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Modeling Temperature Profile of Hot-Mix Asphalt in Flexible Pavement

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Abstract: This study develops pavement temperature prediction models based on temperature and weather data measured from the instrumentation section on Interstate 40 (I-40) in New Mexico, USA. As a first step, pavement temperatures of asphalt concrete at different depths, air temperature and solar radiation were continuously monitored from October 15, 2012 to October 14, 2013. Using this data, statistical models were developed to predict the temperature of asphalt concrete at any depth. Comparison of additional temperature data from October 15, 2013 to January 21, 2014 validates the models. Using these models, asphalt concrete inner pavement temperature at any depth of asphalt concrete can be predicted if the surface or air temperature is known. The study outcome expects to be highly beneficial for analyzing temperature related stress-strain, validating numerical models developed to predict pavement temperature and calibrating the Pavement Mechanistic-Empirical (ME) Design Guide for pavement design.

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***Key words**: Asphalt concrete; Model development; Temperature profile; Temperature probes; Validation.*

Introduction

Hot Mix Asphalt (HMA) is a mixture of crushed stone aggregate and asphalt binder. The mechanical properties of crushed stones are usually independent of temperature, however, asphalt binder properties are largely dependent on temperature even if the temperature variation is small. The asphalt concrete mixture is thus largely dependent on temperature. Pavement temperature is dependent on solar radiation, wind speed, surface absorption, binder percentage of mixtures, time of day, etc. [1]. This is why prediction of an actual temperature profile is near impossible. Temperature at any depth of pavement is usually determined by installing temperature probes, which is often quite impossible in existing pavement.

Determining pavement temperature is essential for analyzing and interpreting Falling Weight Deflectometer (FWD) test data to backcalculate layer stiffness, estimating frost-thaw action and frost penetration, calculating cooling rates for freshly compacted asphalt layers, and assessing the diurnal and seasonal effects to the structural response of flexible pavement [2, 3].

Study of the effect of temperature on flexible pavement began more than fifty years ago [4-6]. For this purpose, it is essential to predict temperature variations inside the pavement. Numerous studies predict temperature profiles in flexible pavement based on statistical, numerical and probabilistic methods based on climate and pavement data. The data is usually collected through the Long-Term Pavement Performance Program (LTPP) under the Strategic Highway Research Program (SHRP). However, such statistical and probabilistic methods routinely underestimate high pavement temperature or overestimate low pavement temperature.

Wang [2] developed an algorithm using thermal properties of HMA, pavement depth and surface temperature to predict one-dimensional (1D) temperature profiles in a multilayered pavement system. The algorithm can be applied when estimating temperature profiles in a multilayered pavement system. Results are validated using field data from Kallas [7] measured during 1964 to 1965. This type of old data is not valid in today's asphalt conditions, however, as significant changes have occurred in HMA mix design and compaction methods. In addition, the fitted value is not very good at greater depths (>0.15 m).

Khadrawi et al. [1] developed a heat transfer model to predict transient thermal behavior of HMA using the thermal properties of asphalt concrete, surface and ambient temperature and solar radiation. Pavement temperature at any depth can be predicted. However, the HMA layer is assumed infinite in depth and typical thermal properties of HMA are assumed. The model also needs to be field validated before using in any other sites.

Yavuzturk et al. [3] analyzed a two-dimensional (2D) finite difference model capable of determining temperature on an hour-by-hour basis at any arbitrary point in an asphalt pavement. The model considers thermal ambient conditions such as the ambient dry bulb temperature, global solar radiation intensity, pavement geometry and orientation, ambient wind conditions, and pavement thermal properties. This model is not user-friendly for practicing pavement engineers and includes a lot of variables, which are very often difficult to obtain.

Diefenderfer [8] developed two statistical models, referred herein as Diefenderfer Statistical Model (DSM), based on an instrumentation section in Virginia named the Virginia Smart Road (VSR), to predict the maximum and the minimum temperature at any depth of the pavement. However, these models are quite inappropriate for New Mexico (NM) pavements as the HMA mixture design and geometry of NM pavements are not similar to VSR.

Some examples of other existing models are the SHRP LTPP Models [8]. The models were evaluated for validity on Interstate 40 (I-40) pavement in NM. The maximum temperature for the I-40 pavement at 263 mm depth was determined using these models and the results are plotted in Fig. 1. It shows that the DSM and LTPP

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models produce much greater temperature at this depth whereas the SHRP models produce much lower temperature when compared to the I-40 pavement. It also shows that the measured temperature at the I-40 instrumented section is consistent. The equations for these models are presented in Eqs. (1) to (3).

SHRP Model:

$$T_{pav(max)}=T_{s(max)}(1-0.0063d+0.007d^2-0.0004d^3) \quad (1)$$

where $T_{pav(max)}$ is the maximum pavement temperature (°F) at depth, d (in.), $T_{s(max)}$ is the maximum surface temperature (°F).

LTPP Model:

$$T_{pav(max)} = (T_{s(max)} + 17.8)(1-0.00248d+0.000011d^2-0.0024d^3)-17.8 \quad (2)$$

$T_{pav(max)}$ is the maximum pavement temperature (°C) at depth, d (m), $T_{s(max)}$ is the maximum surface temperature (°C).

DSM Model:

$$T_{pav(max)} = 0.686x_1 + 0.000567x_2 - 27.87x + 2.7875 \quad (3)$$

$T_{pav(max)}$ is the maximum pavement temperature (°C) at depth, x_1 is the maximum air temperature (°C), x_2 is the calculated daily solar radiation (kJ/m^{2}day), and x is the depth from the surface (m).

Formal statistical analysis was conducted to evaluate the mean (average) of the maximum temperature and the measured data of these models. One-Way Analysis of Variance (ANOVA) was performed with null hypothesis that the mean (average) values of the maximum temperature data were equal. The alternative hypothesis was that the mean values were not equal. The test yielded the p-value (probability of null hypothesis being true) closer to zero (much less than 0.05). The null hypothesis was rejected in favor of the alternative hypothesis, concluding that the mean values were not equal at 95% Confidence Interval (CI). The ANOVA test requires that the data be normally distributed. This assumption was evaluated by the formal normality test namely Shapiro-Wilk Normality test. The null hypothesis of this test was that the data was normally distributed and the alternative hypothesis was that the data was not normally distributed. This test produced p-value ranges between 0.64 and 0.72 for the four sets of data presented in Fig. 1. As the p-value was much greater than 0.05, the alternative hypothesis was rejected in favor of the null hypothesis. Therefore, the normality assumption of the data was satisfied and the result produced in the ANOVA test was valid.

A pair-wise t-test was also conducted to evaluate which pair or pairs of means differ(s). Fisher's least significant difference method (FSD) yields the output listed in Table 1. The LTPP and the DSM models have p-value greater than 0.05 and thus, the two models produce the equal mean value at 95% CI. No other combination has the equal mean value. Therefore, no existing model perfectly represents the field condition of I-40 pavement in NM. The reason for this is based on climate conditions in New Mexico. It is a rocky and arid area, where typical day-night temperature fluctuation is high, while humidity and rainfall are low. The authors of the present study conducted their research to develop statistical models to predict the HMA temperature at any depth using measured temperature data from the I-40 pavement. The resulting models are expected to be appropriate for pavement in areas of climate conditions similar to New Mexico.

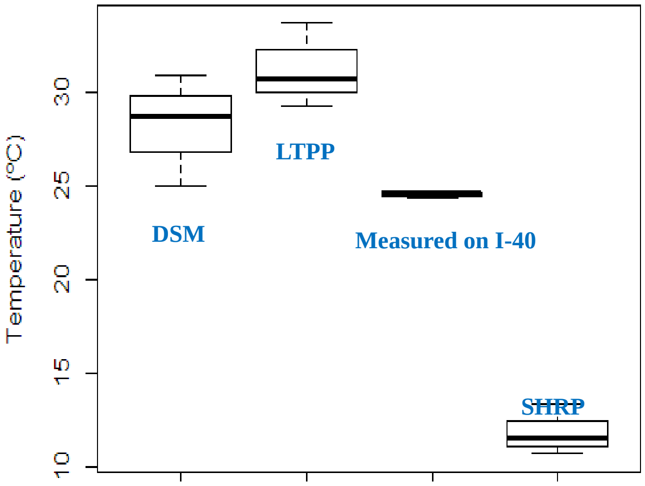

Fig. 1. Comparisons of Measured Temperature with other Studies.

Table 1. *p*-values of Multiple Comparison Tests Using FSD Method.

	DSM	LTPP	Measured
LTPP	0.097	-	-
Measured	0.0405	0.003	-
SHRP	0.000008	0.00002	0.00005

Objectives

The study is primarily conducted to develop statistical models to predict temperature at any depth of HMA using the collected data from the I-40 pavement. The maximum, minimum and average HMA temperature at any depth can be determined using the developed models, which were verified with further field data and statistical analysis.

Field Installation

Description of the Instrumentation Section

The instrumentation section is located on Interstate 40 (I-40) east bound lane, at milepost 141 in the state of New Mexico, USA. Installation of the sensors was executed in cooperation with the National Center for Asphalt Technology (NCAT) of Auburn University, USA and New Mexico Department of Transportation (NMDOT). The section has four layers. The top layer is 263 mm (10.5 in) thick asphalt concrete. There is a base course of 150 mm (6 in) thickness followed by a 200 mm (8 in) subbase layer and finally, the natural soil. The asphalt concrete used in the pavement is a dense graded SuperPave (SP) mix, type SP-III, which is widely used in NM. This mix contains 35% Reclaimed Asphalt Pavement (RAP) RAP materials. The RAP materials were collected from local street millings, which were screened by the contractors prior to mixing with the aggregates. Performance Grade (PG) binder PG 76-22 is used at a ratio of 4.4% by weight of the mixture. The maximum aggregate size is 25 mm (1 in). About 5% of the material passed through a No. 200 sieve (0.075 mm). It was noted that blending of RAP in the HMA mixture did not change the thermal properties of the original HMA [9].

Forty sensors were installed in the instrumentation section to measure the vertical stresses, horizontal strain, air temperature, solar radiation, pavement temperatures, moisture, and wheel wander and vehicle weight. The sensors were placed at different elevations and positions within the section. This study deals with solar radiation, air and pavement temperature measurements that were taken with the weather station and temperature probes.

Weather Station

Two types of sensors were installed to measure temperature related parameters such as solar radiation, and air and pavement temperature. The weather station measures air temperature, solar radiation, wind speed, humidity, etc. Fig. 2 shows the installed weather station, and cabinet box for the data acquisition system and data gathering computer. The system is solar powered.

Temperature Probes

Six temperature probes were installed at different depths in the pavement. The probes were bundled together such that after installation they remained at the surface, and at 50, 100, 263, 340 and 490 mm depth. The bundled probes are shown in Fig. 3. A 37.5 mm diameter hole was drilled with an electric drill machine. Then, the hole was cleaned with a vacuum cleaner. The probes were inserted into the hole as straight as possible, keeping the top probe at surface level as shown in Fig. 4. The temperature probes were installed around 300 mm outside the edge line. The installed temperature probes' functionality was checked by connecting the probes to the data acquisition system.

Data Collection

Temperature and solar radiation data were collected for one year, from October 15, 2012 to October 14, 2013. Based on the data, regression analysis was conducted to develop temperature prediction models to determine the maximum, the minimum, and the average temperatures at various depths of the HMA. The models were then validated using further data collected from October 15, 2013 to January 21, 2014.

Results and Discussion

Temperature Variations

The pavement surface heated up during the day and cooled down at night. Therefore, temperature of the pavement materials varied at all times. The air and the pavement temperatures at various depths are shown in Fig. 5. The air temperature was the minimum around 8:00 am and the maximum around 15:00 pm. However, the minimum and the maximum temperatures at the bottom of the asphalt concrete were observed around 11:00 am and 21:00 pm respectively. These values were measured at 8:30 am and 16:30 pm, respectively, at the 90 mm depth. Fig. 5 also shows that the average pavement temperature may occur at either 12:00 am or 12:00 pm. The maximum and the minimum temperatures along with the depth of HMA can be used to determine the required asphalt grade. The temperatures can also be used to correlate pavement temperature with structural responses such as stress-strain due to wheel load and material property such as stiffness of the HMA. In addition, determining the maximum, the minimum, and the average temperatures of a pavement may offer a close understanding of the continuous temperature variation of the pavement. This is why the current study focused on determining the maximum, the minimum,

Fig. 2. Installed Weather Station.

Fig. 3. Bundled Temperature Probes.

Fig. 4. Inserting the Probes.

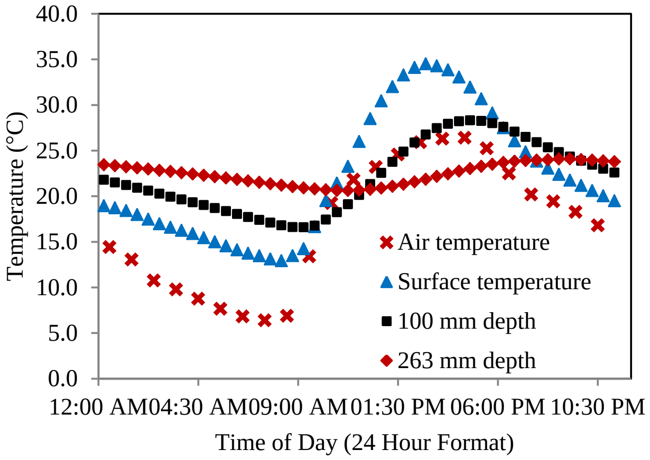

Fig. 5. Temperature Variations on October 24, 2012.

and the average temperatures at any depth of a pavement.

The temperature at any depth of a pavement is largely dependent on the surface temperature, solar radiation and the depth of the pavement. Linear regression analysis was conducted to determine the best-fit regression model to predict the temperature at any depth. The independent variables were solar radiation, pavement surface temperature and pavement depth. The dependent variable was pavement temperature at a particular depth.

Predicting the Maximum Temperature

The maximum temperature at any depth of the pavement depends on the maximum surface temperature and the concerned depth of the pavement. Solar radiation may affect the maximum temperature. This is why, it was also considered as an independent variable. Based on regression analysis, the following two models, Eqs. (4) and (5) were developed.

$$y_{\min} = 2.5 + 0.91x_{\max} - 25.6x - 0.004S_{\max} \tag{4}$$

$$y_{\max} = 0.8 + 0.87x_{\max} - 25.6x \tag{5}$$

where $y_{\max}$ = predicted daily maximum pavement temperature (°C) at any depth

$x_{\max}$ = daily maximum surface temperature (°C)

x = concerned depth from surface (m)

$S_{\max}$ = daily maximum solar radiation (W/m^2)

The maximum surface temperature can be determined from the maximum air temperature using the following relationship:

$$x_{\max} = 1.33a_{\max} + 3.21 \tag{6}$$

where $a_{\max}$ = daily maximum air temperature (°C).

The coefficients of determination (R^2) of all equations (Eqs. (4) to (6)) are between 0.96 and 0.98, which are very close to unity. The R^2 value shows sufficient evidence for the correlation is strong. Eq. (4) predicts the maximum temperature at any depth of the pavement using the maximum surface temperature, the maximum solar radiation and the concerned depth. However, solar radiation may not be at maximum at the time of the maximum surface temperature. Thus, the effect of solar radiation may not contribute significantly. Therefore, another regression model (Eq. (5)) was developed excluding solar radiation. This model produced a similar output to the previous model (Eq. (4)) and the weightage of solar radiation was very small. The models also showed that the maximum temperature at any depth of HMA was always smaller than the maximum surface temperature.

Predicting the Minimum Temperature

The minimum temperature of the pavement at any depth depends on the minimum surface temperature and the concerned depth. The minimum temperature usually occurs late at night or in the morning when solar radiation is insignificant. This is why solar radiation was excluded when developing the model to determine the minimum temperature at any depth of the HMA. The regression model for predicting the minimum temperature ($y_{\min}$ in °C) is shown in Eq. (7). The model is strongly correlated as depicted by the R^2 value of 0.99.

$$y_{\min} = 1.84 + x_{\min} + 20x \tag{7}$$

where $x_{\min}$ = daily minimum surface temperature (°C) and can be found from:

$$x_{\min} = 0.925a_{\min} + 6.76 \tag{8}$$

x = concerned pavement depth (m) and $a_{\min}$ is the minimum air temperature.

This model indicates that it can never be colder inside the pavement than the minimum surface temperature and that the minimum temperature will always be greater further down in the pavement.

Predicting the Average Temperature

The regression model to determine the daily average temperature (y_{avg}) at any depth of the HMA (°C) was developed using the average surface temperature, the average solar radiation and the depth. It is noted that the daily average temperature at any depth of HMA may occur in daytime or in nighttime. The average surface temperature could also be related to the average air temperature. Another issue was that the average temperature might occur in daytime or nighttime. The regression models are shown in Eqs. (9) and (10).

$$y_{avg} = 1.1 + 0.93x_{avg} + 3.65x + 0.0002S_{avg} \tag{9}$$

$$y_{avg} = 1.1 + 0.94x_{avg} + 3.65x \tag{10}$$

where x_{avg} is the daily average surface temperature (°C), S_{avg} is the average solar radiation (W/m^2). Both of the equations have the R^2 value of 0.69. Both equations can be used to predict the average temperature. Eq. (10) excludes solar radiation; however, it is observed that both of these equations produce similar outputs, as the weightage of solar radiation is very low. Therefore, it is better to use

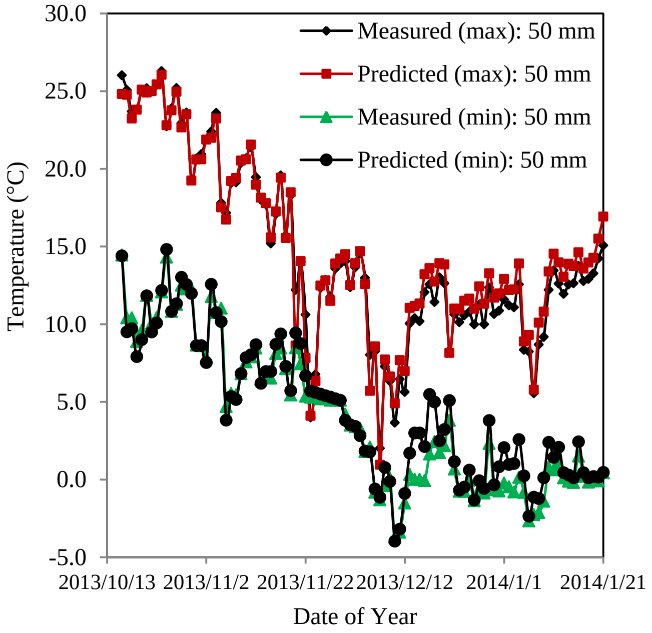

Fig. 6. Predicted and Measured Temperatures at 50 mm Depth.

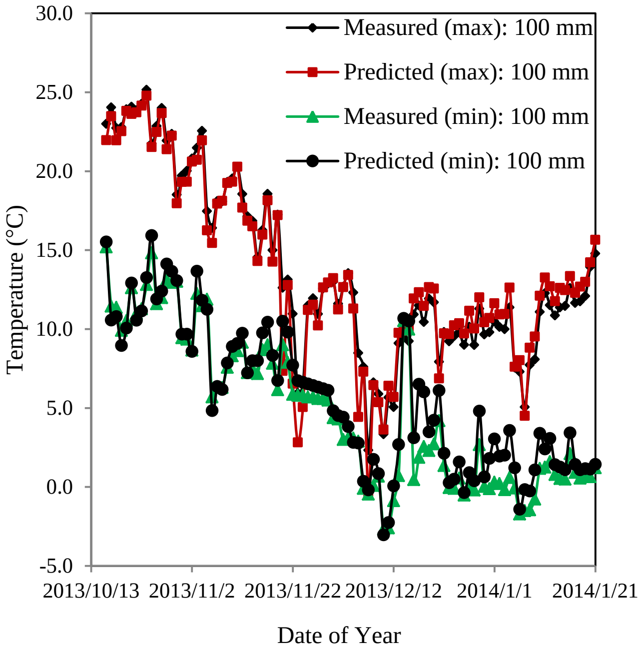

Fig. 7. Predicted and Measured Temperatures at 100 mm Depth.

the shorter model, Eq. (10). Eq. (9) can only be used if the x_{avg} occurs in daytime because S_{avg} is only available in daytime. The average surface temperature (℃) can be correlated with the average air temperature (℃) (with the R^2 value of 0.92) by Eq. (11).

$$x_{avg} = 1.136 a_{avg} + 4.956 \tag{11}$$

Model Validations

The predicted models were compared with the measured data. Figs. 6 and 7 plot the predicted, the minimum, and the maximum values with the measured ones at two different depths, 50 mm and 100 mm. It was observed that for both of these depths, the models predict temperature values very close to the measured data. The predicted models, for some cases, produced lower temperature than the measured minimum, and greater temperature than the measured maximum. Formal statistical tests were conducted to evaluate these differences.

ANOVA test was conducted to evaluate the developed models. The null hypothesis was that the mean values are equal and the alternative hypothesis was that the means are not equal. The minimum, the average and the maximum predicted and measured temperatures at 50 mm depth for the period of October 15, 2013 to January 21, 2014 were compared. The ANOVA test produced p-values of 0.96, 0.12 and 0.89 for the minimum, the average and the maximum predicted and measured temperatures respectively. All the p-values were much greater than 0.05. The alternative hypothesis was therefore rejected in favor of the null hypothesis at 95% CI. Therefore, the mean values of the predicted and measured minimum temperatures at 50 mm depth were equal, which verified the developed model.

Conclusions

This study develops regression models to determine the maximum, the minimum and the average temperatures at any depth of HMA in an asphalt pavement. The models are based on an instrumented section in New Mexico, which is a rocky and arid area. Typical day-night temperature fluctuation in New Mexico is high, while humidity and rainfall are low. The authors highly expect that the developed models will be enormously suitable for pavement in areas of climate conditions similar to New Mexico. The maximum, the minimum and the average temperatures at any depth of HMA can be determined if the surface or air temperature is available. However, the actual temperature of the pavement at a specific time is not investigated.

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