PREDICTION OF ASPHALT PAVEMENT TEMPERATURES IN SOUTH AFRICA

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INTRODUCTION

The subject of temperature variations in pavement layers has been studied at various times in the past, but recently with the advent of the SHRP Superpave project become of vital importance. Superpave programmes characterise the required binder properties in terms of expected pavement temperatures, and hence the ability to predict temperature extremes at any depth in an asphalt pavement at a proposed construction site is vital. Similarly the current testing of pavements with the Falling Weight Deflectometer (FWD), which is used in rehabilitation design, also requires accurate predictions of real time asphalt temperature at defined depths in order to understand the nature of the moduli determined. This report utilizes data collected during a project funded by the South African National Roads Agency, and undertaken by Bradford and Conning, Civil Engineers and the Civil Engineering Programme, University of Natal, Durban, as well as some subsequent temperature monitoring. The later monitoring was carried out under supervision, by students R F Ngcobo (1999) and O J Maimane (2000), as part of an undergraduate research programme at the University.

SITES

Site choice was governed by budget considerations and the availability of staff in close proximity. This resulted in three being chosen for the original project at:
- Durban, at the Marianhill Toll Plaza on the N3, (Section 1, NBC km 27,0).
- Newcastle on the N11, (Northbound lane km 9) and
- Pretoria (Hammanskraal) on the N1, (Section 22 NBC km 27,18).

They were considered to be representative of at least three of the climatic zones of South Africa discussed by Williamson and Marais (1975) and in addition they are close to Weather Bureau stations and are spread evenly over degrees of latitude and altitude. Subsequently a further site was established in the courtyard of the Centenary Building on the University of Natal's Durban campus.

INSTRUMENTATION

At each site a 150 mm diameter core was drilled through the asphalt and careful removed. Thermocouples were installed at different depths in horizontal holes drilled in the sides of the core hole and it was carefully backfilled with asphalt and sealed. The wires from the thermocouples on the trafficked sites were taken via a similarly sealed 6 mm saw cut, 20 mm deep to a data unit situated at the edge of the shoulder. A further thermocouple was mounted in a grey perforated PVC tube adjacent to the data logger to record "site air temperatures". It was hoped that this would approximate surface temperature but was found not to be successful. The data logger read all temperatures every hour and these were downloaded weekly when the batteries were changed. Regrettably, due to the financial constraints the data loggers lacked robustness, and this together with constant problems with vandalism resulted in the record being incomplete at each site. At the

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university site the data logger failed completely and manual readings at convenient times had to be used.

Commissioned in August 1997, records from the Marianhill site were received from 1 November 1997 until 16 January 1998 at depths of 5, 25, 45, 65, and 85 mm. The site was then closed due to equipment failure and damage to the thermocouples. It had to be completely reconstructed and reopened on 11 March 1998, from when it operated until 26 August 1998 with temperature readings of the site air, and at depths of 15, 50, 85, and 120 mm depths.

The Newcastle site operated from 15 November 1997 until 3 September 1998 with temperature readings of the site air, and at depths of 5, 25, 65, and 85 mm.

The Pretoria site experienced the most problems but operated from 16 January 1998 until 30 August 1998 with temperature readings of the site air, and at depths of 20, 40, and 70 mm.

The site at the University of Natal was used for the period 8 to 18 November 2000, 24 November 2000 and 27 November to 4 December 2000 mainly as a check and to attempt to calibrate infra-red surface temperatures and a surface probe to the depth probe readings and algorithms. In addition to infra-red and surface probe temperatures, data was collected from 5, 65, 120 and 200mm depths.

ASPHALT TEMPERATURES

The typical curves for a day in Pretoria in Fig 1 and 2.
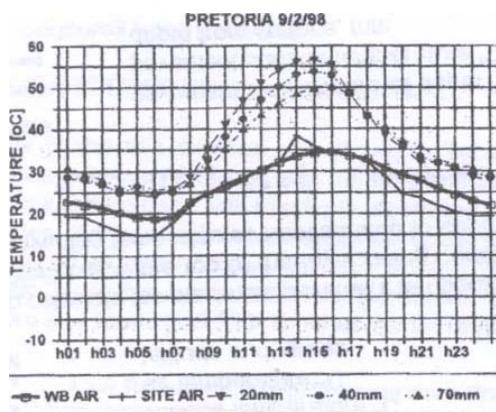

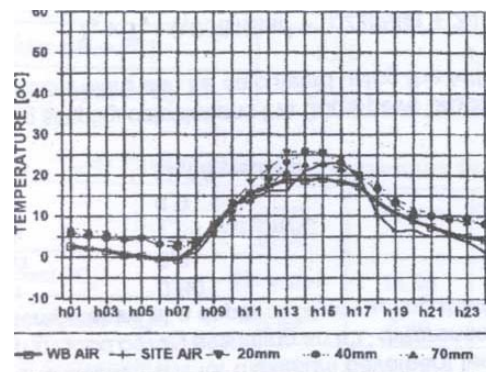Fig 1   Fig 2

It will be noted that there is a significant lag between the achievement of the maximum and minimum temperatures at the surface and at depth. It is obviously important that the algorithms model this. This means that any model for use with Superpave must predict the actual maximum and minimum at any depth regardless of time, while for use in FWD tests the actual real time temperatures at all/any depths are required. In addition it was found that the nature of the Superpave algorithms was such that as they are developed specifically to predict maximum and minimum temperatures from weather bureau temperatures, they are only really accurate for extremes. The depth algorithms in Superpave need to take the lag into account, while those for FWD must predict real time.

STANDARD ALGORITHMS

SUPERPAVE

The Superpave programme of the SHRP makes use of environmental data to characterise the requirements of the bitumen specification. The method in which it is stated that this should be done is as follows (Kennedy *et al* (1994):

Environmental conditions are specified in terms of design temperatures which are derived from air temperatures for the site in question by using

- Average 7-day maximum air temperature for the design maximum and
- Minimum air temperature for the design minimum temperature

where the average seven day maximum pavement design temperature is the mean of the seven hottest days in a year. The lowest annual pavement temperature is the coldest day of the year.

Design pavement temperatures can be obtained from direct measurement or calculated from air temperature data as follows:

- convert average seven day maximum air temperature to pavement surface temperature
- calculate 7-day maximum pavement temperature at design depth
- convert minimum air temperature to minimum pavement surface temperature
- calculate minimum pavement temperature at design depth

MAXIMUM ASPHALT TEMPERATURES

Maximum air temperature can be converted to a pavement surface temperature using the rigorous equation below which requires techniques of numerical analysis, but can readily be solved in spreadsheets:

$$1331" J_a^{1/\cos z}.\cos Z + {}_,{}_aFT^4{}_a - h_c(T_s - T_a) - 164k - {}_,FT^4{}_s = 0 \qquad [1]$$

where

"	-	pavement surface absorptivity
J_a	-	transmission coefficient for air
z	-	latitude(-20°)
,	-	pavement surface emissivity
F	-	Stefan-Boltzman Constant (5,67 x 10-8 watts per m^2 ^{o}K^4)
h_c	-	surface coefficient of heat transfer (watts per m^2 ^{o}C)
k	-	thermal conductivity coefficient (watts per m^{o}C)
T_a	-	Air temperature (^{o}K)
T_s	-	surface temperature (^{o}K)

The calculations for maximum pavement temperature were performed for sunny days (no cloud cover) assuming an 8°C difference between the surface temperature and the temperature at a depth of 50mm using the following default values. (The 8°C difference was checked against the data collected and found to be a reasonable assumption):

J	-	0,80
"	-	0,9
k	-	1,38 watts/m^{o}C
,	-	0,9
h_c	-	19,88 watts/m^{2o}C

To simplify calculations the Superpave procedures recommend that pavement surface temperature can be calculated using the following regression equation (Huber 1994)

$$T_s = T_a - 0{,}00618\text{lat}^2 + 0{,}2289\text{lat} + 24{,}4 \qquad [2]$$

where

T_s - surface temperature ^{o}C
T_a - air temperature ^{o}C
lat - latitude in degrees

Utilising the default constants quoted above for the rigorous equation, a check on the difference in results was made as shown in table 1 below (Everitt et al 1999).

Table 1   Difference (Rigorous - Huber)

LATITUDE	TEMPERATURE [^{O}C]				
o	25	30	35	40	45
20	1,55	1,24	0,92	0,60	0,29
25	1,63	1,32	1,01	0,69	0,37
30	1,69	1,38	1,08	0,77	0,46
35	1,73	1,43	1,14	0,84	0,54
40	1,76	1,48	1,19	0,91	0,62

To calculate the maximum pavement temperature at depth Superpave uses a depth of 20mm below the top of the layer being considered. The recommended formula for converting temperatures from surface to depth is

$$T_{d(max)} = [T_{s(max)} + 17{,}8][1 - 2{,}48(10^{-3})d + 1{,}085(10^{-5})d^2 - 2{,}441(10^{-8})d^3] - 17{,}8 \qquad [3]$$

where

$T_{d(max)}$ - pavement temperature at depth ^{o}C
$T_{s(max)}$ - pavement surface temperature ^{o}C
d - depth from surface, mm

HIGH PAVEMENT TEMPERATURE PROCEDURES

In a similar fashion to the check for low temperature, a check of high "design temperatures" was carried out for the three sites using the Superpave recommendations. This was done using both the rigorous equation [1], with the default values and Huber's approximate equation [2]. Both these equations use the latitude of the site in the expression. The results were as shown in TABLES 11, 12 and 13.   In these tables the algorithms are used to predict both the temperatures on the hottest day of the 7 day sequence and the average temperatures which would be used for design purposes.

Table 2:   High Temperature Design Procedures

Newcastle	Average 7 day maximum 29.60 °C			
08/02/98	5 mm	25 mm	65 mm	85 mm
actual hottest 31.09 °C	57,68	53,04	48,88	46,72
Rigorous Superpave [°C]	58,37	54,91	49,61	47,60
Huber [°C]	57,08	52,92	47,94	46,04
Highest actual ave 02-08/02/98 29,60°C	56,78	52,01	48,33	45,74
Predicted highest ave [°C] rigorous	56,97	53,58	48,37	46,04
Predicted highest ave [°C] Huber	55,09	51,04	46,19	44,35

Table 3:   High Temperature Design Procedures

Marianhill	Average 7 day maximum 29.59 °C (08/02/98 no site data) use highest recorded average 7 day maximum being 31/12/97 , 27.39 °C; - WB maximum 33.50 °C				
31/12/97	5 mm	25 mm	45 mm	65 mm	85 mm
actual hottest 33.5°C	60,00	53,84	49,60	46,08	43,44
Rigorous Superpave [°C]	60,39	56,84	53,87	51,40	49,33
Huber [°C]	59,23	54,95	52,15	49,83	47,88
Highest actual ave 25-31/12/97 27,39 [°C]	40,78	37,78	36,21	35,27	33,91
Predicted highest ave [°C] rigorous	54,67	51,37	48,62	46,36	44,42
Predicted highest ave [°C] Huber	53,13	49,19	46,61	44,47	42,62

Table 4:   High Temperature Design Procedures

Pretoria	Average 7 day maximum 34.16 °C			
09/02/98	5 mm (est)	25 mm	45 mm	75 mm
actual hottest 34.8 °C (WB air)	No probe	56,40	53,68	50,16
Rigorous Superpave °C]	62,02	59,23	56,06	52,27
Huber [°C]	60,98	55,60	53,74	50,32
Highest actual ave 27/01-02/02/98 30,61 [°C] (WB air)	No probe	53,17	50,31	47,7
Predicted highest ave [°C] rigorous	58,09	55,44	52,43	48,82
Predicted highest ave [°C] Huber	56,79	52,64	49,94	46,70

In this instance it will be seen that the Superpave equation appears to predict surface temperatures well, although at depth it appears slightly conservative. It should be noted however that the predicted average values for the Marianhill site are much higher than actually measured. This may have been due to cloud cover while the air temperatures remained high on some of the days.

MINUMUM ASPHALT TEMPERATURES

To convert the minimum air temperature, the minimum surface temperature *is defined in the original SUPERPAVE as the minimum air temperature*

To calculate the minimum temperature at depth (the depth used is the surface of the layer in question and the following equation used:

$$T_{d(min)} = T_{s(min)} + 5,1(10^{-2})d - 6,3(10^{-5})d^2 \qquad [4]$$

where

$T_{d(min)}$ - pavement temperature at depth d ^{o}C

$T_{s(min)}$ - pavement temperature at surface ^{o}C

d - depth below the surface mm.

Some slight modifications are introduced by McGennis *et al* (1994), for low pavement design temperature. The assumption originally recommended by SHRP researchers to use the low air temperature is conservative as the pavement at depth is almost always warmer. The method now finding favour was developed by Canadian SHRP researchers ie:

$$T_{min} = 0,859T_{air} + 1,7^o \quad [5]$$

where

T_{min} - minimum pavement design temperature in ^{o}C

T_{air} - minimum air temperature in average year in ^{o}C

The method of converting low air to low pavement temperature has a profound effect on the binder selection process.

The findings of the research programme as reported at CAPSA by Everitt et al (1999) was that the predictions could be improved by using the Canadian equation with modified constants as follows:.

$$T_{min} = 0,88838T_{air} + 5,8835^o \qquad [6]$$

These values were optimised for *all* the South African sites but as can be seen in Table 5 below the optimised values did not work well with the Pretoria site minimum data:

Table 5:

SITE	NEWCASTLE				
Depth [mm]	Weather Bureau	5	20	60	80
Actual coldest °C	-2,6	4,4	5,0	7,6	8,9
Orig Superpave °C		-2,6	-1,6	0,2	1,1
Canadian °C		-0,5	0,5	2,3	3,1
SA Modified °C		3,6	4,6	6,4	7,3

SITE	MARIANHILL					
Depth [mm]	Weather Bureau	5	15	50	85	125
Actual coldest °C	5,9		13,4		14,7	18,6
Orig Superpave °C		5,9	6,4	8,1	9,6	11,1
Canadian °C		6,8	7,3	8,9	10,4	12,0
SA Modified °C		11,1	11,6	13,3	14,8	16,3

SITE	PRETORIA				
Depth [mm]	Weather Bureau	5	25	45	75
Actual coldest °C	-0,8		2,9	2,3	3,8
Orig Superpave °C		-0,8	0,2	1,1	2,5
Canadian °C		1,0	2,0	3,0	4,3
SA Modified °C		5,2	6,2	7,1	8,4

BELLS EQUATIONS

Literature surveys during this research indicated that recent work overseas utilised an algorithm called "BELLS" (the authors initials!) (Stubstad R N, et al) uses a series of readily available time, air temperature, and AC thickness data plus the AC surface temperature measured by an infra-red sensor mounted on the FWD. This allows the engineer to adjust the derived (back calculated) AC modulus to seasonal or standard values at any other appropriate mat temperature.

Development of the method required knowledge of:

- Thickness of AC
- Temperature vs depth measurements within the mat.
- Air temperature together with previous 5-day mean air temperature (local highs and lows divided by 10).
- IR AC surface temperature.
- Time and date of temperature and FWD measurements.

The original method was modified further by engineers at Dynatest (Kim et al (1994) to give "BELLS2". This utilises the more easily obtained temperatures from the previous 24 hours rather than 5 days and has been adjusted to account for the fact that the daily temperature does not follow a uniform sin wave but is skewed to a shorter warming time and a longer cooling time. To approximate this the sin functions of the original BELLS were replaced with two sin functions based on an 18 hour cycle. The final resulting equation as follows:

$$T_d = 1.4+0.907*IR + \{\log(d) - 1.25\}\{-0.540*IR + 0.764*(1-day) + 2.39*\sin(hr_{18} - 15.5)\} + 0.060*IR*\sin(hr_{18} - 13.5) \qquad [7]$$

where

T_d -   pavement temperature at depth d, ^oC,

IR   -   infrared surface temperature, ^oC,

log   -   base 10 logarithm

d   -   depth at which mat temperature is to be predicted, mm,

1-day   -   average air temperature the day before testing, ^oC,

sin   -   sin function in 18 hour clock system with 2π radians equal to one 18-hour cycle,

hr_{18} -   time of the day in the 24-hour system but calculated using an 18-hour AC temperature rise and fall time cycle, as indicated below..

When using the $\sin(hr_{18} - 15.5)$ (decimal) function, only use times from 11:00 to 05:00hrs. If the actual time is not within this time range then calculate the sin as if the time is 11:00 hrs (where the sin = -1). If the time is between midnight and 05:00hrs then add 24 to the actual (decimal) time. Then calculate as follows: If the time is 13:15, then in decimal form 13.25-15.50 = -2.25; -2.25/18 = -0.125; -0.125 x 2π = -0.785 radians; sin(-0.785) = -0.707. (Note that an *18 hour* sin function is assumed with "Flat" -1 segment between 05:00 and 11:00 hours.]

When using the $\sin(hr_{18} - 13.5)$ (decimal) function, only use times from 09:00 to 03:00hrs. If the actual time is not within this time range, then calculate the sin as if the time is 09:00 hrs (where the sin = -1). If the time is between midnight and 03:00 hrs, add 24 to the actual (decimal time. Then calculate as follows: If the time is 15:08, then in decimal form 15.13 - 13.5 = 1.63; 1.63/18 = 0.091; 0.091 x 2π = 0.569 radians; sin(0.569) = 0.539. [Note that an 18 hour sin function is assumed, with "flat" -1 segment between 03:00 and 09:00 hours.]

It was decided to check this equation against the data collected form the South African sites. Unfortunately no infra-red surface temperatures were available at the road sites so that initially it had to be assumed that temperatures at 5mm depth would be equivalent (Ngcobo, 1999). The site at Centenary Building was established in order that in addition to routine monitoring surface probe and 5mm depth probe temperatures could be correlated with a recently purchased infra-red thermometer. This work is still ongoing but the results to date (Maimane, 2000) indicate:

▪ On average the infra-red and surface probe temperatures are equal but variations of up to 9% up and down occur in the ratio infra-red/surface temperature.

▪ On average the infra-red and 5mm probes temperatures are also equal but variations of up to 24% up and 16% down occur.

▪ On average the surface and 5mm depth probes temperatures are also within 1% but variations of between 24% up and 12% down in the ratio surface probe/5mm probe temperature.

▪ Although some attempts have been made to modify the constants in the algorithms for local conditions, to date these have been unsuccessful.

▪ The absolute value of the mean of the error between prediction and actual temperatures at depth is less than 2,1^oC.

▪ The standard deviation of error is also less than 2,1 ^oC.

▪ The error increases with depth.

▪ The error is much greater at night. As all sites are close to the 30° E meridian, which in SA is used for local time it is assumed that sun time is applicable, elsewhere adjustments may need to be made.

Plots of actual and simulated temperatures using the equation are shown in figures 3, 4, and 5 overleaf.
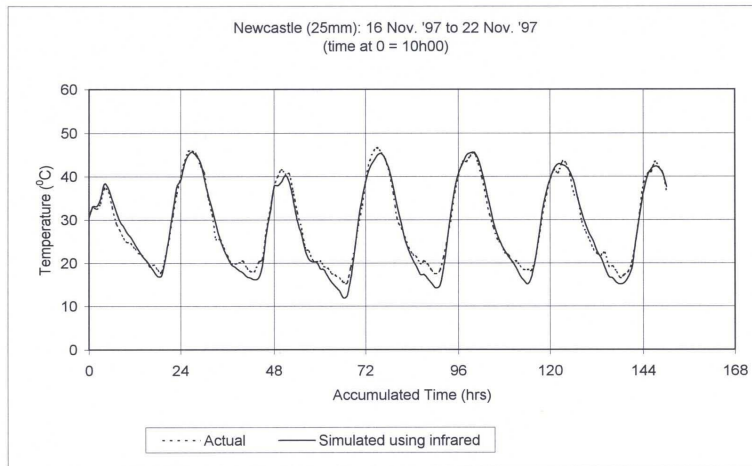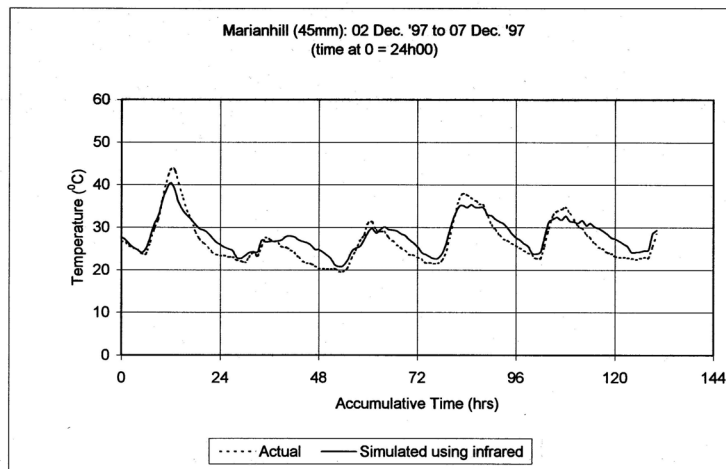
Comparison between simulated and actual temperature (summer)

Fig 3 (Maimane, 2000)
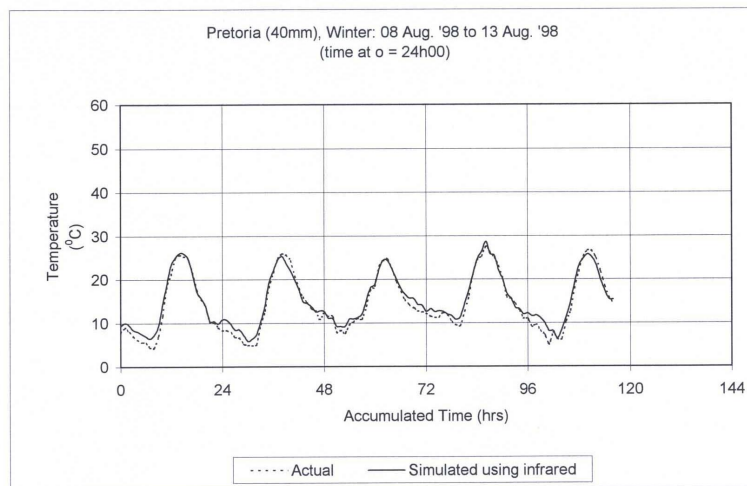
: Comparison between simulated and actual temperature (winter)

Fig 4 (Maimane 2000)

Comparison between simulated and actual temperature (summer)

Fig 5 (Maimane, 2000)

SUMMARY AND CONCLUSIONS

To date this research has shown that
- In the absence of locally developed algorithms or constants the procedures developed in other parts of the world, may be used to predict pavement temperatures in the asphalt mat.
- In this respect the SUPERPAVE equations may be used to estimate extreme temperatures for binder selection, preferably using the constants developed in SA for the minimum temperatures.
- The BELLS2 equation provides an estimate for real time temperature estimation for FWD testing.
- Neither method predicts well for thickness of asphalt cover more than about 70mm and care should be taken if this thickness of asphalt is being considered.
- The BELLS method is also unreliable for night temperatures, although fortunately it is expected that road testing will normally be carried out during the daylight hours.

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