10 Million E80s are predicted, a higher grade should be considered. If more than 30 Million E80s are predicted a higher performance grade than dictated by the design temperature should always be used (McGennis et al, 1995).

Implementing the PG system in South Africa has long been a topic of discussion. Recently the bitumen from the four South African refineries were graded according to the Superpave methodology. Table 3 shows the results as published (SABITA, 2006).

Table 3: Performance Grades (PG) for South African bitumen (after SABITA 2006; p2)

Pen grade	40/50	60/70	80/100	150/200
Refinery I	X	PG 64-16	PG 58-22	X
Refinery II	PG 64-16	PG58-22	PG 58-22	X
Refinery III	PG 64-16	PG64-22	PG 58-16	PG 52-22
Refinery IV	PG 70-20	PG 64-16	PG 58-22	PG 52-22

With both the PG grades of local binders and temperature prediction software available, it is now possible to start the process of validating the PG selection method for use in South Africa. Table 4 shows the design temperature values for the location of some of the weather stations. No attempt was made to complete the table for all 65 weather stations, because the values should be calculated for the correct latitude of every road project. The values in the table are therefore purely indicative. The software should be used to select a weather station near to the site of interest that is positioned in a climate that closely resembles the climate on site. The values in the table for the Pretoria weather office for instance are not valid for the Pretoria area north of the Magaliesberg, as average temperatures are several degrees higher then in the central part of the town where the weather station is located.

A minimum of 20 years of data is required to calculate the maximum and minimum temperatures with the required reliability. Although only long term air temperature datasets were requested, some of the datasets only contain 15 years of data. It has been found however, that in many cases 15 years of data also provide a fair indication of design temperatures.

By comparing Tables 3 and 4 it can be seen that, the low temperature requirements are not likely to cause problems for binder selection in South Africa. On the high temperature side of the spectrum, binder selection, especially in for cases with high required reliability and slow traffic conditions such as uphills, may be more problematic. In such cases, the selection of modified binders with a high PG may be required.

Table 4: Maximum and minimum temperature values for PG selection

Place	7-day avg. maximum temp. at 20mm depth [ºC]			Minimum surface temperature [ºC]		
	mean	Stdeva	98th percentile	mean	Stdeva	98th percentile
Bethlehem	51.29	1.89	55.08	-2.14	1.54	-5.23
Bloemfontein	56.80	1.72	60.25	-2.49	1.53	-5.54
Cape Town	50.75	1.44	53.63	8.81	1.90	4.38
Durban	50.75	1.19	53.13	10.72	1.50	7.72
Johannesburg	50.74	2.07	54.89	3.12	1.32	0.46
Mara	56.56	1.23	59.02	4.65	1.46	1.72
Messina	59.61	1.19	61.99	6.52	1.68	3.16
Pofadder	58.58	1.22	61.06	4.97	1.33	2.31
Pretoria	53.45	1.72	56.88	4.62	1.50	1.62
St. Lucia	50.97	1.46	53.89	13.03	3.15	6.74
Warmbaths	56.11	1.20	58.50	2.87	1.61	-0.34

5. CONCLUSIONS

The temperature algorithms developed by Viljoen (2001) provide an acceptable prediction of extreme surface temperatures of four LTPP sections in Gauteng and the Western Cape. The prediction model developed based on data from various parts of the country and although further validation of the model is desirable, the model yields acceptable results to start implementing and validating PG binder selection in South Africa.

6. RECOMMENDATIONS

- As indicated by Viljoen (2001), more temperature pavement measurement datasets are required, especially from the most northern and southern parts of the country. A secure and cost effective way of data gathering is the use of prefabricated asphalt briquettes with i-buttons at fixed depths (top, centre, bottom) as tested at CSIR (refer Denneman, 2007).
- The number of weather stations for which air temperature data is included in the CSIR ThermalPADS software should be increased as much as possible, to allow the engineer to select the most suitable weather data for the road of interest.
- To further improve the HMA design process, temperature prediction models could be linked with HMA stiffness and deformation algorithms. These models could be calibrated using the data produced in the HMA permanent deformation research project currently in progress.

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