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REVIEW PAPER ON PAVEMENT TEMPERATURE PREDICTION MODEL FOR INDIAN CLIMATIC CONDITION

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Abstract— The performance of asphalt pavements is greatly influenced by environmental conditions. One of the most important environmental factors that significantly affect the mechanical properties of asphalt mixtures is temperature. Thus, accurate prediction of the temperature distribution within the pavement structure is important . Flexible pavements comprise a majority of the primary highways in the India and in United States also. These primary roads are subjected to heavy loading that can cause significant damage to the hot-mix asphalt (HMA) pavements. As HMA is a viscoelastic material, the structural or load-carrying capacity of the pavement varies with temperature. Thus, to determine in-situ strength characteristics of flexible pavement, it is necessary to predict the temperature distribution within the HMA layers. To determine the pavement temperature profile, the influence of ambient temperature and seasonal changes must be understood such that the effects of heating and cooling trends within the pavement structure can be quantified. Recent investigations have shown that it is possible to model daily pavement maxima and minima temperature by knowing the maximum or minimum ambient temperatures, the depth at which the pavement temperature is desired, and the day of year at a particular location. This paper presents a review of models to predict high and low asphalt pavement temperatures in India and extends the model to incorporate either the calculated daily solar radiation or latitude such that the model can be applied to any location in India.

Keywords— Pavement, Temperature, prediction, model, and climate

I. INTRODUCTION

One of the most important environmental factors that significantly affect the mechanical properties of asphalt mixtures is temperature. The structural capacity of the hot mix asphalt concrete layers depends on many factors including its temperature.

Moreover, temperature can be a major contributor to several types of distresses. Therefore, temperature is a significant factor that affects the performance and life span of a pavement. After the introduction of the Super pave pavement temperature estimation procedures in 1993, many researchers expressed concerns regarding the accuracy of the temperature algorithms and the implications of using the estimated values. The objective of this study is to make a valid model for predicting the pavement temperature at a certain depth for characteristic region. Like the modern logistics systems bring us back to the beginning of scientific development [1], accurate prediction of the asphalt pavement temperature at different depths based on air temperatures and other simple weather station measurements can help engineers in performing back calculations of asphalt concrete modulus and in estimating pavement deflections. The temperature distribution of flexible pavements is directly affected by the environmental conditions, to which it is exposed, Figure 1 [2]. The main task, then, is to determine physical and mechanical properties of materials in the conditions equivalent to the conditions in the real pavement structure [3]. Pavement temperature is very important in evaluating frost action and frost penetration. Modeling pavement surface temperature as a function of such weather condition (air temperature, dew point, relative humidity and wind speed) can provide an additional component that is essential for winter maintenance operations. Like heat transfer properties for nanofluids [4] and other materials and structures are very important, for pavement structures are especially important.

Characterization of the in-situ strength performance of roadways constructed using HMA is difficult due to the nature of the material. Hot-mix asphalt is a viscoelastic material; that is, it exhibits the properties of both a viscous and an elastic material. At low temperatures, HMA acts as an elastic solid in which low amounts of applied strain are recoverable; thus, permanent deformation is not likely to occur until this low strain limit is surpassed. However, at high temperatures, HMA acts as a viscous fluid in which the material begins to flow with an applied strain. The temperature within a pavement varies due to several factors including ambient temperature, solar radiation, wind speed, and reflectance of the pavement surface.[1]

The properties of asphalt mixtures changes drastically with temperature. Asphalt concrete is hard, brittle and susceptible to cracking at low temperatures and soft and prone to permanent deformation at high temperatures.

Accurate prediction of the asphalt pavement temperature at different depths based on air temperatures and other simple weather station n measurements can help engineers in performing back calculations of asphalt concrete modulus and in estimating pavement deflections. Pavement temperature is very important in evaluating frost action and frost penetration as well as in the selection of the asphalt grade in the pavement structure [2].

The pavement is exposed to great strains and stresses when subjected to traffic and thermal loadings.

1. Thermal stresses from thermal fatigue, which occurs when temperature variations induce cyclic openings and closures of cracks in the pavement, which induce stress concentrations in the overlay.
2. Thermal stresses as a result of rapid cooling down of the top layer, which induces critical tensile stresses on overlay.
3. Repetitive traffic loads induce additional distress in the overlay and increase the rate of crack propagation, whether or not these cracks originate from thermal stresses.
4. Soil movements – settlements (downwards), frost.

Daily temperature variations have an important influence in the pavement thermal state on depth below the surface of few decimeters. Depending on the level of temperature variation, stress is induced in the overlay in two different ways, which need to be distinguished: through restrained shrinkage of the overlay and through the movements of the existing slabs.

II. LITERATURE REVIEW

Pavement temperature prediction has been extensively investigated by many researchers all over the world. The Enhanced Integrated Climatic Model (EICM) (NCHRP 1 -37A [5]) is used in the mechanistic empirical pavement design guide (MEPDG) for pavement temperature prediction. The Enhanced Integrated Climatic Model (EICM) (NCHRP 1 - 37A [5]) is used in the mechanistic empirical pavement design guide (MEPDG) for pavement temperature prediction. The EICM consists of three parts: the CMS (Climatic -Materials-Structural) model originally developed at the University of Illinois (Dempsey [6]), the CRREL Frost Heave and Thaw Settlement Model and the Infiltration and Drainage Model (NCHRP 1 - 37A [5]). The CMS is a forward finite difference one -dimensional heat transfer model that determines the temperature distribution and the frost penetration within the pavement. The model considers radiation, convection, conduction and latent heat. Heat fluxes due to transpiration, condensation and precipitation are neglected in this model (Dempsey [6]). The inputs used in this model include heat capacity and thermal conductivity of the asphalt mixture, pavement surface absorptivity, air temperature, wind speed and incoming solar radiation. Some of these input parameters were not measured directly but were estimated using empirical correlations. Several empirical models based on linear regression analysis have been developed to predict maximum and minimum temperatures in the pavement. Dempsey [6] developed nomographs to predict pavement temperatures at the surface and at a depth of 50mm. The collected data included pavement temperature and hourly solar radiation. A simulation model based on the theory of heat transfer and energy balance at the pavement surface was later developed. Until the initiation of the Long-Term Pavement Performance (LTPP) program, there was little information present in the general literature on this topic. The Strategic Highway Research Program (SHRP) established the LTPP program in 1987 as a 20-year study to better characterize the in-situ performance of pavements. Approximately 2,500 sites throughout North America were selected to represent a broad range of pavement types and climatic conditions. To specifically deal with the challenges of studying climatic conditions, 61 LTPP sites were selected to become part of the Seasonal Monitoring Program (SMP). The 1994 SMP research was designed to measure and evaluate the effects of temperature and moisture variations on pavement performance; thus making it possible to monitor the appropriateness of the varying Superpave mixture designs [7].From the initial SHRP testing and the more recent SMP data, pavement temperature models were developed to assist with the selection of the proper asphalt binder performance grade for usage in a particular location [7].Pavement temperature prediction using energy balance equations include studies performed by Hermansson [7], Christison and Anderson [8],Straub *et al.* [9] and Yavuzturk *et al.* [10].

Several empirical models based on linear regression analysis have been developed to predict maximum and minimum temperatures in the pavement. Barber [11] was among the first researchers to discuss the calculation of maximum pavement temperatures based on weather reports. He observed that the changes in pavement temperature measured in Hybla Valley (Virginia ,USA) roughly followed a sine curve with a period of one day. The analyses showed that when solar radiation and air temperature was included, the sine approximation provided reasonable estimates of surface temperatures. However, his model incorporates a total daily radiation factor instead of a more accurate measure such as hourly radiation and he proposed a model to correlate pavement surface temperatures and temperatures at 3.5 in. depth with weather station information.

Solaimanian [12] developed a quadratic model that determines the maximum and minimum surface pavement temperature based on the latitude of the location of the pavement.

A computer simulation model that predicts summertime pavement temperatures based on the theoretical heat transfer models given Lukanen *et al.* [13] developed an empirical prediction model based on regression analysis and data from the Long -Term Pavement Performance Program to estimate the seven -day average maximum pavement temperature using the seven –day average maximum air temperature and also presented an analytical approach to predict pavement temperatures by employing heat and energy transfer theory. Diefenderfer *et al.* [14] developed and validated models for daily maximum and minimum pavement temperatures based on data obtained at the Virginia Smart Road and two LTPP test sites. The models proposed incorporated the depth within the pavement, calculated daily solar radiation and maximum or minimum air temperature. Rania E. Asbahan[15] studied effects of temperature and moisture gradients on slab deformation for Jointed Plain concrete pavements. Khraibani [16] has developed a nonlinear mixed-effects model enabling accounting for the correlation between observations on the same pavement section. On the basis of this nonlinear mixed-effects modeling, author investigated and identified structural and climatic factors that explain differences in the parameters between pavement sections, and quantify the impact of these factors on pavement evolution. The proposed model provides a good fit for describing the evolution law of different pavement sections.

III. REVIEW OF FINDINGS

A. VARIABLES USED IN THE MODELS

The temperature distribution of flexible pavements is directly affected by the environmental conditions to which it is exposed. The heat transfer between the surface of the pavement and the environment is affected by incident solar radiation, thermal and long-wave radiation between the surface and the sky, convection between the pavement surface and fluids like air or water, and conduction inside the pavement (Figure 1).

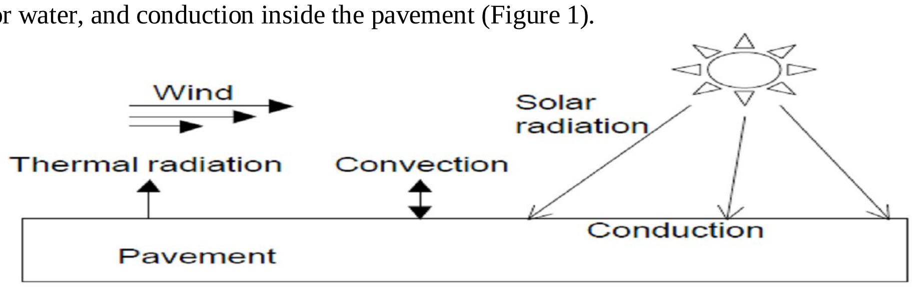

Figure 1. Energy ba lance on the surface of the pavement

Incident solar radiation is an important factor that needs to be included in pavement temperature models for reliable and location independent predictions . Solar radiation at any location (latitude) and day of the yea r can be calculated using the equations proposed by Iqba l [16]

$$H_0 = \frac{24 I_{SC} E_0}{\pi} \sin\phi \sin\delta\left(\frac{\omega_s \pi}{\pi} - \tan\omega_s\right) \quad (1)$$

where,

H0 = daily solar radiation on a horizontal surface (kJ/m ^{2})
ISC = solar constant = 4871 kJ/m ^{2}
ϕ = latitude (deg)
E0 = eccentricity factor, calculated using (2)

$$= 1.00011 + 0.034221\cos\Gamma + 0.001280 \sin\Gamma + 0.000719\cos 2\Gamma + 0.000077 \sin 2\Gamma \quad (2)$$

Γ = day angle (rad), calculated with: $\Gamma = \frac{2\pi d_{n-1}}{365}$

dn= day number of the year from 1 to 365
δ = solar declination (deg), calculated as follows:

$$= (0.006918 - 0.399912 \cos\Gamma + 0.070257 \sin\Gamma - 0.006758\cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma)\frac{180}{\pi} \quad (3)$$

ω_S= sunrise hour angle (deg), calculated using :

$$\omega_S = \cos^{-1}(-\tan\phi \tan\delta) \quad (4)$$

B. LINEAR MODEL FOR MAXIMUM PAVEMENT TEMPERATURE

A linear model which includes all the variables described before and the interact ion terms was fitted to the MnROAD data. In this model , the asphalt binder type is included and treated as a dummy variable to study the effect of different binders on the
pavement temperature prediction. The proposed linear model is as follows:

$$T_{MAX\_PAV} = a + bT_{MAX\_AIR} + cD + dS + eH + fW + gB_1 + hB_2 + iB_3 + jDT_{MAX\_AIR} + kST_{MAX\_AIR} + lB1D + mB2D + nB3D \quad (5)$$

where:

$T_{MAX\text{-}AIR}$ = Maximum air temperature (°C).
D = depth (m).
S = Calculated solar radiation (kJ/m ^{2} day).
H = Humidity (%).
W = Wind speed (m/s).
$B1$ = PG 58 -34 binder.
$B2$ = PG 58 -28 binder.
$B3$ = PG 58 -40 binder.
The constants of the model described by (5) can be estimated using the least squares method.

C. REDUCED MODEL FOR MAXIMUM PAVEMENT TEMPERATURE

The maximum air temperature is the independent variable that contains most of the explanatory information for t he maximum pavement temperature. Therefore, polynomials of degree up to five are fitted using only this variable in the model and AIC is used to estimate the degree of the polynomial to be used in the proposed reduced model.

The following reduced model is proposed based on the previous analysis and by removing the terms that are not statistically significant:

$$T_{MAX\_PAV} = a + bT^2_{MAX\_AIR} + cT_{MAX\_AIR} + dD + eS + fH + gW \quad (6)$$

D. REDUCED MODEL FOR MINIMUM PAVEMENT TEMPERATURE

The following model is proposed for minimum pavement temperature prediction :

$$T_{MIN\_PAV} = a + bT^2_{MIN\_AIR} + cT_{MIN\_AIR} + dD + eS + fH + gW \quad (7)$$

Development of pavement prediction models based on data
collected at the Virginia Smart Road can be found in **Diefenderfer et al. (*14*).**

The basic form of the temperature prediction model presented within this study is expressed as follows:

$$Tp = a + bTm + cY + dPd \quad (8)$$

where
Tp = predicted pavement temperature (°C);
a = intercept coefficient;
b = ambient temperature coefficient;
Tm = measured ambient temperature (°C);
c = day of year coefficient;
Y = day of year (1 to 183);
d = depth coefficient; and
Pd = depth within the pavement (m).
Given the depths of temperature measurement upon which the above model was developed, the maximum depth considered

E. To develop the pavement temperatures prediction model, basic principles needed to be adopted.

The following sections present the main principles adopted in the proposed model once the hourly temperature distribution was governed by heat conduction principles within pavement and by energy interaction between the pavement and its surroundings.

Conduction heat transfer

Conjugating the first law of the thermodynamics, which states that thermal energy is conserved, and Fourier's law, that relates the heat flux with the thermal gradient, the problem of heat transfer by conduction within the pavement is solved. For an isotropic medium and for constant thermal conductivity, this adopted principle is expressed as follow :

$$\nabla^2 T = \frac{1}{\alpha} \cdot \left(\frac{\partial T}{\partial t} \right)$$

where: $\nabla^2 = \left(\partial^2 / \partial x^2\right) + \left(\partial^2 / \partial y^2\right) + \left(\partial^2 / \partial z^2\right)$ (9)

$\alpha = \dfrac{k}{\rho \cdot C}$ Thermal diffusivity

k – thermal conductivity;
ρ – density;
C – specific heat;
x, y, z – components of the Cartesian coordinate system;
T – temperature;
t – time.

Interaction between the pavement and its surroundings

On a sunny day the heat transfer by energy interaction between pavement and its surroundings consists of radiation balance and of exchanges by convection. The radiation balance (or thermal radiation) involves the consideration of outgoing longwave radiation, longwave counter radiation and the shortwave radiation (or solar radiation).

The earth surface is assumed to emit longwave radiation as a black body. Thus, the outgoing longwave radiation follows the Stefan-Boltzman law :

$$q_e = \varepsilon_e \, \sigma \, T^4_{sur} \quad (10)$$

where: q_e – outgoing radiation;
ε_e – emission coefficient;
σ – Stefan-Boltzman constant;
T_{sur} – pavement surface temperature.

As the atmosphere absorbs radiation and emits it as longwave radiation to the earth, this counter radiation absorbed by the pavement surface is calculated as:

$$q_a = \varepsilon_a \, \sigma \, T^4_{air} \quad (11)$$

where: q_a – absorbed counter radiation;
ε_a – pavement surface absorptivity for longwave radiation and the amount of clouds;
T_{air} – air temperature.

Several authors consider the longwave radiation intensity balance (or thermal radiation) through the following expression:

$$q_r = h_r \left(T_{sur} - T_{air} \right) \quad (12)$$

where: q_r – longwave radiation intensity balance:

h_r – thermal radiation coefficient.

The expression used to obtain h_r is the following :

$$hr = \varepsilon\sigma \, (Tsur + Tair)(T^2sur + T^2air) \quad (13)$$

where: ε – emissivity of pavement surface.

Part of the high frequency (shortwave) radiation emitted by the sun is diffusely scattered in the atmosphere of the earth in all directions and the diffuse radiation that reach the earth is called diffused incident radiation. The radiation from the sun reaching the earth surface, without being reflected by clouds or absorbed or scattered by atmosphere, is called direct incident shortwave radiation. The total incident radiation (direct and diffused) can be estimated using the following equation:

$$qi = \eta s_c f \cos\theta \quad (14)$$

where: q_i – thermal incident solar radiation;

η – loss factor accounting scattering and absorption of shortwave radiation by atmosphere;

s_c – solar constant assumed to be 1353 W/m^2;

f – factor accounting the eccentricity of earth orbit;

θ – zenith angle.

The effective incident solar radiation absorbed by pavement surface may be determined by the equation :

$$qs\cdot=\alpha s\cdot qi \qquad (15)$$

where q_s – incident solar radiation absorbed by pavement surface;

α_s – solar radiation absorption coefficient.

In the model suggested in this paper, shortwave radiation is given as input data obtained measured values.

The convection heat transfer between the pavement surface and the air immediately above is given as:

$$q_c=hc\,(Tsur-Tair\,) \qquad (16)$$

where: q_c – convection heat transfer;

h_c – convection heat transfer coefficient.

The convection heat transfe coefficient can be calculated as:

$$hc=698.24[(1.44x10^{-4}\,T^{03}ave\cdot\,U^{0.7})+(9.7x10^{-4}(Tsur-Tair\,)^{0.3}\,)]$$

where:

T_{ave} – average temperature given by $Tave=hr\,(Tsur-Tair\,)/2$

U – wind speed.

F. 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.

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.

$$Ts(max)=Tair(max)+24.5(\cos Zn)^2\cdot C \qquad (17)$$

where:

Ts(max) = the daily maximum asphalt surface temperature in ºC

Tair(max)) = the daily maximum air temperature in ºC

Zn = Zenith angle at midday

C = Cloud cover index

with:

C = 1.1 if Tair(max) > 30 ºC

C = 1.0 if monthly mean air temperature < Tair(max) < 30 ºC

C = 0.25 if Tair(max) < monthly mean air temperature

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

$$\cos(Zn)=\sin(latitude)\sin(declination)+\cos(latitude)\cos(declination) \qquad (18)$$

The equation for maximum asphalt surface temperatures recommended in Superpave:

$Ts(max) = Tair(max) - 0.00618 \cdot latitude^2 + 0.2289 \cdot latitude + 24.4$

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 20.

$$Ts(min) = 0.89\, Tair(min) + 5.2 \quad (19)$$

$$Ts(min) = 0.859\, Tair(min) + 1.7 \quad (20)$$

where:

Ts(min) = the daily minimum surface temperature in ºC

Tair(min) = the daily minimum air temperature in ºC

Asphalt temperature at depth

The prediction algorithm for maximum pavement temperature at depth, shown as Equation (21), was validated by Viljoen (2001) against some 600 temperature gradients.

$$Td(max) = Ts(max)(1 - 4.237\times10^{-3}d + 2.95\times10^{-5}d^2 - 8.53\times10^{-8}d^3) \quad (21)$$

where

Td(max) = Maximum daily asphalt temperature at depth d in ºC

Ts(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 (22)

$$Td(min) = Ts(min) + 3.7\times10^{-2}d - 6.29\times10^{-5}d^2 \quad (22)$$

where

Td(min) = Minumum daily asphalt temperature at depth d in ºC

Ts(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 23 and 24.

$$Td(max) = (Ts(max) + 17.8)(1 - 2.48\times10^{-3}d + 1.085\times10^{-5}d^2 - 2.441\times10^{-8}d^3) - 17.8 \quad (23)$$

$$Td(min) = Ts(min) + 5.1\times10^{-2}d - 6.3\times10^{-5}d^2 \quad (24)$$

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 25 at daytime and Equation 26 at nighttime.

$$T_{d(t)} = T_{d(min)} + \left[T_{d(max)} - T_{d(min)}\right]\sin\left[\pi \frac{(t - t_r - \beta)}{DL + 2(\alpha - \beta)}\right] \quad (25)$$

where

DL = Day length

$= \frac{2}{15} \times \cos^{-1}[-\tan(latitude) \times \tan(solardecilnation)]$

t = hour t

d = depth in mm

Td(t) = asphalt temperature at depth d at hour t

Td(max) = Maximum temperature at depth from Equation 7

Td(min) = Minimum temperature at depth from Equation 8

tr = time of sunrise

α = time lag between 12 noon and occurrence of maximum pavement temperature

$$\alpha = 2 + \frac{d}{50}$$

β = time lag between sunrise and occurrence of minimum asphalt temperature, the best fit found for β is 1.5 hours

$$T_{d(t)} = T^{n}_{d(min)} + \left[T_{d(t_s)} - T^{n}_{d(min)}\right]\exp\left[-\frac{\gamma(t-t_s)}{24-DL+\beta}\right] \quad (26)$$

where

ts = time of sunset

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

Td(ts) = is temperature at sunset

γ = a decay parameter, assumed to be 3.9

With these equations the temperature prediction model is complete.

IV. CONCLUSION

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 model yields acceptable results to start implementing and validating PG binder selection in South Africa and can be implemented for Indian climate also.

Measurement of pavement temperature is an important step in the implementation of mechanistic pavement design procedures. Considering the fact that no automated weather data collection procedures exist currently in India and in most of the Southeast Asian countries, this investigation re-looked at a classical yet simple technique for pavement temperature prediction.

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