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Temperature predictions for asphalt pavement with thick asphalt layer

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HIGHLIGHTS

- A statistical model was developed to predict temperatures of thick asphalt layer.
- Five sites were selected to collect measured temperatures and meteorological data.
- Q_N and $\bar{T}_{aN}$ can largely affect pavement temperatures.
- T_m was incorporated for the impact of the ground temperature on pavement.

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ABSTRACT

Temperature is one of the most important factors affecting functional as well as structural performance of asphalt pavements with thick asphalt layer (>30 cm). For a successful pavement design, it is vital to accurately predict the pavement temperatures at various depths. However, most previous researches focused on the temperature predictions for conventional asphalt pavements, of which the asphalt thickness is less than 30 cm. This suggests their proposed models are applicable in top layers, but may not be so effective for temperature predictions at deeper depths. As a result, the primary objective of this research was to develop a statistical model to predict temperatures at deep depths. Three test sites were selected, and they were instrumented with a number of sensors and a data logger to record the pavement temperature hourly. Also, all test sections can provide meteorological monitoring to collect hourly air temperatures and hourly total solar radiation. The recorded meteorological conditions were found to have cumulative effect on the measured pavement temperatures at various depths. On basis of their relationship, a statistical regression was performed, and the temperature prediction model was determined as a function of depth, average air temperature and total solar radiation calculated in the cumulative time. For an improvement in applicability, historical mean monthly air temperatures were also incorporated into the mode. The accuracy and applicability of the improved model were validated by applying it to additional sites for which the measured pavement temperatures and meteorological data were available. Also, by comparing with existing models, the developed model was testified to be more effective for asphalt pavements with thick asphalt layer, promising the model's potential use.

1. Introduction

Functional as well as structural performance of asphalt pavements can be greatly affected by pavement temperatures. At low temperatures, asphalts stiffen and the cracking of asphalt layers is accelerated due to shrinkage. At high temperatures, asphalts soften and the distortion of asphalt layers is increased due to bleeding of asphalts [1,2]. Therefore, it is vital to know the range of temperatures over which an asphalt pavement will be subjected. This importance calls for special attention and interest in research to develop procedures for pavement temperature predictions.

Approaches for temperature predictions within asphalt pavement have been proposed by a number of researchers. These approaches can be divided into two categories. One is analytical approach, which is based on the heat transfer theories and thermal properties of asphalt pavement. The other is statistical method, which uses regression models to obtain the relationship between measured pavement temperatures and climatic data.

In 1975, among the first researchers taking analytical approach, Barber [3] presented a method for calculating maximum pavement temperatures from weather report and thermal diffusion theory. Based on his pioneering work, Dempsey [4] developed an analysis program named Climatic-Materials-Structural (CMS) model in

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1970. The CMS model was improved by Thompson [5] in 1987, and temperatures were computed by a one-dimensional, transient finite-difference heat transfer model with climatic data input. In 1993, Solaimanian and Kennedy [6] discussed an analytical approach for predicting critical temperature extremes in pavements. Similarly, it uses the theories of heat and energy transfer. Based on their approach, Hermansson [7] proposed a simulation model to predict maximum pavement temperatures in 2000. Although all the models mentioned above do calculate temperatures with reasonable accuracy, the large number of inputs makes approach rather cumbersome and hard to use.

As a result, more and more researchers adopt statistical approach to predict pavement temperatures. From 1960 s to 1980 s, due to the limitations of temperature sensors and data recorders, just a few studies measured pavement temperatures and climatic data. In 1968, Southgate and Deen [8] presented two sets of figures for temperature predictions. Pavement temperatures in the top 2 in. are directly dependent upon surface temperatures, whereas temperatures at depths greater than 2 in. are assumed to be a function of the surface temperatures and 5-day mean air temperature history. In 1970, Rumney and Jimenez [9] developed empirical nomographs to predict pavement temperatures at the surface and at a depth of 2 in. These nomographs suggested that measured pavement temperatures have a good relationship with air temperatures and hourly solar radiation in Tucson, Arizona.

By the 1990 s, the Strategic Highway Research Program (SHRP) started. It developed the binder and mixture specifications that closely related to yearly maximum and minimum pavement temperatures. Therefore, the aim of studies was to determine critical pavement temperature extremes with sufficient accuracy for various regions. For this purpose, Bosscher et al. [10], Marshall et al. [11], and Diefenderfer et al. [12] all developed statistical models between measured pavement temperatures and meteorological data. These data are from initial SHRP testing, or Seasonal Monitoring Program (SMP), or other data sets.

More recently, efforts have been made to predict pavement temperatures on a smaller time scale. In 1994, Baltzer et al. [13] proposed the BELLS model to predict pavement temperatures at different time. It is based on a statistical regression analysis using infrared surface temperatures and previous 5-day air temperatures before testing. In 2000, several modifications were made to the BELLS model by Lukanen et al. [14]. The sine functions of BELLS model were replaced by two sine functions to approximate the shape of the warming and cooling trends. Besides, average air temperature the day before testing was a substitute for previous 5-day air temperatures in BELLS model. After that, Park et al. [15] developed a statistical temperature prediction model in 2001. It takes into account temperature gradients due to diurnal heating and cooling cycles and needs fewer parameters than BELLS models. Additionally, Jia et al. [16] determined a regression model for hourly temperature predictions in different regions of China. It

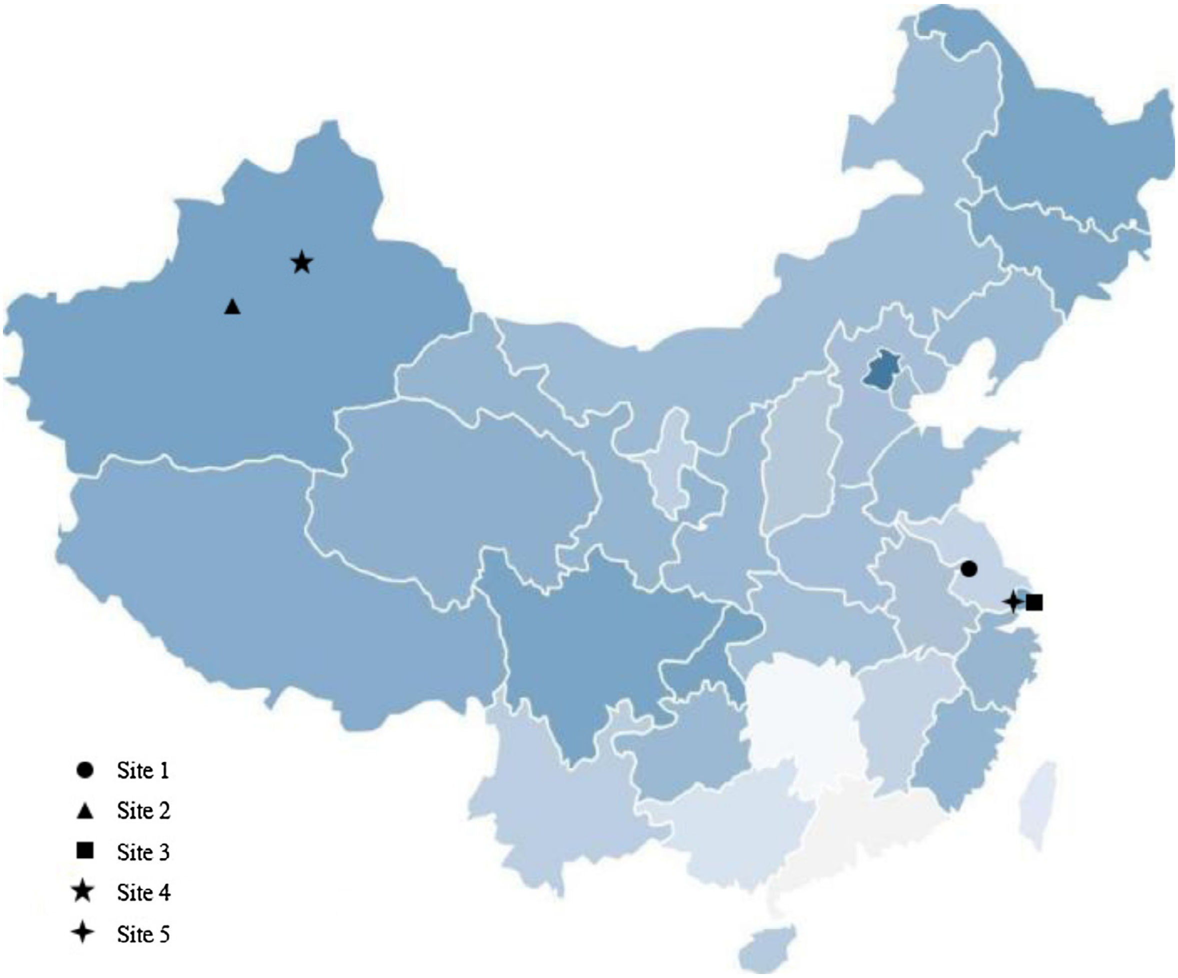

Fig. 1. Location of test sites.

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was found that the pavement temperatures were mostly sensitive to the meteorological condition in the previous 5 h.

Although considerable researches have been devoted to describing temperature profiles within conventional asphalt layers (<30 cm), rather less attention has been paid to temperatures at deeper depths. For example, BELLS models were derived from the LTPP program's database, which provided a range of asphalt thickness ranging from 4.6 cm to 30.5 cm [14]. By the discussion of Hermansson and Knutsson [15], they indicated that Park's model may have limitations in temperature predictions at depths greater than 18 cm. Meanwhile, the measured pavement temperatures in Jia's research were collected from the asphalt layers of which the thickness is less than 20 cm [16]. This suggests that these existing models are applicable in top layers, but may not be so effective for temperature predictions at deeper depth.

However, because of the increasing number of automobile and heavy trucks, as well as the increasing size of modern aircrafts, the asphalt layer is getting thicker and thicker. Asphalt pavements, of which the asphalt thickness is greater than 30 cm, has recently attracted the attention of researchers as a long life pavement structure. The performance of this asphalt pavement is also highly dependent on temperatures. Therefore, concern has grown over the range of temperatures that can be expected in these newer deep asphalt pavements.

This paper describes research performed to develop a statistical model to predict temperatures for asphalt pavements with thick asphalt layer. The model derived from measured pavement temperatures at different depths, which were collected from three asphalt pavement sections. All test sites were also instrumented to record hourly air temperature and hourly solar radiation. Statistical regression was used to develop the model relating cumulative meteorological data to pavement temperatures. By incorporating historical mean monthly air temperatures into the model, the model was validated to be extended for use in other locations.

2. Field instrumentation and data collection

2.1. Data collection system

Before presenting and analyzing the actual collected data, it is necessary to know about the locations and conditions of the test sections. Five asphalt pavement sections were selected in different regions of China, and their general locations are shown in Fig. 1. Other detailed information regarding each of the test sections is contained in Table 1. As shown by the dots in Fig. 1, the geographical distribution of the test sites results in a good representation of three typical environmental conditions in China. Site 1, Site 2 and Site 3 were selected as sub-humid inland, arid inland and costal environments, respectively. Meanwhile, data from Site 4 and Site 5 were used for validation. All of the test sites were positioned away from trees and buildings for direct sunlight.

All test sites were instrumented with PT100 platinum resistance thermo sensors and a data logger to monitor pavement temperatures. Since temperatures may vary considerably throughout the pavement depth, sensors were placed at different depths to record the temperature profile throughout the pavement. Table 1 gives detailed information about the depths of sensors.

To install the sensors at the preselected depth, 10-cm diameter cores were removed from the pavement slabs. For each core, holes of 3-mm diameter and 2-cm depth were drilled along the core's entire length at the selected depths. These holes were used to accommodate the sensors. By hot asphalt, the sensors were secured in holes, leaving the wires along the side of cores and gathering at the top side. Then, all of the cores were placed in the corresponding holes, and the gap between the cores and sides of the holes was filled by hot sand-asphalt mixture. The wires of sensors were then led from the core location to the edge of the slab.

There was a data logger in a wooden cabinet near the edge of the pavement slab. The data logger is a multichannel paperless

Table 1
Detailed information of the test sites.

Site No.	City	Location		Asphalt layer thickness (cm)	Monitoring time	Depths of sensors (cm)
		Lat. (°)	Lng. (°)			
1	Zhenjiang	32	120	45	2016.9–2017.4	2, 6, 6.3, 9.2, 12, 16, 19.9, 23.7, 27, 32, 37, 42
2	Korla	42	86	50	2016.11–2017.4	0.4 (surface), 2, 4, 6, 8, 10, 13, 16, 19, 22, 29, 35.5, 37, 49
3	Shanghai	31	121	15	2002.8–2002.9	0.5 (surface), 1.7, 3.9, 6.1, 7.5, 9.5, 12.6, 14.5
4*	Shanghai	31	121	15	2003.11–2003.12	1.4, 2.5, 4.3, 5.9, 9.8, 11.5, 13.8
5*	Urumchi	88	44	12	2003.3–2003.5	1, 2, 3.5, 8, 10, 11.5

* Data from these sites were used for validation.

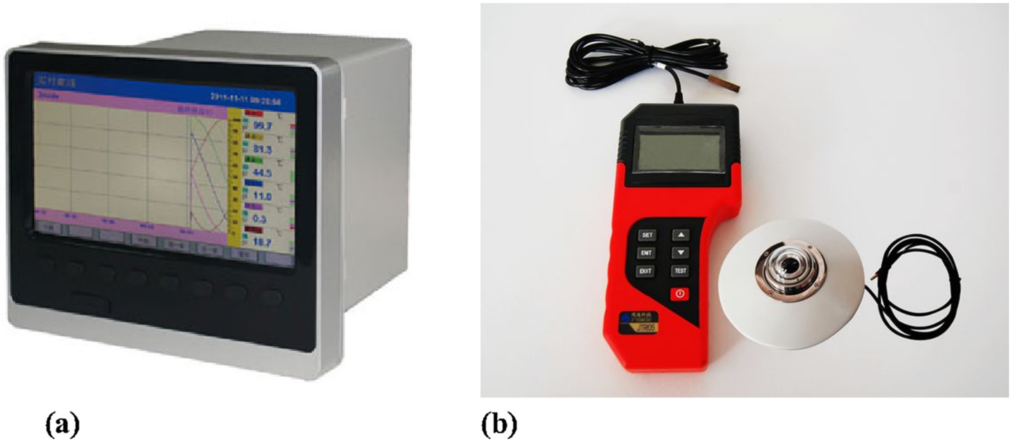

Fig. 2. Equipments used in the research including (*a*) data logger, and (*b*) solar radiation collector.

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recorder, Model NZ8700, made by Nanjing NENGZHAO Technology Co., Ltd. All of the sensors were connected to the data logger, and it recorded the average hourly temperatures at different depths. Fig. 2(a) shows the data logger used in this research.

Additionally, all test sections can provide meteorological monitoring. Solar radiation is known to be the most important factor affecting pavement temperatures, followed by air temperature [1,17]. Therefore, hourly air temperatures and hourly total solar radiation were collected. The measuring device of solar radiation is an Eppley Pyranometer, Model JTR05, made by Beijing JT Technology Co., Ltd. As shown in Fig. 2(b), it consists of a visible black thermopile in a double layer glass bulb and an invisible thermopile in the equipment. The instantaneous solar radiation intensity can be determined by interpreting the potential difference between the two thermopiles. Besides, the device includes a sensor to record the air temperature synchronously. The air temperature sensor should be sheltered to minimize the effects of solar radiation.

2.2. Data collection results

The typical variation of recorded pavement temperatures, air temperatures and solar radiation is shown in Fig. 3. As is evident from the figure, pavement temperatures have a strong correlation with air temperature and solar radiation. As a result, the effects of these two climate factors should be considered in the development of the model.

Fig. 3 also presents that the top asphalt layer commonly experiences greater temperature variation by far. Temperatures of the top layer vary synchronously with air temperatures and solar radiation, and all of them can reach peaks at almost the same time. This characteristic suggests that real-time meteorological conditions may greatly affect temperature cycle of the top layer.

With the increasing depth, the layers follow the same pattern as the top layer except that their temperature variation is much less severe. Additionally, the deeper layers take a longer time to reach peaks depending on their depth. Due to the time required for heat conduction, there is an obvious lag between the pavement temperatures and real-time meteorological conditions. It suggests that temperatures of deeper layers may be affected by the average air temperature and total solar radiation in last few hours, rather than the real-time conditions. The air temperature and solar radiation have cumulative effects on pavement temperatures at various depths.

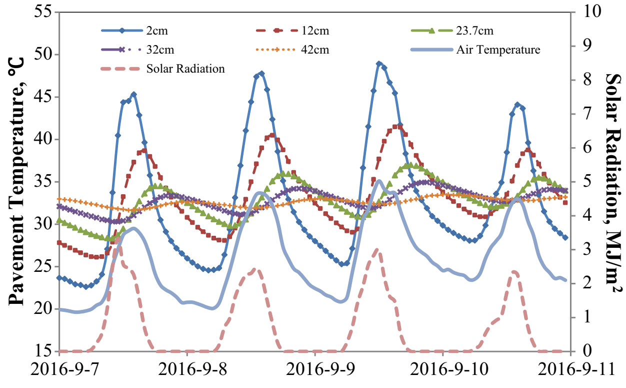

Fig. 3. Pavement temperature, air temperature and solar radiation profile over time.

3. Development of temperature prediction model with collected data

3.1. Relationship between pavement temperatures and meteorological data

To develop the temperature prediction model, the cumulative effects of air temperature and solar radiation should be considered. In light of the above analysis and discussion, temperatures at different depths are affected by air temperatures and solar radiation in different cumulative hours. However, the previous researches commonly defined temperatures at all depths as a function of real-time climatic data and previous mean 1-day or 5-day air temperatures [10,14,16]. This neglect of differential between depths may result in the existing models' inapplicability in temperature predictions at deep depths.

Therefore, a concern at the beginning of this research was to make a concrete analysis of the cumulative effect of air temperature and solar radiation. On this basis, three parameters, N, $\bar{T}_{aN}$ and Q_N were introduced. N is defined as the cumulative time. It is the last few hours preceding the time at which the pavement temperatures are predicted. Based upon the definition of N, $\bar{T}_{aN}$ is the average air temperature calculated during N hours, while Q_N is the total solar radiation calculated over N hours. Additionally, the range of N is from 0 to 24 h. The minimum value indicates the influence of real-time air temperature and solar radiation on specific depth, whereas the maximum value describe that the specific depth is mainly affected by the previous 1-day meteorological conditions.

A correlation analysis was conducted between the pavement temperatures at every depth and $\bar{T}_{aN}$ calculated over different cumulative time ($N = 0, 1, 2 \ldots, 24$). For every specific depth, the maximum correlation coefficient and its corresponding N value were selected from 25 values. The selected N value indicates that $\bar{T}_{aN}$ calculated over this period of time is most correlated to pavement temperatures. Also, temperatures at this specific depth are supposed to be mainly affected by average air temperature in N hours. Similar correlation analyses were performed between temperatures at every depth and Q_N ($N = 0, 1, 2 \ldots, 24$).

Fig. 4 shows the selected N values for different depths. There is a significant difference between the cumulative time (N) of air temperature and that of solar radiation. At the same depth, the former is longer than the latter. This finding clarifies that solar radiation can heat up the pavement faster and has a greater effect on pavement temperatures. Specially, the selected N values of solar radiation are all zeros within the top 10 cm layers, which suggest that the top asphalt layers are mainly influenced by real-time solar radiation.

Meanwhile, as is evident from Fig. 4, segmented linear regression models can define the relationship between depth and

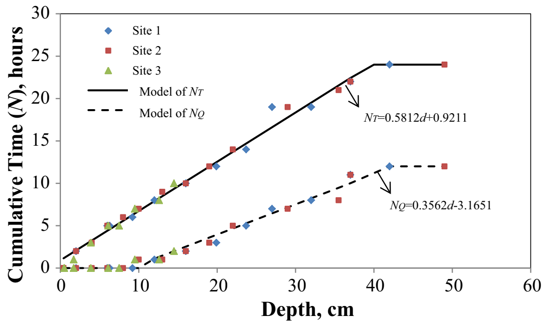

Fig. 4. Relationship between cumulative time (N) and depth.

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selected cumulative time (N) for both air temperature and solar radiation. The relationship can be described as follow:

$$N_T = \begin{cases} 0.5812d + 0.9211 & \text{if } 0 \leqslant d < 40 \\ 24 & \text{if } \quad d \geqslant 40 \end{cases} \tag{1}$$

$$N_Q = \begin{cases} 0 & \text{if } 0 \leqslant d < 10 \\ 0.3562d - 3.1651 & \text{if } 10 \leqslant d < 42 \\ 12 & \text{if } d \geqslant 42 \end{cases} \tag{2}$$

where N_T and N_Q are the selected cumulative time (N) of air temperature and solar radiation, respectively, and d means the depth form pavement surface, cm. The R^2 of these above equation are 0.98 and 0.97, indicating a very good fit. Since N_T and N_Q are in hours, the calculated results by these above equations should be rounded to the nearest whole number.

3.2. Temperature prediction model of specific regions

Based upon the analysis of cumulative effects of meteorological conditions, pavement temperatures at a specific depth can be defined as a function of the average air temperature ($\bar{T}_{aN}$) and total solar radiation (Q_N) calculated over their cumulative time. The following equation describes this relationship.

$$T_d = F \cdot \bar{T}_{aN} + G \cdot Q_N + C \tag{3}$$

where F, G and C are all coefficient functions. They are supposed to be related to depth, due to the decreasing influence of air temperature and solar radiation as the depth increases.

By applying the above model, regression analyses were performed between pavement temperatures at every depth and the corresponding values of $\bar{T}_{aN}$ and Q_N. The values of the regression coefficients (F, G and C) can be obtained for various depths. Fig. 5, for example, shows the regression coefficient changes at Site 1. Because of space limitation, relationships at other sites are not presented.

As is evident from the figure, the values of F, G and C change regularly with depth. It validates that these coefficients can be described as functions of depth. Several forms of depth (d) were considered as parameters, including d, d^2, d^3 and the interaction between these forms of d. As shown in Fig. 5, the best functions to relate depth to coefficients were found to be a linear function for F, a quadratic function for G, and a cubic function for C. Substituting these functions into Eq. (3), yields

$$T_d = (a_1 d + a_2) \cdot \bar{T}_{aN} + (a_3 d^2 + a_4 d + a_5) \cdot Q_N + a_6 d^3 + a_7 d^2 + a_8 d + a_9 \tag{4}$$

where T_d is the pavement temperature at depth d, and a_i ($i = 1, 2, \ldots, 9$) are regression coefficients.

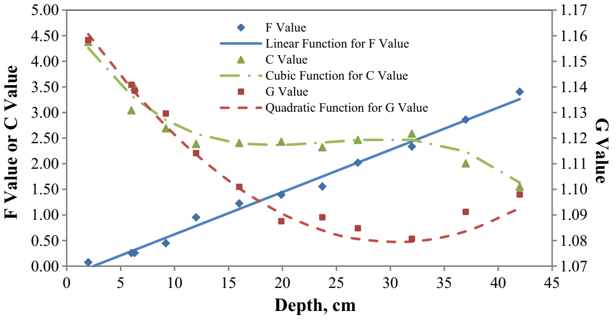

Fig. 5. Relationship between depth and coefficients.

For every site, the above temperature prediction model was developed by a regression analysis using measured temperatures and corresponding values of $\bar{T}_{aN}$ and Q_N at all depth. Table 2 presents the regression result for every site.

Table 2 gives the statistics for the above regressions. There is a high R-squared and an acceptable standard error of estimate for every site, indicating a good fit of the measured pavement temperatures. Besides, the table shows that all coefficients in the models are significant at a 5% level of significance, as given by the t-statistics. All the absolute values of t-statistics are greater than the critical value of $t_{\alpha/2}$, 1.9570.

However, since the three models were developed with the data from their own corresponding site, they were supposed to not have wide ranging applicability in other regions. For example, by using the meteorological data from site 2, the predicted pavement temperatures were calculated by the model developed for site 1. The R^2 value fell to 0.88, indicating inaccuracy of the predictions. This characteristic shows that, to be extended for used in other locations, the model had to be improved by adding new parameters.

3.3. Temperature prediction model of general regions

On basis of the above analysis, the temperature prediction model described as Eq. (4) does not have wide ranging applicability. It indicates that factors other than air temperature and solar radiation can affect pavement temperatures. These factors should be found and incorporated into the model for an improvement in applicability.

According to previous researches, pavements are affected by climate factors with daily cyclic variation, such as air temperature and solar radiation. Moreover, pavements have a sustained heat exchange with the ground beneath the structure [16,18]. The ground has a relatively invariant temperature, which is determined by long-term climate changes. With the increasing depth, the influence of the climate factors diminishes, while the impact of the ground temperature is enhanced. As a result, the pavement temperatures of deep layer are close to the ground temperature and little affected by climatic conditions. This can explain the much less severe temperature variation of deep layers as shown in Fig. 3.

Obviously, the above temperature prediction models neglect the impact of the ground temperature. Two locations with same air temperatures and solar radiation may have different pavement temperatures. But the neglect of the ground temperature may result in the same temperature predictions. The result is unreasonable and indicates the model's inapplicability.

Therefore, ground temperature should be considered in the development of the model. Since it is relatively invariant, historical mean monthly ground temperature can roughly reflect its changing trend. However, in most cases, it is hard to obtain the required data. As a result, parameters reflecting the historical mean monthly ground temperature should be incorporated into the model. Several parameters were compared and it was found that historical mean monthly air temperature (T_m) was a promising option. According to the research by Toy et al. in 1978 [19], historical mean monthly air temperature (T_m) is the indicator of the long-term climate changes and can affect the thermal cycle of the ground temperature. The report presented a simple, linear model for estimating historical mean monthly ground temperature with reasonable accuracy, using only historical mean monthly air temperature for all 12 months during the 10-year-period.

To validate the above relationship, data for Shanghai in the period of 1981–2010 were collected from the database of China Meteorological Administration. Fig. 6 shows the collected data and the relationship between T_m and historical mean monthly ground temperature. As is evident from the figure, these two parameters have a strong correlation.

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Table 2
Regression results for every site.

Coefficients	Site 1		Site 2		Site 3	
	Results	*t*-stat	Results	*t*-stat	Results	*t*-stat
a_1	−0.003	−30.989	−0.003	−41.282	−0.041	−13.375
a_2	1.124	563.438	0.936	605.741	1.508	63.442
a_3	0.003	118.296	0.001	69.672	0.013	6.198
a_4	−0.233	−141.086	−0.123	−90.908	−0.368	−10.190
a_5	3.997	171.700	2.684	120.753	2.760	21.582
a_6	-5.410×10^{-5}	−9.093	4.759×10^{-5}	13.922	−0.010	−16.082
a_7	0.004	9.412	−0.003	−10.741	0.202	15.013
a_8	0.019	2.738	0.058	12.259	0.132	2.728
a_9	0.522	12.977	1.386	58.210	−8.717	−13.506
R-squared	0.953		0.959		0.940	
Std. error of estimate (°C)	1.763		1.693		1.7688	
No. of observations	49,238		38,977		2866	

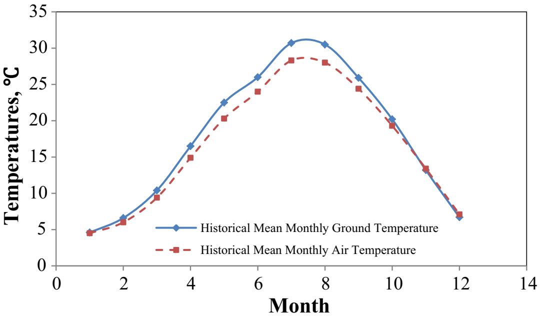

Fig. 6. Historical mean monthly ground temperature and historical mean monthly air temperature profile.

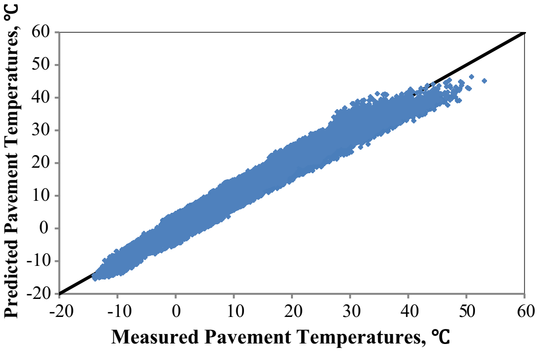

Fig. 7. Measured versus predicted pavement temperatures at sites 1, 2, and 3.

Based upon the above analysis, historical mean monthly air temperature (T_m) can be incorporated to reflect the influence of ground temperature. Since the influence of the ground temperature increases along with depth, the form of $T_m \cdot d$ was also incorporated. The improved model can be described as follows:

$$T_d = (b_1 d + b_2) \cdot \bar{T}_{aN} + (b_3 d^2 + b_4 d + b_5) \cdot Q_N + b_6 d^3 + b_7 d^2 + b_8 d + b_9 + (b_{10} d + b_{11}) \cdot T_m \quad (5)$$

where b_i ($i = 1, 2, \ldots, 11$) are regression coefficients.

A regression analysis was run to develop the coefficients of the improved model, using 91,081 measured temperatures from the three sites in Table 1. Remarkably, the R-squared using 0.972 and the standard error of estimate is 1.702 °C. Besides, all coefficients in this model are significant at a 5% level of significance, as given by the *t*-statistics. All the absolute values of *t*-statistics are greater than the critical value of $t\alpha/2$. The coefficients for the new model are:

$$T_d = (-0.008d + 0.884) \cdot \bar{T}_{aN} + (0.002d^2 - 0.152d + 2.924) \cdot Q_N - 4.745 \times 10^{-5} d^3 + 0.004d^2 - 0.007d + 1.454 + (0.006d + 0.203) \cdot T_m \quad (6)$$

where $\bar{T}_{aN}$ (°C) is average air temperature during the last N_T hours, while Q_N (MJ/m^2) is the total solar radiation calculated over the last N_Q hour. N_T and N_Q can be obtained from Eqs. (1) and (2), respectively. Since N_T and are in hours, the calculated results by these above equations should be rounded to the nearest whole number.

Fig. 7 compares the measured temperature with the predicted temperature for Sites 1, 2 and 3. Results from the model overlap the 1:1 or 45-degree line, indicating a very good fit.

4. Validation and comparison of prediction models

4.1. Validation of the improved model

As shown in Table 1, two additional test sites were available, and have been used to validate the improved model described as Eq. (6). The data for the site in Shanghai covers a period from November through December, while the new data set for Urumchi is from a monitoring period from March to May.

With the measured meteorological data from the two sites, the pavement temperatures were predicted by the improved model. The pavement temperature predictions were then plotted against the measured temperatures. The relationship is presented in Fig. 8, and it can indicate how well the model predicts the temperature variations. Since the results from the improved model again overlap the 1:1 or 45-degree line, the improved model has been validated to have wide ranging applicability.

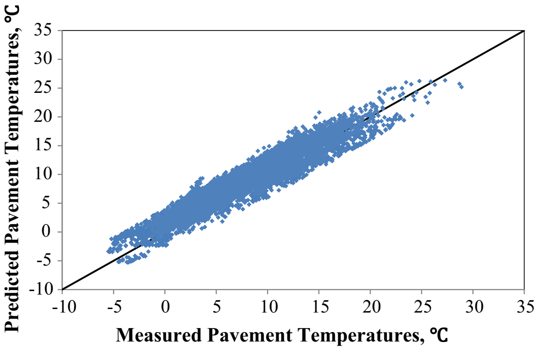

Fig. 8. Measured versus predicted pavement temperatures at sites 4 and 5.

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4.2. Comparison with other existing models

Since there was no shading effect on test sites, the existing BELLS 2 model [14] and the temperature prediction model developed by Park et al. [15] are compared with the improved model in this research. These two models are shown as the follows:

With the meteorological data and surface temperatures from Site 2, the pavement temperatures were calculated by applying these models. Then, the predicted temperatures were subtracted from the measured values to produce a set of residuals. Fig. 9, for example, shows the cumulative frequency of the absolute error of three depths, 6 cm, 16 cm and 35.5 cm. Because of space limitation, calculation results of other depths are not presented.

As is evident from Fig. 9, BELLS 2 model and Park's model are not so effective in predicting temperatures at deep depth. The accuracy of these two models decreases greatly as the depth increases. But in general, BELLS 2 model is better than Park's Model, except for the temperature predictions of top layers. On the contrary, the model developed in this research has rather accuracy for temperature predictions at deep depth. It will be effective when applied to asphalt pavements with thick asphalt layer.

The possible reasons for this result were also discussed. Firstly, the data for other models were collected from the asphalt pavements of which asphalt thickness is less than 30 cm. For example, BELLS models were derived from the LTPP program's database, which provided a range of asphalt thickness ranging from 4.6 cm to 30.5 cm [14]. The asphalt thickness in Park's research was less than 25 cm [15]. Secondly, temperatures at different depths are affected by air temperature and solar radiation in different cumulative hours. But the previous researches neglected the differential between depths and commonly defined temperatures at all depths as a function of real-time climatic data and previous mean 1-day or 5-day air temperatures [14].This cannot explain the increasing lag between the pavement temperatures and real-time meteorological conditions as the depth increases. Moreover, the sustained heat exchange between pavements and the ground beneath the structure was not considered in previous research. As a result, the much less severe temperature variation of deep layers cannot be described by existing models.

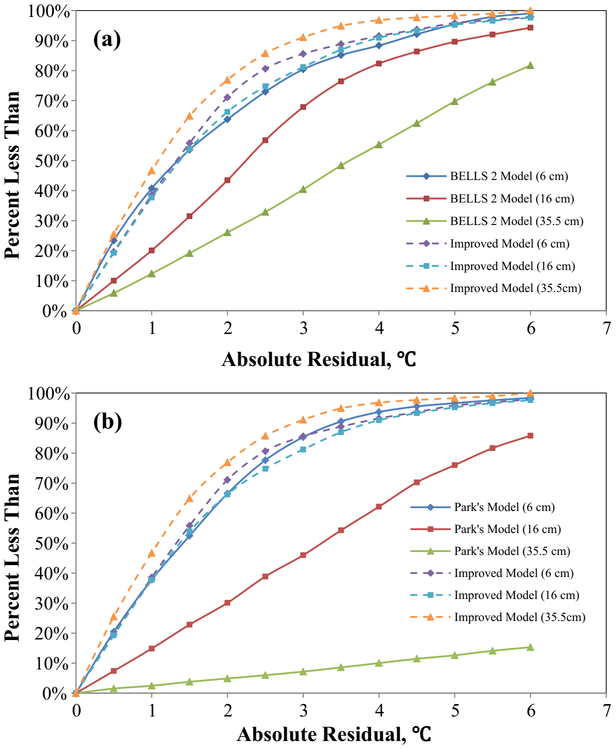

Fig. 9. Comparisons of prediction errors between (*a*) BELLS 2 model and improved model, and (*b*) Park's model and improved model.

5. Conclusions

A practical and reasonably accurate temperature prediction model was developed for asphalt pavements with thick asphalt layer. This statistical model developed focuses on three main factors, including air temperature, solar radiation and the ground temperature.

Average air temperature ($\bar{T}_{aN}$) and total solar radiation (Q_N) in different cumulative time (N) can largely affect temperatures at different depths. This cumulative time (N) was determined as the last few hours preceding the time at which the pavement temperatures are predicted. It was found that the cumulative time was related to depth.

Additionally, the ground temperature has a great impact on pavement temperatures. It can affect the heat exchange between the pavement and the ground beneath the structure. Historical mean monthly air temperature was selected as the indicator of the ground temperature. It was incorporated into the model for an improvement in applicability.

By applying the developed model, the predicted temperatures at various depths were in good agreement with the measured values. Meanwhile, the model was validated with data from additional test sites. The validation results confirmed that the model could be extended to use in other climatic and geographic regions. Furthermore, the comparisons with other existing models show that the developed model is more effective when applied to asphalt pavements with thick asphalt layer, promising the model's potential use.

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