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Temperature Prediction Model for Flexible Pavements in Taiwan

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ABSTRACT: In this study, a large amount of temperature measurements were obtained from a test site incorporating 3 typical pavement sections to establish a pavement temperature prediction model for freeways in Taiwan. Using thermocouples embedded at 20-mm distance in depth, temperature profiles of 3 different pavement structures were determined for 24-hr periods covering seasonal variations. Predictions made by BELLS model revealed that, at pavement temperature higher than 40℃, the model tends to underestimate pavement temperatures. Considering the climatic characteristics in Taiwan, the air temperature at testing time is used in the model. Also, a single sine function on a 24-hr clock system is used to simplify the predicting equation. The proposed pavement temperature model shows a good correlation between measured and predicted temperatures and has a coefficient of determination greater than 0.93. The pavement temperature prediction model is judged to be easier to use than the BELLS model, due to the fact that temperature data for the previous day are no longer needed, and will be used for temperature adjustment of future falling weight deflectometer data in Taiwan.

INTRODUCTION

In the assessment of pavement capacity, the falling weight deflectometer (FWD) has been used extensively. Since the stiffness of asphalt concrete (AC) is greatly influenced by ambient and pavement temperatures, it is critical for the use of FWD to be able to determine an effective temperature of the asphalt layer. As the temperature of the asphalt concrete increases, its stiffness decreases that may lead to rut occurring on the asphalt pavement from wheel loads. A decrease in asphalt concrete stiffness results in lower structural capacity to support vehicle loads. In routine FWD data collection, in addition to the deflections of pavement obtained by FWD, the in situ temperature of asphalt concrete needs to be determined non-invasively. In order to interpret FWD data appropriately, it is essential to estimate the pavement temperature accurately using information readily collectable at the time of testing.

The 1986 AASHTO Guide for Design of Pavement Structures (AASHTO, 1986) presented a temperature correction protocol for FWD deflections. This procedure requires the use of the average air temperature for the previous 5 days to predict pavement temperatures at selected depths. However, this procedure does not take into account temperature gradient effects due to diurnal heating and cooling cycles, which have a significant effect on the effective pavement temperature and its relationship with the AC modulus and the surface deflection (Lukanen et al., 2000). Therefore, there is an urgent need to develop new temperature models for predicting pavement temperatures in a convenient manner.

In the past, Park et al. (2001) developed a pavement temperature prediction model in Michigan. Unlike the 1986 AASHTO method, the model no longer requires temperatures for the previous 5 days but takes into account temperature gradients due to diurnal heating and cooling cycles. Lukanen et al. (2000) developed new temperature prediction and deflection correction procedures using data collected from the long-term pavement performance (LTPP) study. This temperature prediction model of LTPP is BELLS3 that can be used generally to predict effective temperature of AC pavement in the US. It provides a convenient temperature measurement procedure to obtain effective temperature for AC pavements. However, the BELLS3 model was developed based on daytime pavement temperature data, and it's applicability to nighttime remains unclear. Moreover, this model is valid only for AC thickness of 45 to 305 mm (1.8 to 12 in.), based on the LTPP program's database. Due to the very heavy traffic on freeways in Taiwan, there is a need to conduct routine FWD testing in the nighttime so as to minimize the impact of blocking traffic for testing. In addition, thickness of asphalt layers for freeways in Taiwan ranges from 320 to 415 mm, which is much thicker than typical pavements in other countries. Hence, the main objective of this study is to establish a pavement temperature prediction model applicable to the freeway pavements in Taiwan, such that FWD data can be used effectively for pavement structural evaluation.

EXPERIMENTAL PROGRAM

In this study, a test site incorporating 3 pavement sections representing typical freeway pavement structure in Taiwan was constructed. All pavement sections were instrumented with temperature sensors connected to portable data logger. The pavement cross-section information is summarized in Table 1. It is noted that freeway pavements in Taiwan are comprised of aggregate base, bituminous treated base (BTB), and asphalt concrete with a 15-mm open graded seal course on top.

Since the total thickness of asphalt layers ranges from 315 mm to 415 mm, it was decided to install thermocouples in the lower portion of asphalt layers and use temperature probe in the upper portion. In the lower portion, thermocouples were embedded at the interface of AC and BTB, and at 20, 30, 40 mm down to the BTB layer, and 10, 20 mm up from the bottom of AC. In the upper portion, to profile the temperature gradient for AC, test holes were drilled approximately 0.5 cm in diameter and 20, 40, 60, 80, 100 mm in depth. A digital thermocouple probe was inserted in each hole for measurement. The air temperature and pavement surface temperature were obtained using an infrared temperature gun. Fig. 1 shows the schematic of temperature measurement layout. All temperature data were recorded at 10-minute intervals within a day. Temperature data collected in this study range from 12℃~37℃ for air temperature and 15℃~60℃ for pavement surface temperature, which cover the typical temperatures for the subtropical climate in Taiwan.

Table 1. Typical pavement cross-sections of freeways in Taiwan (mm)

Freeway number	Thickness			Total thickness of asphalt layer
	AC	BTB	Aggregate base	
Freeway 1	165	250	350	415
Freeway 3	115	200	250	315
Freeway 6	180	150	300	330

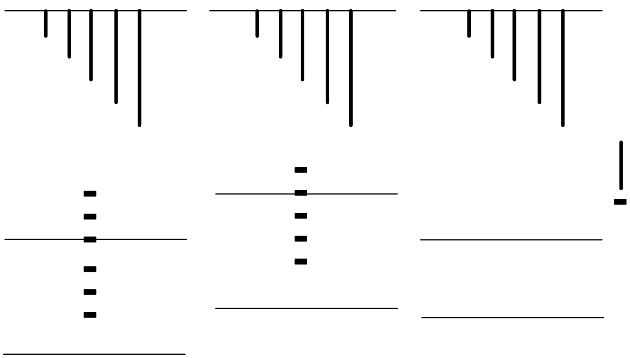

FIG. 1 Schematic of pavement cross-sections and temperature measurement set-up (mm).

BELLS3 TEMPERATURE PREDICTION MODEL

BELLS3 temperature prediction model was developed with data from the Long-Term Pavement Performance Project's Seasonal Monitoring Program. Named BELLS after the first letters of the author's last names. BELLS3 model predicted the effective temperature of AC layer by using the infrared surface temperature reading, the average of previous day's high and low air temperatures, the time of day, and the AC layer thickness. BELLS3 model was established for routine FWD testing. The BELLS3 model for routine testing is as below:

$$T_d = 0.95 + 0.892IR + (\log d - 1.25)\left[1.83\sin(hr_{18} - 15.5) - 0.448IR + 0.621T_{avg}\right] + 0.042IR\sin(hr_{18} - 13.5) \quad (1)$$

where T_d is pavement temperature at layer mid-depth (℃), IR is infrared surface temperature (℃), T_{avg} is the average of previous day's high and low air temperatures on the day before testing (℃), and d is layer mid-depth (mm). $\sin(hr_{18} - 15.5)$ and $\sin(hr_{18} - 13.5)$ are sine function times with 18 hour period.

RESULTS OF AC TEMPERATURE MEASUREMENT

Pavement temperature data obtained from Freeway 3 on May 14, 2008, are shown in Fig. 2. It can be observed that, in the daytime, the highest pavement temperature occurred at the surface, while that in the nighttime (after 17:00) occurred in the BTB layer. Pavement temperature fluctuates more significantly in the daytime than in the night. The highest air temperature of 34℃ occurred at between 12:00 and 13:00, and the highest pavement surface temperature occurred at about the same but with a much higher value of 55℃. But as the depth increases, the time that the highest temperature occurs gets later. The variations in temperature at both pavement surface and mid-depth are found to be much higher than that of the BTB layer. Actually, the results indicate that the greatest temperature difference within a day at pavement surface, mid-depth, and BTB layer was found to be 25, 19, and 7℃, respectively. It was found that the maximum greatest temperature difference observed in July at the 3 locations were 30, 21, and 11℃, respectively. In summary, temperature variation in BTB layer is less notable, while AC is the principal layer to be considered for temperature effects in pavement structural analysis.

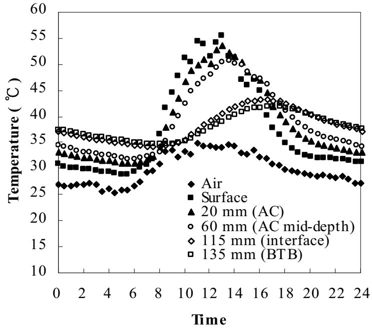

FIG. 2 Variations of temperature at different depth in a 24-hr period (Freeway 3 pavement section).

TAIWAN TEMPERATURE DATA WITH BELLS3 MODEL IN TEMPERATURE PREDICTION

Temperature data at the test site were collected continuously for a 12-month period, covering the full range of temperatures to be experienced in Taiwan. These data were fed to the BELLS3 model and evaluated for applicability of BELLS3 model to pavements in Taiwan. The relationships between the measured and predicted AC pavement temperatures are shown in Fig. 3. Regression analysis on the 8047 data points against the 45° straight line gives a coefficient of determination (R^2) of 0.88, which is considered acceptable. However, it is also noted in Fig. 3 that the predictions over the high temperature range (≧ 40℃) are relatively poor, and a tendency of under-prediction can be observed in this temperature range. It is judged that the BELLS3 model was developed using database obtained from north America, which is rarely exposed to a temperature regime of this high. Fitting the local temperature data of Taiwan to BELLS3 may generate under-predicted temperature of AC layer. Therefore, it was decided to develop a new pavement temperature prediction model that is suitable for local temperature situations in Taiwan.

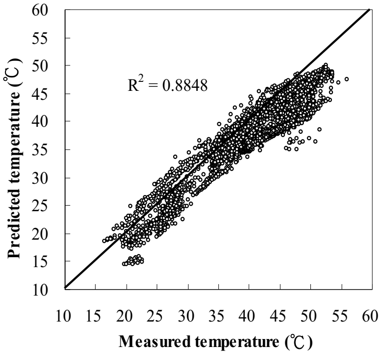

FIG. 3 Measured versus predicted pavement temperature using BELLS3 model.

PROPOSED TEMPERATURE PREDICTION MODEL

Published temperature models indicated that the input variables for a prediction model should be easily obtainable in the field during FWD testing and adequate to predict subsurface temperature. Hence, pavement depth, time of testing, air temperature, and pavement surface temperature were selected as input variables for proposed pavement temperature prediction model. Time variable is an important factor in describing temperature variation of pavements within day and night time. Fig. 4 shows the temperature variations with time in a 24-hour period. Eight 24-hour temperature variations obtained from different months in a year show closeness in their undulation, when they are transferred to sine function value between 1 and -1. This reveals that the behavior of temperature variations can be described by one representing sine curve. Fig. 5 shows the representing sine curve for pavement temperature variation with time. The equation for the sine curve is $f(t) = \sin(-6.3252t + 5.6989)$, where t is time when the AC surface temperature was measured, e.g., 1:30 p.m. = 13.5/24 = 0.5625. The time equation was used as a parameter in the development of Taiwan temperature prediction model.

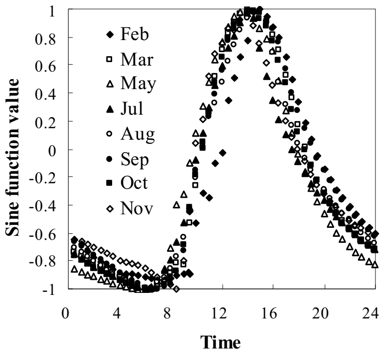

FIG. 4 Sine function curves at different months.

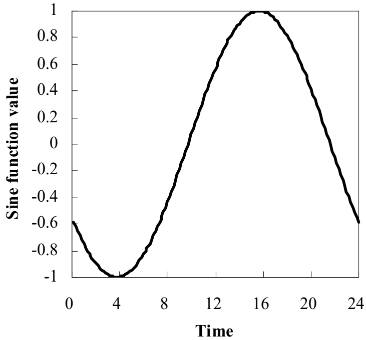

FIG. 5 The representative sine function curve of sin (-6.3252*t* + 5.6989).

Pearson correlation analyses showed that the correlation coefficient of the selected input variables and the mid-depth temperature were all higher than 0.8. Hence, all these variables are used in the proposed model. Using 8047 temperature observations from those sites summarized in Table 1, the following model is proposed to be used for prediction of pavement temperature in Taiwan.

$$
\begin{aligned}
T_d = {} & f(t)\left[21.8450 + T_{air}(-1.5547 + 0.0223IR + 0.6433\log(d))\right] \\
& + \log(d)\left[IR(-0.8662 - 0.0109T_{air} - 0.4155f(t)) + (-18.5074 + 1.9254T_{air})\right] \\
& - 2.0030T_{air} + 2.4840IR + 10.2546 \qquad (2)
\end{aligned}
$$

where: T_d = pavement temperature at depth d in AC layer (℃),
T_{air} = air temperature when testing on t time (℃),
IR = infrared surface temperature (℃),
d = AC layer depth (mm), and
$f(t)$ = sine function time with 24 hours system.

Fig. 6 shows the relationships between the measured and predicted pavement temperature using the proposed model. When fitted to the 45° straight line, a coefficient of determination of 0.93 was found, which exhibits an improvement over that of the BELLS model. To validate the effectiveness of the proposed temperature prediction model, a total of 278 extra temperature observations were collected from other sections on Freeway 1 and 3. The measured vs. predicted mid-depth temperature relationships are shown in Fig. 7. The result shows these additional data have an R^2 value of 0.98, indicating a good fit.

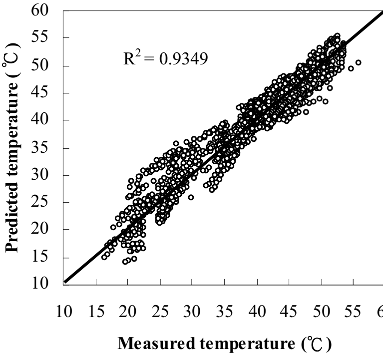

FIG. 6 Measured versus predicted temperature using the proposed model.

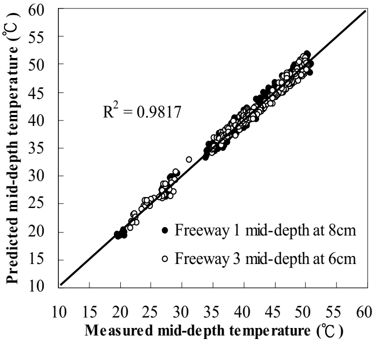

FIG. 7 Validation of the proposed model using field temperature data obtained from Freeway 1 and 3.

CONCLUSIONS

Based on a large amount of pavement temperature data obtained from a test site covering 3 typical freeway pavement sections, a pavement temperature prediction model is proposed for Taiwan's freeways. In this model, the air temperature at the time of testing, rather than the average air temperature in the day before testing, is used for predicting pavement temperature. In response to the necessity of conducting FWD tests in the nighttime, a single sine function time variable on a 24-hr clock system is adopted in the proposed temperature prediction model. With the climatic characteristics in Taiwan, the use of air temperature at the time of testing and a single sine function of time on a 24-hr clock system provide not only convenience during testing but also improved accuracy in predicting pavement temperatures for freeways in Taiwan.

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Parallel Direct Solver for Linear Systems Resulting from Constitutive Modeling of Pavement

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ABSTRACT: Reliable and realistic computer simulations of pavement behavior are important for improving the design process of pavement materials. Most simulations involve 3D modeling and therefore large finite element meshes. Hence, the systems that result from discretization involve many degrees of freedom and are difficult to solve. Constitutive modeling is an expensive process when mesh sizes increase. The introduction of a parallel direct solver reduces both computation time and the number of iterations to solve the system and yielding more realistic simulations.

INTRODUCTION

Within the field of structural mechanics, pavement engineering plays an important role in understanding and modeling the effects on heavy duty materials like asphalt and concrete when exposed to different kind of forces. Not only the appliance of force but also weather conditions and aging have to be taken into account. It is of crucial importance that the industry is able to predict how materials react to various circumstances under different time spans. Understanding these effects may result in more careful engineering of these materials, which may replace the current trial and error design process. Moreover CAD methods will be more time and -cost efficient compared to laboratory tests.

COMPUTATIONAL FRAMEWORK

A framework for calculating material response, stresses and strains has been provided in (Scarpas 2004) and (Kringos 2007). In this framework both small and large strains are considered. The balance of forces and conservation of energy yields the virtual work