Modeling Temperature and Resilient Modulus of Asphalt Pavements for Tropic Zones of Iran

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Abstract: In the present study, a temperature model and a resilient modulus model of asphalt pavements are developed for tropical zones of Iran. Through the investigation of asphalt mixtures reactions to temperature increase, a mathematical model is developed. This model makes the prediction of asphalt course temperature in various depths (with different parameters) possible. Twenty-four samples were made with different mix designs and located in settings that a real pavement experiences in its service life in tropical zones. Four variables that were considered for making samples are bitumen percent, bitumen type, level of compaction and gradation of aggregates. By means of gathering the samples' temperatures in three different depths and corresponding air temperatures for nine months a data base was made by which the model was developed. Using indirect tensile tests in three different temperatures, the resilient modulus of samples similar to the samples of study were measured to develop the model. The results show that there is a significant correlation between three out of four variables of the study and predicted temperatures. The variables are bitumen percent, bitumen type and level of compaction. Moreover, it was found that, besides temperature, bitumen type is the only variable that appears in the resilient modulus model.

Keywords: Asphalt pavement, pavement's temperature, prediction model, resilient modulus

INTRODUCTION

Increase in the temperature of asphalt layer is one of the major factors of failure in asphalt pavements in tropic zones. In these areas, high air temperature and severe radiation of solar ray cause increase in asphalt layer temperature. In this condition, loads made by wheels of heavy vehicles produce vertical strains caused by compression force and would cause rutting in the wheel path and bleeding in the asphalt surface. Moreover, skid resistance of asphalt pavement surface decreases with increase in temperature and this will reduce the safety of road (Bazlamit, 2005). By considering the asphalt mix components exposed to increasing temperature, detecting the effective factors in increasing asphalt layer's temperature and finally, choosing the major factors we could develop a mathematical model that predicts the asphalt temperature in various depths by different given parameters.

Asphalt cement in asphalt mixtures has complicated viscoelastic and thermo-plastic behavior that depends on loading duration and temperature. It is not possible to consider an elastic modulus, like cement concretes mixes that is determined by compressive strength test, for asphalt concretes mixes.

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Other moduli like Resilient modulus (M_r), Dynamic modulus (|E*|) and Stiffness modulus (S_r) are developed for asphalt concrete, considering viscoelastic, viscoplastic and thermo-plastic behavior of mixture. The resilient modulus is a basic input for most of the mechanistic designs and is an objective for the mechanistic evaluation procedures. The determination of the resilient modulus requires an expensive setup of testing equipment and great expertise on the part of practitioners that might not be readily available for most of the field condition. The development of a regression formula that can be used to correlate the resilient properties of local asphalt mixes to basic material properties, with acceptable accuracy, is of great benefit.

Research on temperature distribution in asphalt pavements has been carried out in many different countries and climatic areas, such as United States, Australia, Saudi Arabia and South Africa (Al-Albdi, Wahhab, 1994, 2001; Nazarian and Alvarado, 2006; Chiasson et al., 2008). In some of these researches the models of temperature prediction of pavement have been developed by considering, similar parameters. Al-Albdi, Wahhab and Balghurain (1994) conducted a research in which he measured the pavement temperature in a land and a coastal area in Saudi Arabia. In this research for considering the effect of pavement layer’s thickness on distribution of the temperature in depth, different thicknesses were studied. The result of the research, in addition to providing a profile of temperature distribution in pavement and a profile of annual changes in the pavement temperature, was a temperature prediction model based on the air temperature and depth. In the same line of argumentation, in 2001, prediction model of resilient modulus was developed. In the model, in addition to the temperature, the softening point and the surface area of aggregates were considered as independent variables (Al-Albdi, Wahhab, 2001).

In Strategic Highway Research Program (SHRP) and especially in Long-Term Pavement Performance project, BELLS model (first letters of researchers’ names) was developed for predicting the pavement’s temperature. In this model, pavements temperature in a given depth is predictable through parameters such as temperature of the asphalt surface, depth, mean temperature of the last five days and time of the day (Marshale et al., 2001). In 1994 after wider research and use of the data from more weather stations the model was slightly corrected and was presented by the name of BELLS2. In the corrected model, the mean temperature of the earlier day was used instead of the mean temperature of earlier 5 days. Time of day was also defined by discrete ranges and determined relations (Lukinen et al., 2000). Using a two-dimensional, transient finite-difference approach, in 2005, Yavuzturk assessed the temperature fluctuations in asphalt pavements (Yavuzturk et al., 2005).

Furthermore as a result of a research in Virginia two models was developed and validated for predicting the daily maximum and minimum pavement temperatures using data from the Virginia Smart Road and two LTPP SMP test sites. Models were developed that incorporate the depth within the pavement, calculated daily solar radiation and daily maximum or minimum ambient temperature (Deifenderfer et al., 2006).

**MATERIALS AND METHODS**

In this study after make asphalt mix specimens with different specifications and mix designs, they are located in condition that a real pavement experiences in its life time. Temperature in three different depth and surface of samples are registered with correspond air temperature. Gathered data of temperature are used to develop the temperature model.

Then in the laboratory another 24 samples with same mix design were subjected to indirect tensile test with repeated load and the resilient modulus values are registered. Tests are conducted under temperature control conditions in three temperatures of 5, 25 and 40°C for each sample. By collecting and analyzing output data, finally, a regression model is also developed for predicting the value of resilient modulus using temperature and mix properties.
Temperature Registration

In mathematical modeling process it is tried to consider all factors that may affect values of the dependent parameter. Variable parameters in temperature modeling for asphalt mix are considered in three categories, including aggregates, bitumen and asphalt mixture. Because of the common use of No. 3 and 5 gradations (code 101) of asphalt pavement, in tropic zones of Iran, midpoints of these gradations are chosen for making samples (Table 1).

According to the code, two bitumen types (i.e., 40/50 and 60/70) are recommended for light and heavy traffic volume in tropic zones. These two types of bitumen are chosen for making samples. In mix-category bitumen content and level of compaction are considered as variables of the study. 4, 4.5 and 5% are three bitumen contents that are obtained from Marshall Test for considering optimum bitumen content. Two levels of compaction including medium and high in regard to the number of blows (sample making process in Marshall Test method) are chosen. Seventy five and fifty blows to each sides of sample are considered for high and medium levels of compaction, respectively. Based on what mentioned above, 24 samples, in Marshal Sample size, are made in laboratory and thermometers are installed in them for temperature registering purposes.

Mercury thermometers are used for measuring surface temperature and 2, 4 and 6 cm depths temperature of samples. Mercurial part of the thermometer is covered by a plastic material, made of mixed fine sand and bitumen and is located in drilled holes in samples. To prevent air flow in the hole, the top of each hole is sealed by the plastic material (Fig. 1). A 2 cm depth groove is made on the surface to install the surface thermometer. The thermometer is made firm horizontally in the groove with a cohesive material.

After installation of thermometers, all samples are located in an open area that is exposed to the sun and hine in all daytime. A place in Shahid Chamran University of Ahwaz campus is utilized for
Fig. 2: Plan of setting of samples in open area

Fig. 3: Typical of mean month temperature plot

The spaces between samples were filled with asphalt mix to make a uniform condition like real pavement (Fig. 2). Mix design of filling mix is near to samples'. Air temperature is also measured by a mercury bulb thermometer that is installed in 1.5 m height. The registration of the temperature is done at 8:00, 10:00, 12:00, 14:00, 16:00 and 18:00 on five days of a week (Saturday to Wednesday) during 9 months (January to September) of 2006.

Because of the large amount of data, monthly means are used in the modeling process. Figure 3 presents the graph of monthly means for the samples.

In the process of making temperature measurement samples, variable parameters are bitumen type, bitumen content, aggregate gradation and level of compaction. The comparison of the temperature for the samples in which these parameters change and plotting the comparative graphs are important in modeling process. The frequency charts with $5^\circ C$ of centigrade range are drawn for samples that are similar concerning one parameter. These charts are drawn for maximum temperature of samples and the frequency percentage is calculated in 9 month temperature measurements for each range. Results
Table 2: Stepwise regression coefficients for temperature data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unstandardized coefficients</th>
<th>Standardized coefficients (Beta)</th>
<th>t</th>
<th>Sig.</th>
</tr>
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<tr>
<td></td>
<td>B</td>
<td>Error</td>
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<tr>
<td>Constant</td>
<td>0.34</td>
<td>0.50</td>
<td>-0.67</td>
<td>0.50</td>
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<td>Surface</td>
<td>0.94</td>
<td>0.00</td>
<td>0.96</td>
<td>293.74</td>
</tr>
<tr>
<td>Time</td>
<td>0.94</td>
<td>0.04</td>
<td>0.06</td>
<td>21.28</td>
</tr>
<tr>
<td>Log d</td>
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<td>0.19</td>
<td>-0.04</td>
<td>-16.10</td>
</tr>
<tr>
<td>Compaction</td>
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<td>0.00</td>
<td>-0.02</td>
<td>-8.79</td>
</tr>
<tr>
<td>Air temperature</td>
<td>0.32</td>
<td>0.09</td>
<td>0.01</td>
<td>3.72</td>
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<tr>
<td>Bitumen content</td>
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<td>0.07</td>
<td>0.01</td>
<td>2.37</td>
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<tr>
<td>Bitumen type</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

show that in all samples, about 50% of Jan to Sep time in one year, the maximum temperature is up to 55°C. These percentages are 48.1 and 50.8 for 60/70 and 40/50 PG samples, respectively. For 4, 4,5 and 5% of bitumen content the percentages are 52.9, 51.5 and 50, respectively. The percentage of No.3 gradation samples (53%) is more than that of No.5 gradation samples (50%). Similar values are obtained in the comparison between high and medium level of compaction.

**Temperature Model**

SPSS package is utilized for statistical analysis of the present study. For the purpose of modeling, stepwise linear regression is used. The regression coefficients and significance level for temperature data are presented in Table 2.

The developed temperature model is shown in Eq. 1. (Correlation factor ($R^2$) for the model is 0.947).

$$T = 0.94 \text{Sur} + 0.94 \sin(2\pi \frac{t}{24}) - 2.99 \log(d) - 0.02 \text{comp} + 0.02 \text{Air} + 0.32 \text{BP} + 0.17 \text{BT} - 0.34$$ (1)

Where:

$T$ = Asphalt temperature (°C)

Air = Air temperature (°C)

Sur = Surface temperature (°C)

t = Time of day in 24-hour system

$d$ = Depth (cm)

comp = Level of compaction (number of blows)

BP = Bitumen content

BT = Bitumen type (1 for 40/50 and 2 for 60/70)

Plots of distribution of residuals and distribution of expected cumulative probabilities versus observed cumulative probabilities are presented in Fig. 4 and 5. Distribution of residuals is close to Normal distribution and distribution of expected cumulative probabilities versus observed cumulative probabilities is close to 1-slope line.

**Determination of Resilient Modulus**

Indirect tensile test for determination of resilient modulus is performed on 24 samples with the above-mentioned properties. In this test, repeated dynamic load with haversine or other suitable waveform is applied in the direction of diametric plan of sample; and then, the horizontal deformation (or vertical deformation) is measured. Instantaneous resilient modulus is calculated by the use of recoverable horizontal deformation that occurs in unloading time (ASTM D 4123-82).
Fig. 4: Residuals distribution plot for temperature model

Fig. 5: Observed vs. Expected cumulative probabilities for temperature model

\[ a = \text{Duration of loading during one cycle} \]
\[ b = \text{Recovery time} \]
\[ c = \text{Cycle time} \]
\[ \Delta V_t = \text{Instantaneous recoverable vertical deformation} \]
\[ \Delta V_T = \text{Total recoverable vertical deformation} \]
\[ \Delta H_t = \text{Instantaneous recoverable horizontal deformation} \]

Total resilient modulus is calculated by use of instantaneous horizontal deformation and the rest-time-dependent deformation in one cycle (ASTM D 4123-82). Eq. 2

\[ M_k = \frac{P(\mu + 0.2734)}{t\Delta H_t} \]  

Poisson’s ratio (\(\mu\)) is about 0.35 for asphalt materials. \(t\) refers to the thickness of asphalt mix sample. To consider the temperature as a variable parameter in the model, the test is performed in three temperatures including 5, 25 and 40\(^\circ\)C on each sample. Figures 7-10 shows the changes of resilient modulus with the change of temperature in regards to the changes of the given parameters of the mix design in the present study. In these figures, values of resilient modulus are the mean values of resilient modulus for samples that are similar in one parameter. For example 3104 is the average value of the resilient modulus for specimens that made by 60/70 penetration bitumen.

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Fig. 6: Load and deformations by time-plots for indirect tensile test with repeated load (ASTM D 4123-82)

Fig. 7: Resilient modulus changes by temperature for two binder types

One of the interpretations of the figures is that resilient modulus values for 40/50 bitumen samples are more than 60/70 bitumen samples, for No. 3 gradation more than No. 5 and for high level of compaction is more than medium level of compaction. These differences are more in 5°C temperature.

Resilient Modulus Model

SPSS software and stepwise linear regression are used for modeling of resilient modulus too. Predictor parameters are temperature, bitumen content and bitumen type, gradation of aggregates and level of compaction. Coefficients of stepwise regression are presented in Table 3.

The Equation that can be induced from the results is as follows (i.e., Eq. 3). Correlation factor (R²) for the model is 0.558.
Fig. 8: Resilient modulus changes by temperature for different bitumen content

Fig. 9: Resilient modulus changes by temperature for two gradations

Fig. 10: Resilient modulus changes by temperature for two levels of compaction

\[ M_R = -106.1T - 727.2BT + 5730 \]  \hspace{1cm} (3)
Table 3: Stepwise regression coefficients for resilient modulus data

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unstandardized coefficients</th>
<th>Standardized coefficients</th>
</tr>
</thead>
<tbody>
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<td>B</td>
<td>Standard error</td>
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<td>Constant</td>
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<td>328.3</td>
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<tr>
<td>Temp.</td>
<td>-106.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Constant</td>
<td>5729.8</td>
<td>599.9</td>
</tr>
<tr>
<td>Temp.</td>
<td>-106.1</td>
<td>11.8</td>
</tr>
<tr>
<td>Binder type</td>
<td>-727.2</td>
<td>336.9</td>
</tr>
</tbody>
</table>

Where:

\[ M_R = \text{Resilient modulus (MPa)} \]
\[ M_k = \text{Temperature (°C)} \]
\[ T = \text{Bitumen type (1 for 40/50 and 2 for 60/70)} \]

**Resilient Modulus Correction Factor**

Performing the test of resilient modulus in 25°C that is close to the temperature of laboratory, is simpler and more reliable than higher and lower temperatures. Equation 4 that is developed by comparing the test results in three temperatures, converts the resilient modulus in 25°C to desired temperature. This equation predicts the correct resilient modulus in target temperature with 74% reliability.

\[ \frac{M_R(T)}{M_R(25)} = 2.35e^{-0.04[T]} \]

\[ R^2 = 0.742 \]

Where:

\[ M_R(T) = \text{Resilient modulus in target temperature} \]
\[ M_R(25) = \text{Resilient modulus in 25 °C} \]
\[ T = \text{Target temperature} \]

The right side term of the equation can be used as a correction factor for converting the resilient modulus to desired temperature.

**RESULTS**

Differences among resilient modulus in low temperature (5°C) is far more than medium (25°C) and high (40 °C) temperatures. In the low temperature, the most difference is between high and medium level of compaction. The value is negligible in comparison between two gradations (No 3 and 5). In high temperature, variance in resilient modulus values in all cases, except for bitumen type, is too slight and around 1 to 2% of its low temperature values. The percentage is up to 22% for bitumen type. As shown in resilient modulus model (Eq. 3), the only variable that has significant correlation with resilient modulus is bitumen gradation. As a conclusion, selection of bitumen PG is too important in accordance to the climate condition of study location, especially for hot regions. Two bitumen gradations are merely used in this project in regards to capabilities and recommended specifications of Iran that its effect is notable in mix properties in the high temperature. It is recommended that other researchers conduct similar studies to compare bitumen by different Performance Grades (PG).

**REFERENCES**
