Prediction of Temperature Cooling Trend of Asphalt Mixtures

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Abstract. Monitoring of the temperature changes of asphalt mixtures during the mix production and pavement construction phases is important to avoid over-heating, and to ensure that optimum mixing and compaction is achieved. Over-heating or prolonged heating of asphalt mixtures would cause ageing, while inadequate mixing or compaction would result in mixtures with a strength and durability less than design optimal. Careful temperature monitoring would help to avoid such undesirable problems. This study develops a finite-element asphalt mixture cooling temperature prediction software as an asphalt pavement mix design planning tool. For any given asphalt paving design mix, it is able to predict the temperature cooling characteristics of the design mix during the laying and compaction phase. The software can provide the temperature cooling characteristics during a multi-lift paving of asphalt pavement layer. The factors affecting the temperature cooling trend are determined and analysed. They include ambient temperature, laying temperature, solar influx intensity, wind velocity, number of lifts, and lift thickness. A sensitivity analysis is conducted to identify the most influencing factors under different paving conditions.

1. Introduction

Temperature monitoring and control of asphalt mixtures is vital in the production of asphalt mixtures and construction (including repair and maintenance) of asphalt pavements. During the mix production phase, too high a temperature would cause over-heating and ageing of the asphalt binder; too low a temperature could lead to inadequate or non-uniform mixing [1]. During the pavement construction phase, adequate temperature must be maintained for effective spreading and compaction [2]. Another phase in which temperature monitoring and control is important, but overlooked in many instances, is the time that a newly compacted pavement is open to traffic during the post compaction phase. When a newly compacted pavement section or a newly repaired pavement layer is opened to traffic too soon before the asphalt materials have cooled down sufficiently, premature failure of the pavement may occur due to excessive deformation or cracking in the asphalt layer under heavy wheel loads. Sufficient time must be allowed for the temperature to cool down and the asphalt material to gain strength before traffic is allowed. Close monitoring of the temperature in the asphalt layer is needed to prevent such premature failures of a newly compacted pavement section. Instead of tedious and manpower demanding field installation of sensors and temperature monitoring, an alternative means is to develop temperature prediction capability to estimate the cooling time required, and plan ahead for the time at which the pavement concerned can be opened to traffic. This is the topic of interest of this paper.
This paper describes the development of a 2-dimensional finite simulation model for predicting the cooling trend of a newly compacted asphalt layer. It provides a numerical solution based on heat transfer theories. The model developed can provide the time-temperature cooling history during a single- or multi-lift paving of an asphalt pavement layer. The solution presents the complete temperature regime within the asphalt layer, thus offering a complete quantitative information to site engineers to help plan for their paving operation to allow sufficient cooling time before the pavement is opened to traffic. It is highlighted in this paper the key factors that must be considered during paving operation in the monitoring of temperature changes in an asphalt layer. Such factors include ambient temperature, laying temperature, solar influx intensity, wind velocity, number of lifts, and lift thickness. A sensitivity analysis is conducted to identify the most influencing factors under different paving conditions.

2. Developing cooling model for multi-lift asphalt layer construction

The 3-dimensional finite element simulation model was developed in this study to obtain the time variation of temperatures within an entire asphalt layer under a given set of pavement thermal properties and environmental conditions. This section presents the formulation of the simulation model based on the theory of heat transfer.

2.1. Theoretical basis for heat transfer modelling

In the temperature cooling process of a newly compacted pavement layer, heat losses and heat gains are considered based on heat transfer theories. Heat losses take place to the ambient atmosphere and the existing underlying pavement layer. Heat gains are received mainly from solar radiation influx. Overall, there are the following three processes influencing temperature changes within a newly laid pavement layer:

1. Heat exchange by means of conduction between newly paved layer and the existing surrounding materials;
2. Heat loss between newly paved layer and the ambient air;
3. Heat gain by the newly paved asphalt mixture under the effect of solar influx.

Figure 1 presents these heat transfer processes schematically after the asphalt mixture is laid on the existing pavement structure.

Heat conduction occurs between the newly paved asphalt layer and the existing pavement structure and governs by Fourier’s law [3]. The distribution of heat over time and space can be expressed by the following equation:

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]

\[\alpha = \frac{k}{\rho c}\]

(1)

where \(T\) = temperature, °C, \(\alpha\) = thermal diffusivity, m²/s, \(k\) = thermal conductivity, W/m·K, \(\rho\) = density, kg/m³, \(c\) = specific heat, J/kg·K, and \(x, y, z\) are the three coordinate directions in a three-dimensional space.

Heat convection can be estimated by the following equation to describe heat transfer between a solid and the surrounding air [3]:

\[q_v = h(T_{m} - T_r)\]

(3)
where \( h \) = convective heat transfer coefficient for air flow, \( W/m^2 \cdot \circ C \), \( Ta \) = temperature of surrounding air, \( \circ C \), and \( Ts \) = surface temperature of newly laid asphalt layer, \( \circ C \).

The radiation energy transmitted from the newly paved layer can be simply represented by the following equation [4]:

\[
q_r = \varepsilon \sigma (T_s^4 - T_a^4)
\]

(4)

where \( q_r \) = radiation heat flux emitted, \( \varepsilon \) = emissivity coefficient of asphalt layer, \( \sigma = 5.669 \times 10^{-8} \) \( W/m^2K^4 \) is the Stefan-Boltzman constant, \( T_s \) = surface temperature of pavement, and \( T_a \) = ambient air temperature.

Besides heat loss in different forms as described above, the newly paved asphalt layer will also absorb energy due to the effect of solar influx, which can be quantified by the following equation [3]:

\[
q_s = aH_s
\]

(5)

where \( q_s \) = solar radiation energy absorbed, \( H_s \) is the net solar flux at a pavement surface, and \( a \) = solar radiation absorptivity coefficient, a dimensionless quantity.

Figure 1. Heat transfer processes considered in thermal cooling simulation model

2.2. Finite-Element Modelling of Cooling of Newly Paved Asphalt Layers

Applying the heat transfer theory described in the preceding section, the temperature changes of newly paved asphalt layers are modeled taking into consideration the following parameters:

• Geometric dimensions of existing pavement structure;
• Geometric dimensions of newly paved asphalt layers;
• Thermal properties of existing pavement materials and newly paved asphalt layers;
• Ambient temperature, solar flux and wind speed;
• Time and thickness increments of newly paved asphalt layers;
• Initial temperature of existing pavement structure; and
• Initial temperature of each newly paved asphalt layers when laid.

The finite element simulation model was developed making use of the finite-element software ABAQUS [5]. The dimension for the simulated area to study the temperature trend is 12 m by 21 m. To
minimize the computation time and also guarantee the accuracy of the simulation results, the layout of the meshes adopted in this study is found in Figure 1. The smallest mesh size is 2 mm.

![Finite Element Mesh](image)

**Figure 2.** Schematic representation of finite-element mesh for proposed simulation model

3. Analysis of example problems

This section presents analyses of several example problems that consider the effects of different environmental conditions on the cooling trend of a newly paved asphalt layer. To study the variation in the length of cooling time needed, 60°C is set as the maximum temperature allowed before a newly paved pavement section can be opened to traffic. The effects of the following three factors on cooling time are examined: (i) Wind speed, (ii) ambient air temperature, and (iii) compaction temperature of asphalt layer. The effects of these factors on the length of pavement cooling time needed is considered for two overlay construction: (1) A 150 mm layer laid in two equal lifts of 75 mm; and (2) a 100 mm layer laid in two equal lifts of 50 mm each.

3.1. Effects of wind speed

The results of wind effect study are shown in Figure 3. The plot illustrates that as the wind speed increases, the time duration to reach to 60°C decreases for both the bottom and the surface layers. Higher wind speed helps to reduce the length of cooling time needed. Compared with the case of 1 m/s wind speed, a wind speed of 8 m/s will cut down the required cooling time by more than 150 minutes. It is noted that the effect of wind speed tends to level off after wind speed reaches 9 m/s.

It can be seen that the controlling factor of the cooling time is the temperature of the bottom layer. For both cases of overlay construction, the bottom layer takes almost 150 minutes to reach 60°C, regardless of the magnitude of the wind speed. Figure 3 also shows that the case with thinner thickness takes shorter time to cool down to 60°C, even though the difference is not very substantial. The case of 100 mm thick layer compacted in two lifts of 50 mm needs about 10 minutes shorter to cool down to 60°C. This difference does not appear to be affected by the magnitude of wind speed.
3.2. Effects of ambient air temperature

The range of ambient air temperature considered is from 24°C to 33°C. Figure 4 presents the bottom layer and surface layer temperature variation when the overlay constructions are carried out under different ambient air temperatures. As can be expected, the length of cooling time increases with the ambient air temperature. For both overlay construction cases at an ambient air temperature of 33°C, it takes about 50 minutes longer than when the ambient air temperature is 24°C. There is a slight tendency that the rate of increase of the cooling time picks up as the ambient air temperature rises.

The results show that the bottom lift pavement temperature governs the total length of cooling needed. Regardless of the magnitude of the ambient air temperature and the lift thickness, the bottom layer takes about 130 minutes longer to cool down to 60°C. As for the effect of lift thickness, when the ambient air temperature rises, the case of 75 mm lift thickness takes longer time to cool down to 60°C than the case of 50 mm lift thickness. The difference is slightly more than 10 minutes, and this difference appears to stay the same for the range of ambient air temperatures studied.

3.3. Effects of compaction temperature

The initial compaction temperatures is an important factor leading to different lengths of time needed for cooling down to 60°C. Figure 5 presents the effect of compaction temperature for the two overlay construction cases studied. In general, the length of cooling time needed increases with the magnitude of initial compaction temperature. Comparing the impacts of initial compaction temperatures of 140°C and 160°C on the bottom layer temperature, it is seen that the case of 160°C compaction temperature...
takes about 60 minutes longer to reach 60℃. It is observed again that the bottom lift takes much longer time to cool than the surface lift. At 140℃ initial compaction temperature, the bottom lift takes slightly more than 100 minutes to cool down to 60℃ than the surface lift; while at 160℃ initial compaction temperature, the difference is 120 minutes. The difference increases with the magnitude of initial compaction temperature.

Between the two overlay construction cases, the case with two 75 mm lifts takes about 10 minutes longer to cool down to 60℃ than the case with two 50 mm lifts. This difference in the length of cooling time remains practically unchanged over the range of initial compaction temperature analyzed.

Figure 5. Effect of compaction temperature on time to reach 60℃ after compaction

4. Conclusion
A 2-dimensional finite element temperature cooling simulation model for asphalt pavement has been developed and presented in this paper. It is applied in this study to analyse the cooling characteristics of two newly laid overlaid asphalt pavements under the influences of three factors: wind speed, ambient air temperature, and initial compaction temperature. It was found that the length of time needed for a newly laid overlay to cool down to 60℃ decreases as wind speed increases, but increases as either ambient air temperature or initial compaction temperature increases. For the two cases of 2-lift overlay constructions analyzed, the bottom lift was found to take the longest time to cool down, and hence governed the length of cooling time needed before the newly laid overlay could be opened to traffic. All three factors considered had significant impacts on the length of cooling time needed, and have to be taken into consideration in determining the cooling time needed for opening a newly compacted asphalt pavement to traffic.

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