Adapting Asphalt Pavements to Climate Change Challenges

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Synopsis— Performance grade specifications for bituminous binders focus on the evaluation of bitumen properties based on the loading and environmental conditions under which the material will be subjected to in the field. The temperature of the asphalt layer (as determined by the climate and geographical location), in conjunction with the grade and age of the bitumen, plays a pivotal role in determining the stiffness or dynamic modulus of the asphalt layer. Most climate models predict an increasing rate in the rise of average air temperatures in the near future. As the average air temperatures increase, it is expected that the frequency and duration of extreme temperatures will also rise. This will have a direct impact on asphalt pavement performance by increasing the potential for permanent deformation of pavements and the rate of age hardening of asphalt binders. In this study, interpolated maps of minimum and maximum pavement temperatures were generated using a climate model for predicted air temperatures for two 20-year periods, up to the years 2040 and 2060. The same model was used to generate two historic 20-year periods, going back to 2000 and 1980. The Viljoen temperature prediction algorithms were used for calculating the pavement temperatures as opposed to the Superpave models. The maps produced in this paper can eventually be used to identify adaptation measures which may include modifying current design and maintenance practices.

Keywords—climate change, temperature maps, performance grade specifications

I. INTRODUCTION

In recent decades, climate change has been of growing concern considering its impact on the natural and built environment. Some of these changes have been linked to human influences and have resulted in increased warm temperature extremes, decreased cold temperature extremes, an increase in extreme high sea levels as well as an increase in the number of heavy precipitation events. Researchers have been able to link climate change effects to regional weather patterns, such as heavy precipitation events in Mozambique, wetter climates in East Africa and particularly dry climates in Zambia and Angola [1] indicating the region-dependant effects of climate change. Recent flooding and cyclone events in Mozambique, Zimbabwe and Malawi signal the importance of climate adaptation strategies for infrastructure planning. It was estimated in 2011 that the African continent could be liable for up to US$183.6 billion to repair and maintain roads damaged from temperature and precipitation events alone, resulting from climate change [2]. In some areas, it was determined that the maintenance and repair costs will more than double when a reactive approach is taken for road infrastructure management as opposed to a proactive adaptation plan. In order to mitigate these effects, the AfCAP/ReCAP programme has commissioned projects across Africa which are aimed at providing regional guidance on the development of a climate resilient road network [3].

Meyer et al. [4] identified three categories of climate change impacts on pavements namely, temperature, precipitation and sea-level impacts. Ten climate change models were assessed in their report. The models showed an average air temperature increase of 2.2°C between the years 2010 and 2050 which was double the increase from the preceding 50 years. Higher extreme temperatures were also projected as well as the duration and frequency of the extreme temperatures. Current literature recognizes the importance of changing pavement design procedures to include the impacts of climate change but fall short of recommending immediate changes in practice. A key issue in adaptation planning is knowing when to modify current practices by monitoring trends over longer periods of time [5]. In this study, the impact of increasing air temperatures on South African asphalt pavement temperatures due to climate change were analysed, as well as the ensuing effect on material selection for asphalt pavements.

Given that asphalt performance is temperature dependent due to the visco-elastic nature of the asphalt bitumen, the principle of Performance Grade (PG) specifications for asphalt bitumen is to address three failure mechanisms of asphalt layers, namely (i) permanent deformation at high temperatures; (ii) fatigue cracking at intermediate service temperatures and; (iii) brittle fracture at low service temperatures. The in-service temperature (climate) and traffic conditions, in conjunction with the ageing effects of bituminous binders, play a pivotal role in selecting bitumen to achieve a given in situ performance within the asphalt layer. Pavement failures due to poor selection of bituminous binders can be reduced by correctly specifying the appropriate binder for a given climate.

This paper specifically looks at the temperature impacts of climate change. The temperature maps provided in this paper indicate the progression of pavement temperatures, and focuses more on the temperature differences predicted, than the actual development of maximum and minimum temperature zones for PG specifications. As part of the binder selection process in an asphalt mix design, pavement temperature maps are used for specifying the correct bitumen for a given geographical location of a given road construction. Twenty year historic air temperature data is typically required to calculate the maximum and minimum pavement temperatures. The temperature maps produced from this study brings into perspective the importance of also considering climate change projections in this process, due to the potentially adverse effects climate change may have on pavement engineering designs.

II. DEVELOPMENT OF PAVEMENT TEMPERATURE MODELS

According to Li et al. [6], albedo (solar reflectance as a ratio of incoming radiation) is the parameter which has the highest effect on pavement temperature in comparison to thermal emittance, thermal conductivity and specific heat. Williamson & Kirby [7] introduced energy balance concepts which rely on the thermal pavement properties, such as albedo, in the South African pavement industry for determining pavement temperatures. This was followed by an introduction of a corresponding methodology to the country in the mid-seventies [8]. The methodology required extensive solar radiation data which was not available in the country at the time, thus limiting its further implementation.

Everitt et al. [9] investigated the use of the Superpave method for South Africa. During the study it was found that maximum surface temperatures were predicted within reason but refined algorithms were suggested to produce more accurate results. The South African National Roads Agency sponsored and conducted a study which was able to produce a database of surface and in-depth asphalt pavement temperatures to calibrate against the Superpave model [10]. Hourly temperatures over one year were produced from three locations in South Africa. They found that Superpave models were able to estimate maximum pavement temperatures within reasonable margins but they needed to be adapted for South African conditions. The method needed to account for South Africa's large diurnal temperature changes rather than large seasonal differences. New constants were then tentatively determined which allowed provision for the large diurnal changes. It was also found that temperature gradients within the pavement were flatter than Superpave predictions, particularly in the Eastern Cape. This necessitated a methodology which was able to predict South African pavement temperatures and from previous research it was evident that the methodology needed to incorporate daily air temperatures, zenith angle and cloud cover.

Viljoen [10] then developed empirically derived algorithms based on recorded pavement temperatures and the zenith angle which accounts for the seasonal and diurnal effect on the pavement temperatures. The algorithms were able to predict 80% of the recorded asphalt pavement temperatures within a margin of 3°C using the same dataset from the Everitt et al. study in 1999. Best fit values for variables in the energy balance equation were identified as part of the algorithm development. The variables were asphalt absorptivity, transmission coefficient of air, emissivity of the asphalt surface, asphalt surface heat transfer coefficient and the conductivity of the asphalt material. Denneman [11] further verified Viljoen's model using an additional dataset of pavement temperatures in Gauteng and Western Cape. Subsequently the development of the CSIR

ThermalPADS software ensued which contains air temperature data from 121 weather stations in South Africa and can be used to determine asphalt pavement temperatures across the country [12].

Denneman also recommended a more extensive air temperature database to be incorporated into the CSIR ThermPADS software to improve its reliability given the sparsely populated dataset obtained from local weather stations. The inclusion of data from climatic models is therefore motivated, given these models are capable of providing climatic data at a significantly higher resolution than weather stations. The climatic model used in this study was able to provide historic as well as predict future air temperature data, based on a realistic scenario of climate change effects.

The Viljoen algorithms described below are used in this study to compute the average 7-day maximum pavement temperature from the air temperature data obtained from the climatic model data. This is the design temperature range and is representative of the asphalt pavement layer 20 mm below the pavement surface.

The equation for calculating the maximum pavement surface temperatures is shown in (1) below.

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

Where:

$T_{s(max)}$ = the daily maximum asphalt surface temperature in °C
$T_{air(max)}$ = the daily maximum air temperature in °C
Z_n = Zenith angle at midday
C = Cloud cover index
with:
C = 1.1 if $T_{air(max)} > 30$ °C
C = 1.0 if monthly mean air temperature < $T_{air(max)}$ < 30 °C
C = 0.25 if $T_{air(max)}$ < monthly mean air temperature

Zenith angle is a function of the solar declination as shown in (2) below:

$$\cos(Z_n) = \sin(\text{latitude}).\sin(\text{declination}) + \cos(\text{latitude}).\cos(\text{declination}) \tag{2}$$

An approximation of the solar declination is provided in (3) below:

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

Where:

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

The prediction algorithm for maximum pavement temperature at depth, as validated by Viljoen is shown in (4) below.

$$T_{d(max)} = T_{s(max)}\left(1 - 4.237\times10^{-3}d + 2.95\times10^{-5}d^{2} - 8.53\times10^{-8}d^{3}\right) \tag{4}$$

Where:

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

The Viljoen equation for calculating the minimum pavement temperature is purely empirical and is presented below in (5) as the best fit to the available local data during that investigation. Note only the surface pavement temperatures are calculated and used for producing the minimum pavement temperature maps.

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

Where:

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

According to Denneman [11], the Viljoen model predictions show less scatter and have a lower standard deviation compared to the Superpave model. O'Connell [13] also reported that the Viljoen algorithms were more consistent, while the Superpave predictions generally overestimated the minimum pavement temperatures and underestimated maximum pavement temperatures. It was observed that although the Viljoen temperature predictions showed less scatter for maximum pavement temperatures, the standard deviations for the minimum temperature dataset were more or less similar. Also, the mean error for the Viljoen equations showed only a slight improvement when compared to the Superpave predictions.

III. METHODOLOGY

A. *Climate Model*

A very high resolution climate model simulation of present-day climate and projections of future climate was performed for South Africa. The spatial resolution of the model simulation over South Africa was 8 km. The regional climate model used to create the high-resolution dataset was the conformal-cubic atmospheric model (CCAM), a variable-resolution global climate model (GCM) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) [14][15][16]. The model's ability to realistically simulate present-day Southern African climate has been extensively demonstrated by authors such as [17][18][19][20][21][22]. CCAM was coupled with a dynamic land-surface model CABLE (CSIRO Atmosphere Biosphere Land Exchange). The model was forced with bias-corrected sea-surface temperatures (SSTs) and sea-ice fields of a Coupled Global Circulation Model (CGCM) to simulate its own climate at high resolution – referred to as the process of downscaling. The bias was computed by subtracting for each month the Reynolds [23]

SST climatology (for 1961-2000) from the corresponding CGCM climatology. The bias-correction was applied consistently throughout the simulation. The global sea surface temperature was used as well as the sea ice concentration output data from the Australian Community Climate and Earth System Simulator (ACCESS1-0) CGCM which formed part of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The high-resolution modelling was done using CCAM prescribed with atmospheric CO_2, sulphate and ozone forcing consistent with a low-mitigation scenario for the 21st century, known as Representative Concentration Pathway 8.5. A multiple-nudging strategy was followed to obtain the 8 km resolution downscaling. After completion of a 50 km resolution simulation, CCAM was integrated in stretched-grid mode over South Africa, at a resolution of about 8 km (0.08° degrees in latitude and longitude). Near-surface (2 m) air temperature was simulated by CCAM at an 8 km spatial resolution, with the broad land-cover class as per CABLE being the surface interacted within the simulations.

B. *Temperature Maps*

The generated air temperature information was then used as input into the CSIR's ThermalPADS software (based on the Viljoen temperature prediction algorithms) to generate the corresponding pavement temperatures.

In order to create interpolated maps of the minimum and maximum pavement temperatures, data from points on an 8x8 km grid across South Africa were processed to determine the 7-day average maximum pavement temperatures at 20 mm depth and the 1-day minimum pavement surface temperatures. The accuracy of the maps is influenced by the number of data points used to generate the maps. In this study, over 20 000 points were used to generate the maps compared to the 118 operating weather stations available in South Africa.

The grid centroids of the abovementioned grid points were processed in ArcGIS using their latitude and longitude information to create a point-s dataset covering the country. In order to interpolate these data points to extend across South Africa an interpolation process had to be applied. The selected general interpolation technique is the Kriging method or a Gaussian process of regression. Kriging is an advanced geostatistical procedure that generates an estimated surface from a set of points with z-values. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. The Kriging tool fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. Kriging is a multistep process; it includes exploratory statistical analysis of the data, variogram modeling, creating the surface, and (optionally) exploring a variance surface [24]. Kriging, like most interpolation techniques, is built on the basis that things that are close to one another are more alike than those farther away (quantified here as spatial autocorrelation). The settings applied to the Kriging method within the ArcMAP GIS software's Geospatial Analyst determined the nature and extent of the resulting surface(s) produced. To ensure comparability between maps the same settings were applied for different time periods. A measure of smoothing was applied to reduce jagged interpolated results. The resulting grid surface was clipped to display only values for South Africa and contour lines were generated from the resulting grid. Several contour lines representing Performance Grades were highlighted to compare the movement over time of critical temperature ranges. No barriers were applied in the interpolation process – thus the possible effect of terrain can only be indirectly gauged through the recorded values of the data points. The effect of barriers might therefore also slightly influence the resulting surfaces produced.

A low mitigation scenario was used for the climate model in this study which assumes minimal intervention to lower current greenhouse gas emissions. It should also be noted that an interpolation process was used to create the temperature maps therefore pavement temperatures calculated between discrete data points are estimated as part of the Kriging technique and not directly from the Viljoen algorithms. The interpolation process may however, carry less of an error due to the high resolution of the dataset in comparison to current pavement temperature maps.

IV. RESULTS AND DISCUSSION

Temperature maps of four time periods, as described below in Table I, were investigated. Each period spans a duration of 20 years where temperature data were generated to demonstrate the effect of climate change on asphalt pavements.

TABLE I. YEARS REPRESENTED BY EACH TIME PERIOD

Period	Years
A	1980-2000
B	2000-2020
C	2020-2040
D	2040-2060

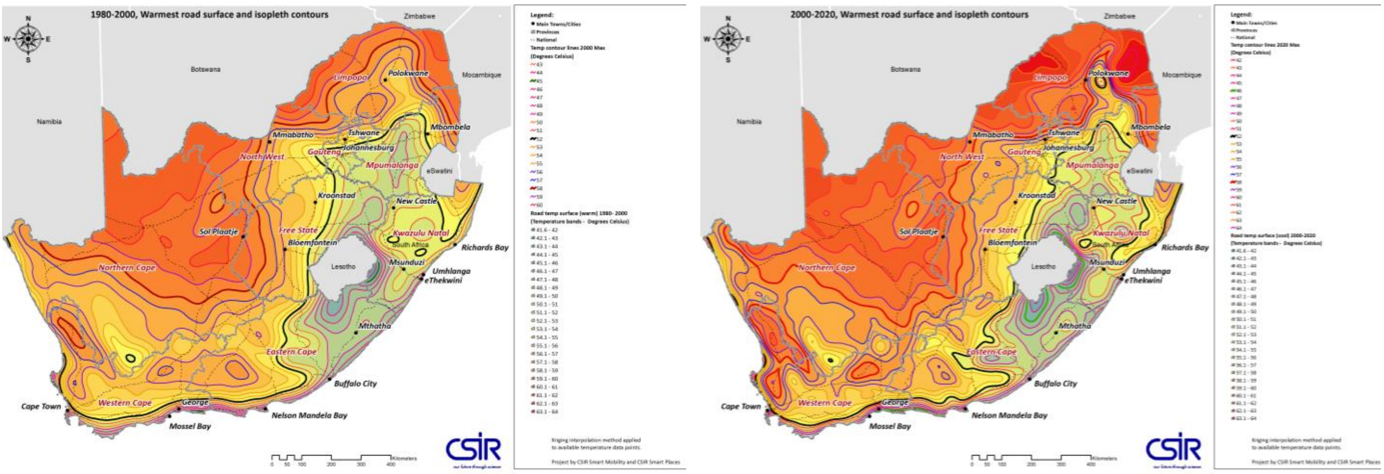
A. *Maximum pavement temperatures*

According to the data for Period A, the country is evenly divided into three regions in terms of the PG maximum temperature classification, namely a PG 64 region (majority of Northern Cape and northern Limpopo), a PG 58 region (Northern Gauteng and majority of Western Cape, Eastern Cape, Free State and Limpopo provinces) and a PG 52 region (most of Mpumalanga and Kwa-Zulu Natal, Southern Gauteng, coastal regions, parts of Eastern Cape and Free State), this is illustrated in Fig. 1a.

An increase in pavement temperatures can be observed over the 80-year period from 1980 to 2060 which will affect the binder selection for any given region. The difference in predicted maximum temperatures is shown in Table II, for specific points in selected cities in the country, between two subsequent periods; the overall change in temperature is shown in the last column over the total 80 year period analysed. Of the selected locations listed in the table, Johannesburg showed the largest change in temperature, an increase in 7.64°C which corresponds to two increases in PG binder selection. Pretoria showed the second highest increase with an increase in at least one PG binder grade. Coastal regions show the least increase in temperatures, with Durban giving the smallest change with an increase in 0.22°C. No change in binder selection is expected for such areas.

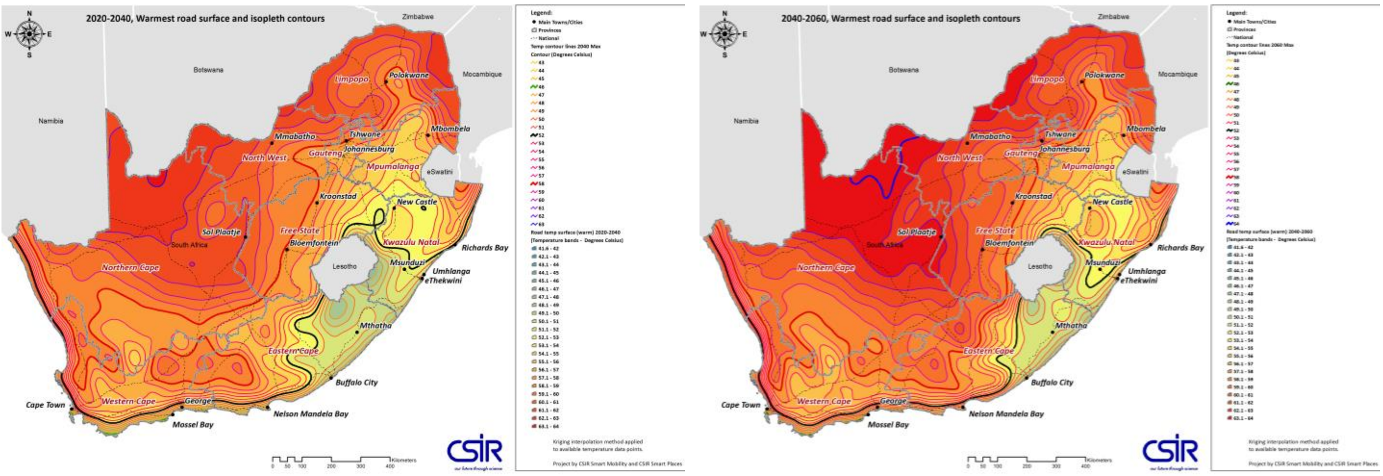
The coastal perimeter of the country remains unchanged classification during the analysed time period with minimal change in pavement temperatures over time. This less pronounced change is most likely influenced by the cooler ocean temperatures as well as the Drakensberg mountain range.

According to the climate model used during this study, pavement temperatures are expected to be in the vicinity of 70°C in the north-western parts of the country; specifically along the border between the Northern Cape and North West province with Botswana during Period D.



(1a) Period A:1980-2000

(1b) Period B: 2000-2020



(1c) Period C: 2020-2040

(1d) Period D: 2040-2060

Fig. 1. Effect of climate change on maximum pavement temperatures over 80 years between Period A and Period D

TABLE II. PREDICTED CHANGE IN MAXIMUM PAVEMENT TEMPERATURES (°C)

Location	Period A to B	Period B to C	Period C to D	Overall
Johannesburg	+2.88	+3.74	+1.02	+7.64
Pretoria	+2.96	+2.13	+1.40	+6.49
Cape Town	+0.88	+0.35	+0.86	+2.09
Durban	-0.34	+1.30	-0.74	+0.22
Pietermaritzburg	+0.14	+0.75	+0.99	+1.88

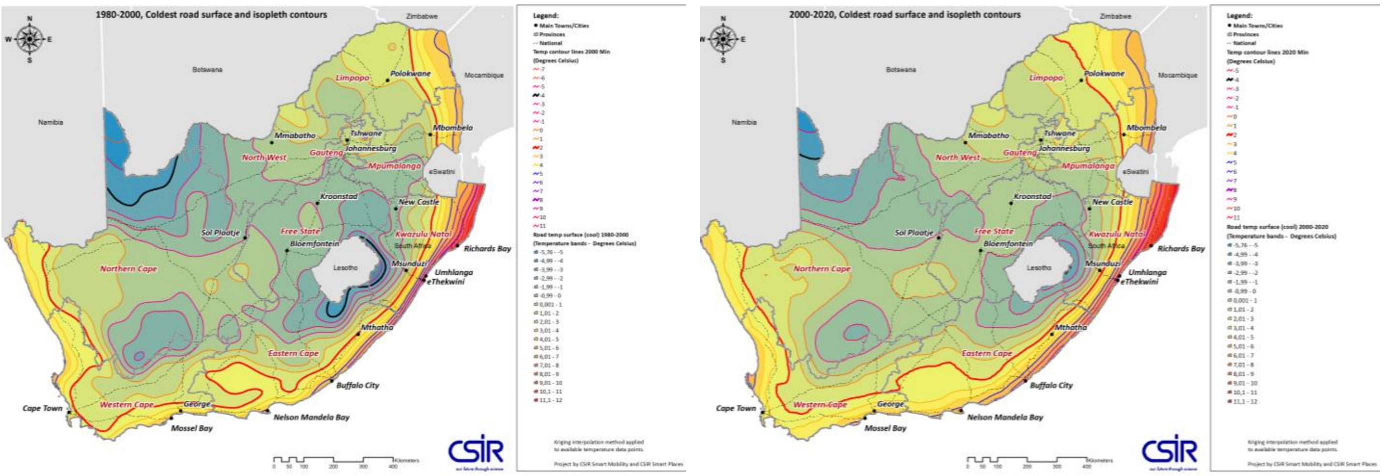
B. *Minimum pavement temperatures*

In general, there is a less pronounced difference in minimum pavement temperatures between 1980 and 2060 as observed in Fig. 2. The predicted change in minimum pavement temperatures is also demonstrated in Table III where smaller temperature differences are observed at the selected locations in comparison to maximum temperatures. Minimum pavement temperatures are generally warmer along the coast compared to inland areas. The uppermost tip of the Northern Cape experiences the lowest minimum pavement temperatures (and highest maximum temperatures) due to the large variation in daily extreme air temperatures in this area.

Larger variations in temperatures were observed inland compared to the coastal regions. Consequently, selecting bitumen as per the exact minimum pavement temperature could create quite a number of PG grades for these areas.

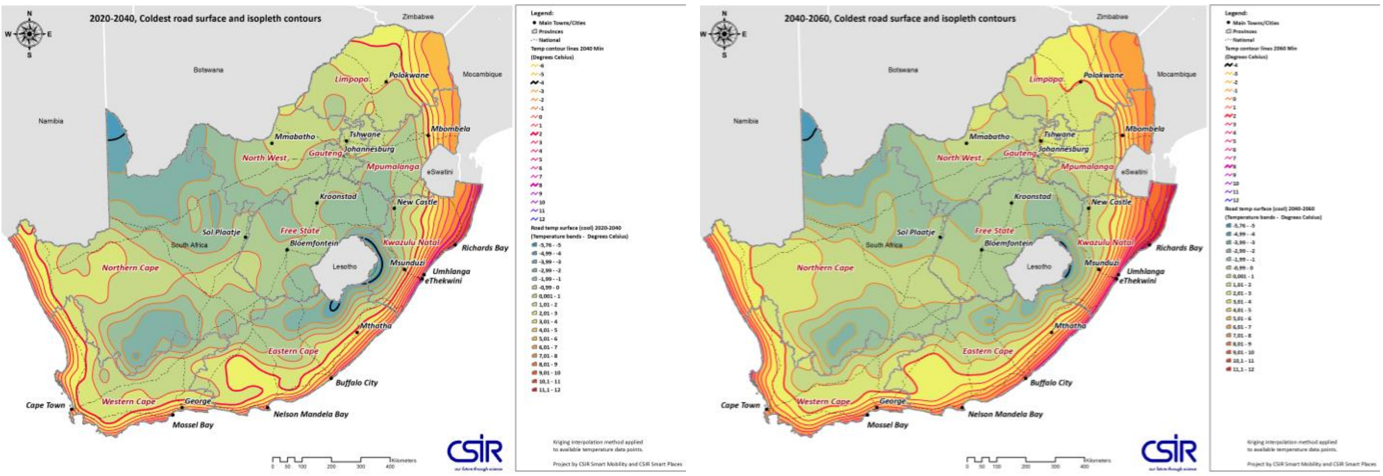
TABLE III. PREDICTED CHANGE IN MINIMUM PAVEMENT TEMPERATURES (°C)

Location	Period A to B	Period B to C	Period C to D	Overall
Johannesburg	0.76	-0.49	2.16	2.43
Pretoria	0.27	-0.42	1.31	1.16
Cape Town	0.63	-0.31	0.99	1.31
Durban	1.35	-2.27	-0.35	-1.27
Pietermaritzburg	0.64	0.10	0.55	1.29



(2a) Period A:1980-2000

(2b) Period B: 2000-2020



(2c) Period C: 2020-2040

(2d) Period D: 2040-2060

Fig. 2. Effect of climate change on minimum pavement temperatures over 80 years between Period A and Period D

V. CURRENT PRACTICE AND ADAPTATION PLANNING

The current national Technical Specification, SATS 3208:2018 [25], for performance grade bitumen indicates two main binder grades namely, PG 58-22 and PG 64-16 based on the maximum pavement temperature map (Fig. 3) and an 80°C interval to determine the minimum temperature specification. This practice sufficiently caters for minimum calculated pavement temperatures in the specification and also for the effects of climate change given the largest temperature difference observed between maximum and minimum pavement temperatures was approximately 59°C for the locations listed in Table II and Table III. Provisions have also been made for the incorporation of a PG 70-10 binder due to higher actual temperatures being recorded on site at certain locations. Given that the current specification is based on actual measured historical air temperatures, a proposed adaptive approach to incorporate climate change and the effects of global warming for binder selection would be to increase the binder classification by one or two grades depending on the area under investigation. This approach would likely not be required along coastal regions, particularly along the east coast given the minimal temperature changes observed from the models.

Besides increasing the binder grade during the design stage, another adaptive measure could be the strategic utilization of asphalt mixes such as using stone matrix asphalt or polymer-modified binders to mitigate increased rutting potential anticipated along high trafficked areas.

Meyer et al. [4] also identified that increased stiffness due to ageing of the binder in asphalt pavements would need to be investigated as this would increase the potential for asphalt pavements to crack. The effects on climate change will not only affect material selection by promoting the use of more robust materials but they will also affect road construction procedures and pavement resilience to endure more frequent extreme weather events [5].

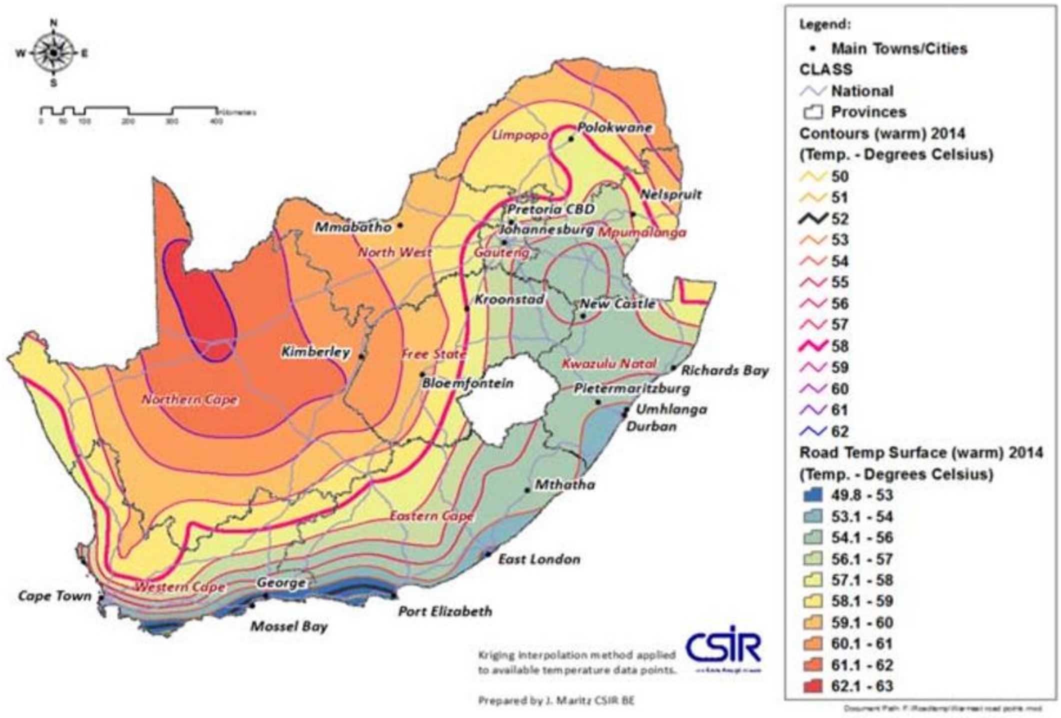


Fig. 3. Maximum temperature at 97,5 % confidence level for 7-day annual average at a depth of 20 mm below the road surface [25]

The current temperature maps used in industry (Fig. 3) differ from the maps generated using the climate change models. One of the reasons why this should be so is that the model predicts changes in average air temperatures and not necessarily individual daily temperatures. This average effect is in sharp contrast to the manner in which the maximum road temperatures are currently calculated, which is aligned with extreme temperature events. Consequently, the limitation of this study is that the climate model creates conservative pavement temperature extremes. The generated maps should therefore not be used as a prediction for future PG requirements but rather as an indication of change in PG requirements.

Further research is recommended to establish the effects on pavement temperatures with the use of extreme air temperatures.

VI. CONCLUSION AND RECOMMENDATIONS

From the study carried out, it is clear that the effects of climate change will affect the binder selection process. Current practice is to use historical temperature data for the design of roads. It is recommended to incorporate the expected increases in temperatures resulting from climate change in order to prevent costly repairs associated with reactive approaches to maintenance and construction. It has also been shown that certain areas of the country (mostly inland regions) will experience larger changes in temperature over time in comparison to coastal regions. The progression in increasing maximum temperatures, from the results of a low-mitigation scenario climate model, has been illustrated in the temperature maps presented in this paper. The incorporation of other models is recommended to observe the effects of a broad case

Road authorities and municipalities will need to take the effects of climate change into account when planning infrastructure activities. Although minimal changes in temperature are observed along the coast, it should be noted that coastal areas exhibited steep temperature gradients; this will be an important aspect in terms of road design and infrastructure planning where a road can cross different PG zones in a relatively short distance therefore the PG binder specification may need to be carefully considered. A closer look at each province in detail is also highly recommended for similar reasons; where one can easily see the pavement temperature patterns at a closer scale.

This paper highlights the need to consider climate change in transport infrastructure design and maintenance. This will inform both local and national road authorities to employ the necessary preventative maintenance measures, which includes the appropriate selection of bituminous binders for asphalt pavements. It should also be noted that temperature is only one factor to consider in the overall pavement structure, therefore the design and maintenance of an effective pavement needs to also consider other parameters relating to climate change which will affect the condition and integrity of the road network. These considerations include other climatic factors such as rainfall and humidity. A sustainability model also includes socio-economic factors such as human settlement patterns that could change due to climate change effects, which could further impact the climate due to factors such as heat islands. The overwhelming conclusion is the importance of incorporating anticipated future conditions when it comes to infrastructure planning and designs.

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