Bruce A. Chadbourn[1], James A. Luoma[1], David E. Newcomb[1] , and Vaughan R. Voller[1]

CONSIDERATION OF HOT-MIX ASPHALT THERMAL PROPERTIES DURING COMPACTION

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ABSTRACT: A computer program was developed at the University of Minnesota to predict asphalt concrete cooling times for road construction during adverse weather conditions. Cooling models require extensive experimental data on the thermal properties of hot-mix paving materials. A sensitivity analysis was performed to determine which thermal properties affect pavement cooling times significantly. The results indicated that more information on asphalt thermal conductivity and thermal diffusivity is required. Two suitable test methods for determining these properties at typical paving temperatures and densities were developed, and preliminary results for dense-graded and stone-matrix asphalt (SMA) mixes agreed well with values reported in the literature.

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INTRODUCTION

Background

        High demand for new asphalt pavements often requires that paving be done in unfavorable construction conditions. Low air temperatures, high winds, and night construction create adverse conditions for hot-mix asphalt paving. These conditions, though most common late in the paving season, may occur at any time. This presents a risk for owners and contractors. To achieve optimum load-bearing and weathering characteristics, an asphalt mix must be compacted to a specific range of density, and the time required for hot-mix asphalt to reach the proper compaction temperature to achieve this density decreases with an increased rate of cooling.
        Hot-mix asphalt compaction is generally begun as soon as the mix can support the roller weight. The roller operator determines the best time to begin compaction by means such as judging the depth of a heel imprint. This method works well when the ambient temperature is high enough. However, low ambient temperatures, high wind speeds, and night construction increase the rate of heat loss from the mix. During these conditions, the ability to predict mix temperature is more critical

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        [1] Research fellow, research assistant, associate professor, and associate professor, respectively, Department of Civil Engineering, University of Minnesota, 500 Pillsbury Dr. SE, Minneapolis, MN 55455.

because the time available for mix compaction is decreased. A computer tool that will predict pavement temperature profiles from easily acquired mix design and weather information will increase the certainty of reaching the desired level of compaction by rapidly providing an estimate of the time to reach a temperature below which compaction cannot be achieved.

J. S. Corlew and P. F. Dickson [1] pioneered the use of computational methods in predicting pavement cooling profiles, and many researchers since have developed similar models. Most of these models take the form of an explicit or partially implicit finite difference scheme. Given the scarcity of experimental data on hot-mix asphalt thermal properties, constant pavement density and thermal properties are typically assumed. A sensitivity analysis was performed to determine the effect varying thermal properties have on pavement temperature profiles and cooling rates. It was determined that a pavement cooling model should incorporate thermal property variations related to mix type, temperature, and density.

Objective

The main purpose of this research was to lay the groundwork for the design of an interactive paving tool. The model required extensive experimental data on the thermal properties of various hot-mix paving materials, including information about how hot-mix thermal properties vary with mix type, temperature, and density. A search of the literature revealed a wide range of reported thermal conductivity values for asphalt concrete and limited information on the specific heat and thermal diffusivity of asphalt concrete. However, mixture types, temperatures, and densities were rarely reported in the literature. Two test methods were developed to measure the required thermal properties.

Scope

A sensitivity analysis was conducted to determine which thermal properties have a significant effect on hot-mix cooling rates. Thermal conductivity and thermal diffusivity tests for hot-mix asphalt were then developed. These tests were conducted on dense-graded and stone-matrix asphalt (SMA) mixtures at temperatures and densities typically found in a hot-mix asphalt lift from initial lay-down through final compaction.

COMPACTION OF HOT-MIX ASPHALT PAVEMENT

The compaction process has a great effect on the strength and durability of hot-mix asphalt pavement. The main objective of pavement compaction is to achieve an optimum density. This helps to ensure that the pavement will have the necessary bearing capacity to support the expected traffic loads and durability to withstand weathering.

In asphalt binders, viscosity changes with temperature. Research has shown a 1,000-fold increase in asphalt viscosity as the temperature drops from 135 to 57°C. There was also a ten-fold increase in resistance to compaction as mix temperature dropped from 135 to 63°C, due entirely to an increase in binder viscosity [2]. Attention to compaction is especially crucial in cold weather conditions, when air voids after compaction can be as high as 16 percent. Pavements with this level of air voids have shown signs of deterioration after two years [2].

Once a paving job has begun, temperature control is the principal means of controlling compactibility. A means of controlling temperature at the time of compaction is by adjusting the lag time between the paver and the roller. There is, however, a limit to the amount the lag time can be reduced. In 1971, contractors determined that 10 minutes was the absolute minimum allowable compaction time needed with the present equipment [3]. Cold air and base temperatures

can reduce the lag time for a given lift thickness to the point where the mix cannot be adequately compacted. This can be rectified by increasing the lift thickness, allowing the mix to retain heat longer [4]. Another consideration is the lack of traffic densification during the winter months. Therefore, pavements constructed late in the season should be roller-compacted as close as possible to 100 percent of the laboratory-compacted density [2].

Assuming density affects pavement thermal properties, a pavement cooling model will require information on how the density and thickness of a hot-mix asphalt lift change with each pass of the roller. Tegeler and Dempsey reported that density changes in hot-mix asphalt have a much greater effect on the thermal conductivity of hot-mix asphalt than temperature changes. A paving mixture will typically leave the spreader with a density at 75 to 80 percent of the laboratory-compacted density. They estimated that thermal conductivity values range from 1.04 W/mK immediately behind the paver to 1.56 W/mK after final compaction [3].

THERMAL PROPERTIES OF PAVEMENT MATERIALS

A mathematical relationship that explains the cooling behavior of hot-mix asphalt is required to predict cooling rates. Cooling occurs by three modes: conduction, convection, and radiation. Although convection and radiation are necessary components of a pavement cooling model, they are not needed for the thermal calculations defined in this paper. Conduction theory describes the transfer of heat through a solid, and is the basis of the basic thermal properties required for a pavement cooling model. Conduction is described by Fourier's law, which states that the heat flux in a given direction, is proportional to the temperature gradient in that direction. The proportionality constant in this relationship is called thermal conductivity [5]. One-dimensional steady-state heat conduction is described by the following equation:

$$q_z = -k \frac{dT}{dz}$$

(1)

where

q_z = heat flux in the z (vertical) direction, W/m^2,

k = thermal conductivity, W/mK,

T = temperature, K

z = vertical distance, m

Describing transient heat flow requires two more thermal properties. Specific heat is a measure of the heat required to increase the temperature of a mass by one degree. Thermal diffusivity is a measure of heat propagation speed. These properties, along with density are related by the following equation:

$$\alpha = \frac{k}{\rho C_p}$$

(2)

where

α = thermal diffusivity, m^2/s,

ρ = density, kg/m^3,

C_p = specific heat, J/kgK.

Transient heat flow is represented by the following relationship, known as the diffusion equation:

$$\frac{d^2T}{dz^2} = \frac{1}{\alpha}\frac{dT}{dt}$$

(3)

where

    t = time, seconds.

Although thermal conductivity was the most commonly reported asphalt thermal property, thermal diffusivity alone was required to predict pavement cooling rates. If thermal diffusivity values are not available, then thermal conductivity, specific heat, and density values are required to predict cooling times.

SENSITIVITY ANALYSIS

A sensitivity analysis was conducted on a spreadsheet program on a personal computer. Thermal conductivity, specific heat, and thermal diffusivity were varied according to the ranges reported in the literature. All other variables were held constant. The model was based on an explicit finite difference algorithm developed by Corlew and Dickson [1]. The model predicted a significant difference in cooling times for hot-mix asphalt pavements over the range of thermal properties reported in the literature. For example, the predicted time for a 60 mm lift to cool from 135 to 80°C ranged from about 10 minutes at the lower values of thermal conductivity and thermal diffusivity to over 60 minutes at the higher values. The effect of specific heat was less significant. These results indicated a need for further analysis of asphalt concrete thermal properties, especially thermal conductivity and thermal diffusivity.

COMPUTER MODEL

The final version of this computer tool will consist of a user interface, a pavement cooling model, and a knowledge-based expert system (Fig. 1). The user interface includes a keyboard and/or a pointing device such as a mouse. The pavement cooling model was based on an implicit finite element scheme utilizing transient heat flow theory. The expert system will be programmed using a commercially available expert system shell.

A pavement cooling model requires information on the densities and thermal properties of the pavement layers, as well as environmental conditions. Jordan and Thomas [6] recommended the following parameters:

1. Densities of pavement layers
2. Thermal conductivity values
3. Specific heat values
4. Ambient temperatures
5. Wind speeds
6. Convection coefficients
7. Incident solar radiation
8. Coefficients of emission and absorption of solar radiation for the pavement surface
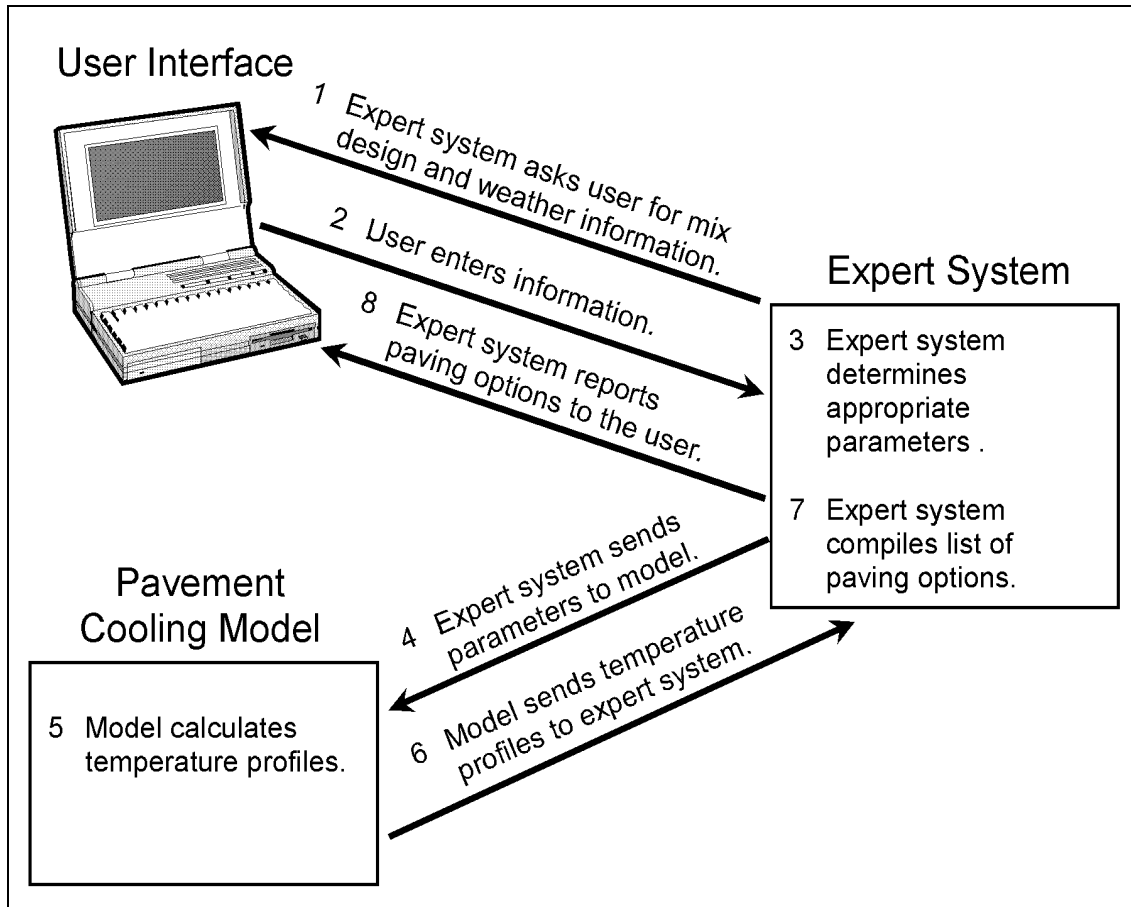9. Time and depth increments
10. Initial pavement temperature profiles

User Interface

1 Expert system asks user for mix design and weather information.

2 User enters information.

8 Expert system reports paving options to the user.

Expert System

3 Expert system determines appropriate parameters .

7 Expert system compiles list of paving options.

Pavement Cooling Model

5 Model calculates temperature profiles.

4 Expert system sends parameters to model.

6 Model sends temperature profiles to expert system.

FIG. 1--Asphalt pavement cooling tool schematic.

Ambient temperatures and wind speeds are easily acquired at the site or estimated from local weather reports. The convection coefficient and incident solar radiation are difficult to determine exactly, but an adequate means of estimating the convection coefficient from wind speeds and estimating the incident solar radiation from location, time, and cloud cover information were included in the cooling model. The coefficients of emission and absorption used were those assumed by Corlew and Dickson [1]. Time and depth increments were chosen to optimize accuracy and computing speed. The initial temperature profile of the existing structure on which the hot-mix will be placed was assumed to be constant and equal to the measured surface temperature. The initial hot-mix temperature profile was assumed to be constant and equal to the mix temperature behind the paver.

The current version of the Asphalt Pavement Cooling Tool consists of an input screen that prompts the user for all necessary data, a finite element model, an output window that displays the cooling time, and a module that plots the cooling curve. The hardware requirements include an IBM compatible personal computer (386 or better), Microsoft Windows 3.1 (or later), at least 1 megabyte of free hard disk space, at least 4 megabytes of RAM memory, and a VGA 640 x 480 monitor. The final version of the program should be available in 1998. It will include an expert system which will provide the user with solutions to many of the paving problems encountered during adverse weather conditions.

THERMAL TEST METHODS

Although there are many standardized methods for determining thermal properties of materials, asphalt pavement presents problems relating to the specimen dimensions required (an assumption of homogeneity requires that the smallest specimen dimension be several times larger than the largest aggregate particle). Another complication involves the change in the asphalt binder as the mix is heated and then allowed to cool. Once a hot-mix specimen is heated above a certain temperature, it must be contained in order to maintain the desired shape. Most of the commercially available thermal property devices were not designed for the standard asphalt specimen sizes or for a loose-mix type of material. Although standard thermal devices can be modified for the purpose of measuring asphalt concrete thermal properties, the cost involved was prohibitive for this investigation.

A test for thermal diffusivity of asphalt concrete slabs was designed in order to provide the necessary thermal information for a pavement cooling model. It involved heating a slab specimen to a constant temperature, and measuring the temperature at several depths over a period of time as the slab cools. The ASTM Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe (D 5334) was modified for use on asphalt concrete cylinder specimens so that experimental results could be compared to the thermal conductivity values reported in the literature. The specimen required for this test was a cylinder similar in dimensions to pavement cores used in triaxial testing of asphalt concrete. Specific heat testing procedures were not considered for this research.

Mixture Design

Mixtures for this study were selected in order to represent two types likely to exhibit different thermal properties. The mixes selected were a standard dense-graded mix, and a 15.9 mm maximum aggregate size stone matrix asphalt (SMA) mix. The dense-graded mix conformed to Minnesota Department of Transportation (Mn/DOT) Type A gradation limits for bituminous mixtures. The SMA mix design followed a typical gradation used in Germany [7]. The aggregate used consisted of crushed granite for particle sizes of 9.5 mm and greater, and a river gravel for particle sizes of 4.75 mm and less. A 120/150 penetration asphalt was used for both mixes. The asphalt and aggregate were mixed by Mn/DOT in a large laboratory mixer. Enough of each mix was prepared to compact three slabs, two cylinders, and conduct a theoretical maximum specific gravity analysis.

The compaction procedure was modeled after a process used by Scholz, et al. [8]. The main advantage of rolling wheel compaction related to this study was the ability to compact a slab specimen that approximates an infinite wall, one-dimensional heat transfer condition. Typical slab dimensions used by Scholz were 710 x 710 x 102 mm. The slabs were compacted with a motorized steel wheel roller.

Slabs of dimensions 380 x 380 x 64 mm were used for this research. The thickness was determined as that of a typical asphalt lift, and the horizontal dimensions were calculated to produce a thickness-to-length ratio less than 0.2. This is the limiting value for square slabs to ensure that temperature variations at mid-slab can be modeled using one-dimensional plane-wall theory [9]. A smaller version of the ramp and mold system used by Scholz was constructed out of wood. Instead of a motorized, steel-wheel roller, a water-filled 457 mm diameter by 560 mm length lawn roller was used to compact the specimen. The total weight of the roller and water at $25^{\circ}C$ was 115 kg.

The thermal probe procedure (ASTM D 5334) required the specimen height to exceed the probe length by 100 mm. Tall cylindrical asphalt specimens, 100 by 200 mm, were compacted by a modified Marshall hammer compaction procedure developed at the University of Minnesota. These specimens satisfied the ASTM requirement for probe lengths up to 100 mm.

The mold consisted of a steel tube with an inside diameter of 100 mm and a height of 254 mm The cylinder rested on top of a base plate. A steel rod 2.4 mm in diameter was fixed to the center of the base plate so that it extended 46 mm into the compacted specimen. This created a hole in one end of the specimen so that a 46 mm thermal probe could be inserted.

The compactor used was a single rotating base Marshall hammer apparatus. It was originally designed to prepare large stone specimens with a diameter of 150 mm, and was adapted to accommodate a 100 mm diameter by 250 mm mold. The specimens were compacted in three 1300 g lifts. The number of blows for each successive lift was increased in order to equalize the compactive effort received by the three lifts to achieve consistent voids of 4 to 5 percent in a dense-graded mix. A study of air voids based on compactive effort on tall SMA specimens has not been completed.   The number of blows used for the bottom, middle, and top lifts were 20, 35, and 55, respectively.

Slab Cooling Method for Thermal Diffusivity of Asphalt Concrete

Given a specimen of dimensions that approximate homogeneity and conditions that approximate one-dimensional conductive heat flow, it was possible to determine the thermal diffusivity from a first-order time-temperature relationship and a second-order space-temperature relationship. Constant heat flow and constant boundary temperatures were not required.   This made thermal diffusivity measurements possible from a very simple test configuration of an asphalt slab, insulated on the sides and bottom, with the top surface exposed to air at a different temperature (Fig. 2). Spatial and temporal temperature gradients were measured with thermocouples at known depths in the specimen.
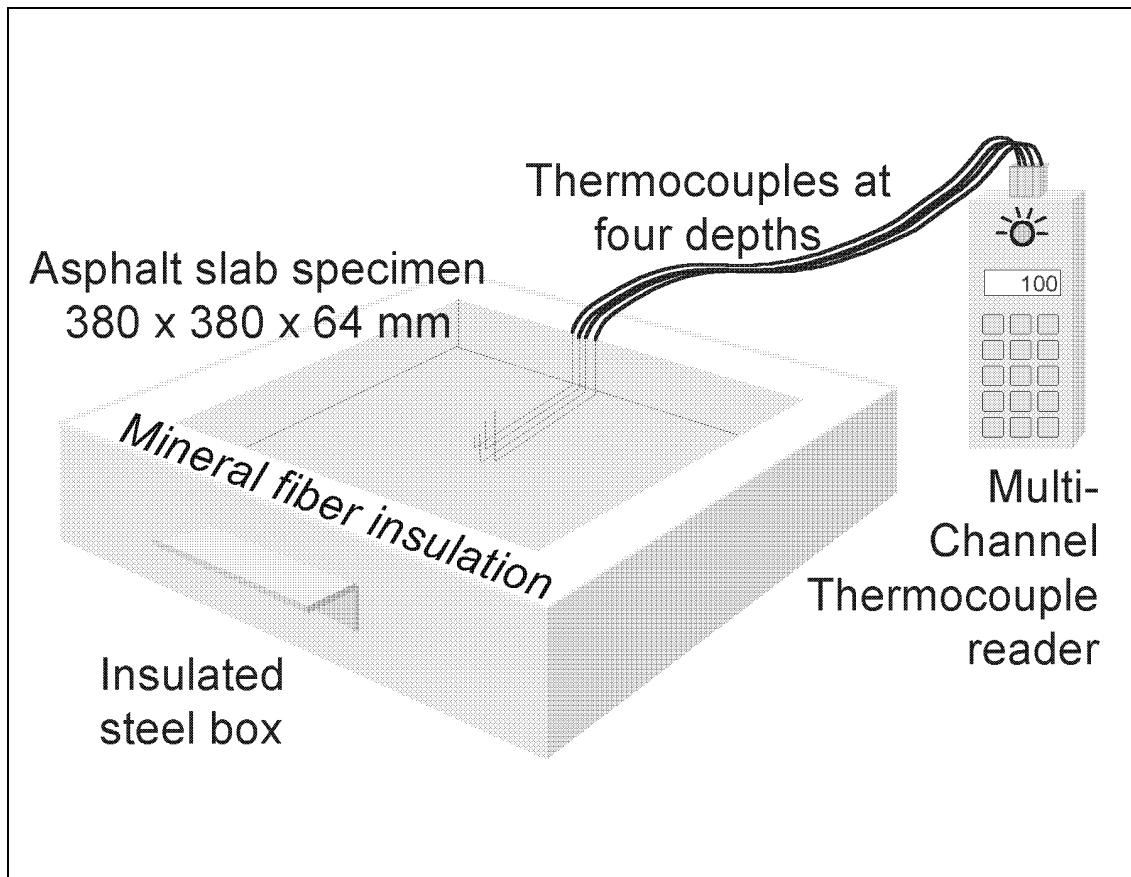

FIG. 2--Thermal diffusivity of asphalt concrete, slab cooling method.

To determine the variation of thermal diffusivity with temperature, small time intervals were selected to approximate linear relationships. At each time step, the average lift temperature was calculated. For each time interval, a linear relationship was fit to a plot of the average temperatures versus time:

$$T = b_1 t + b_2 \qquad (4)$$

where

b_1, b_2 = first-order curve-fitting constants.

To approximate the spatial relationship, the temperature reading at the center of each time interval was plotted against the depth and a second-order relationship was fit:

$$T = a_1 z^2 + a_2 z + a_3 \qquad (5)$$

where

a_1, a_2, a_3 = second-order curve-fitting constants.

Equation 2 was rearranged to produce the following relationship:

$$\alpha = \frac{dT}{dt} \bigg/ \frac{d^2T}{dz^2} \qquad (6)$$

The first derivative of Equation 4 with respect to t was determined:

$$\frac{dT}{dt} = b_1 \qquad (7)$$

The second derivative of Equation 5 with respect to z was determined:

$$\frac{d^2T}{dz^2} = 2a_1 \qquad (8)$$

Equations 7 and 8 were substituted into Equation 6 to determine the thermal diffusivity:

$$\alpha = \frac{b_1}{2a_1} \qquad (9)$$

The measured thermal diffusivity versus temperature for three dense-graded and two stone matrix asphalt concrete specimens indicate that all except the SMA loose mix specimen exhibited a similar decrease in thermal diffusivity as the temperature increased (Fig. 3). A decreasing trend was expected, as the thermal conductivity of asphalt concrete decreases with temperature [11], and the specific heat of dry aggregates increases with temperature [11], as does the specific heat of asphalt binders [13]. A minimal density change within this temperature range is expected, so the thermal diffusivity of asphalt concrete as calculated by Equation 2 would decrease with temperature. The difference in the SMA loose mix specimen may be due to the effect of large air pockets in the mix. The thermal diffusivity of air increases with increasing temperature [5], which may cancel the temperature effects of the solid components.
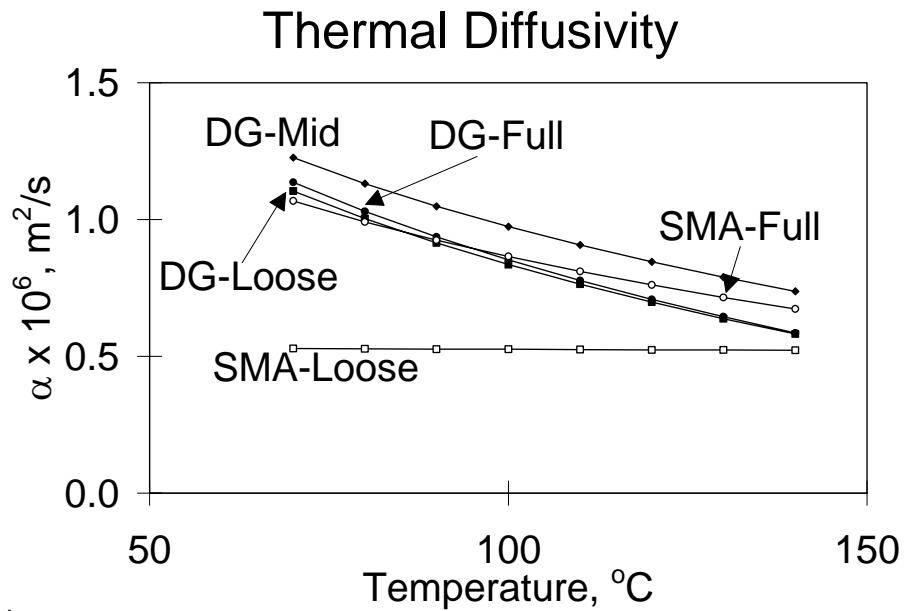
Thermal Diffusivity

FIG. 3--Variation of thermal diffusivity with temperature.
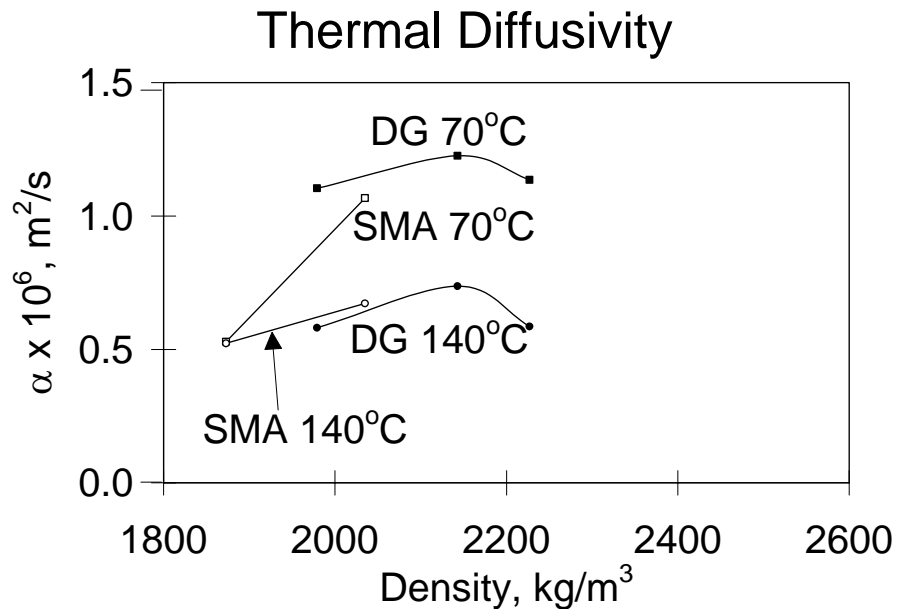
Thermal Diffusivity

FIG. 4--Variation of thermal diffusivity with density.

The thermal diffusivity of the dense-graded specimens peaked at a point between the two density extremes (Fig. 4). The peak was more pronounced at higher temperatures. These trends were more difficult to interpret. The thermal conductivity is expected to increase with increasing density due to greater particle-to-particle contact. This results in increasing values in both the numerator and denominator of Equation 2. Also, very little is known about how asphalt specific heat varies with density. As a consequence, more detailed information is required to make predictions about thermal diffusivity-density relationships. If a similar trend occurred for SMA specimens, it was not evident as there were only two data points for each temperature.
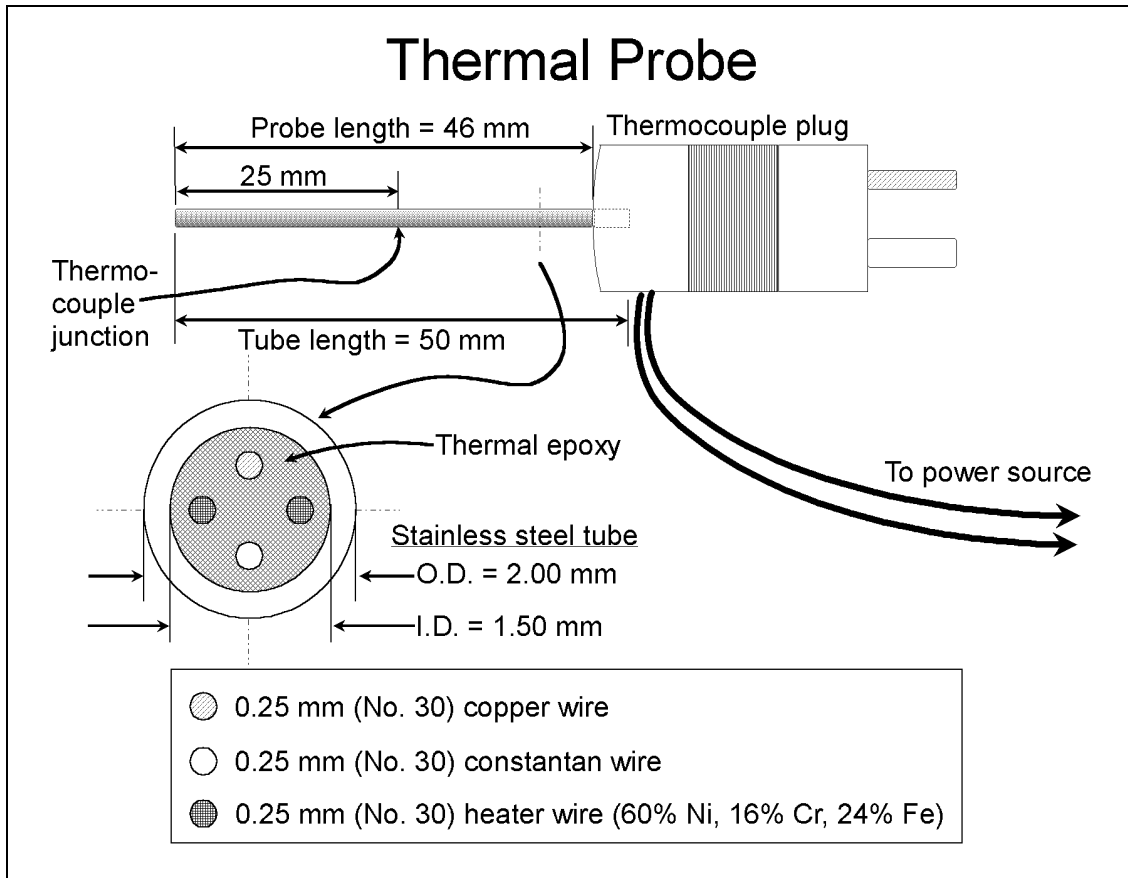
Thermal Probe

FIG. 5--Thermal probe schematic.

Experimental errors were probably responsible for some of the ambiguity in the thermal diffusivity results. There may have been errors due to interference from large aggregate particles or air pockets. Another source of error resulted from asphalt drain-down in the SMA specimens. Stabilizing materials such as cellulose fibers were not used in these specimens.

Thermal Probe Method for Thermal Conductivity of Asphalt Concrete

ASTM D 5334 required the construction of a thermal probe, which consists of a loop of heating wire and a thermocouple enclosed in a small stainless steel cylinder (Fig. 5). A probe was constructed per the instructions in the test method. The main difficulty involved finding a high-conductivity cement that was workable enough to draw through a 50 mm length of 1.59 mm stainless steel tubing. After several unsuccessful attempts, a working probe was constructed using a 2.00 mm tube. The probe was inserted into a cylindrical asphalt specimen and a constant current was applied to the heating wire (Fig. 6).

Temperature was plotted on the standard axis and time on the log axis of a semi-log graph. The linear portion of the curve was identified, and the values representing the temperatures and times at the ends of the linear portion (T_1, T_2, t_1, and t_2) were determined (Fig. 7). The following equation was used to calculate thermal conductivity:

$$k = \frac{EI}{4\pi(T_2 - T_1)} \ln \frac{t_2}{t_1}$$

(10)

where

E = voltage, volts
I = current, amperes
L = heated length of probe = 0.051 m

Thermal Probe Test

Thermal probe

100 x 200 mm
asphalt concrete
specimen contained
in a steel mold

100

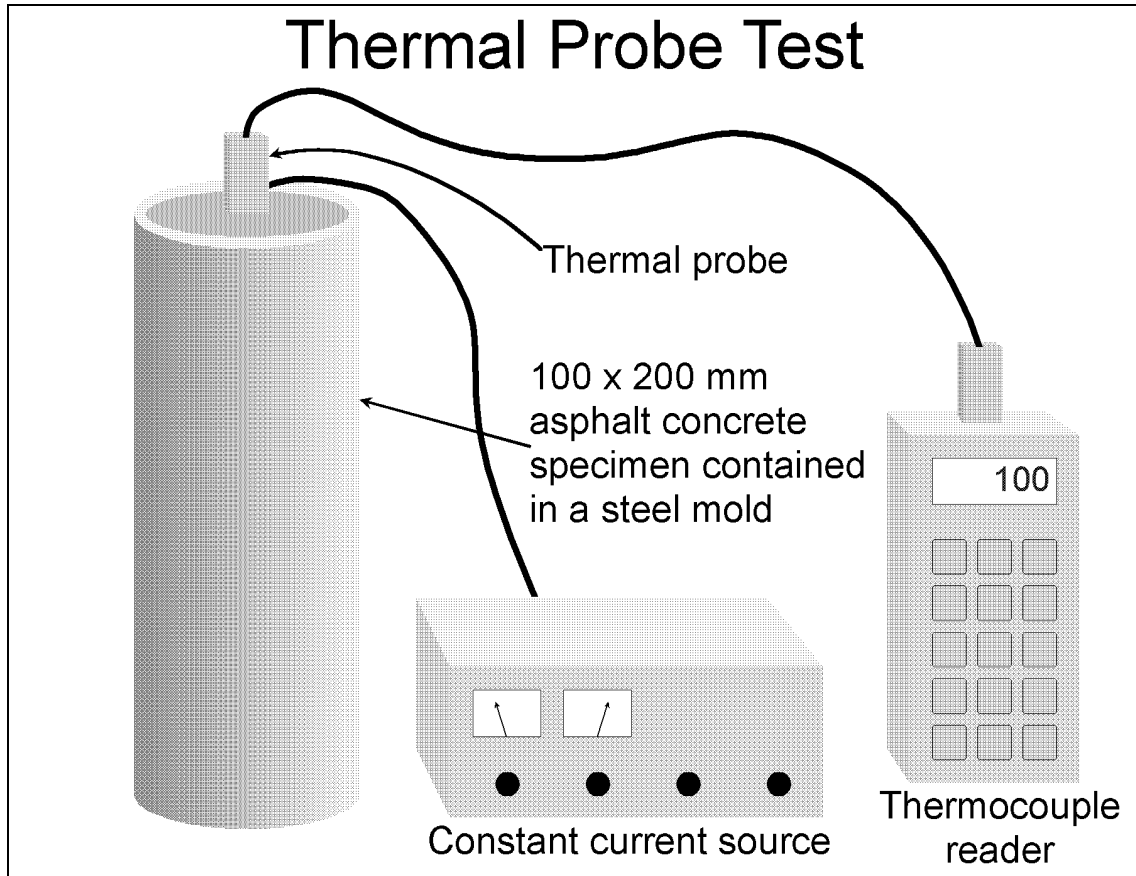Constant current source

Thermocouple reader

FIG 6--Thermal conductivity of asphalt concrete, thermal probe method.

Tests conducted on the dense-graded specimens resulted in curves
with easily recognizable linear segments on the semi-log plots. The SMA
specimens presented difficulties as large temperature gradients
developed between the probe and the specimens. Large gaps between
particles most likely prevented effective heat dissipation away from the
probe resulting in the initial rapid temperature increase. This
resulted in plots with short or non-existent linear portions. Larger
probe sizes may improve the SMA test results.

Thermal conductivity differed significantly with respect to mix
type, although the responses to temperature changes were similar
(Fig. 8). The variation of thermal conductivity with density was also
different for the dense-graded and SMA mixes (Fig. 9). Both mixes
exhibited a positive correlation between thermal conductivity and
density, but the SMA mix had a much steeper slope. This may be due to
the greater degree of inter-particle contact in compacted SMA specimens.

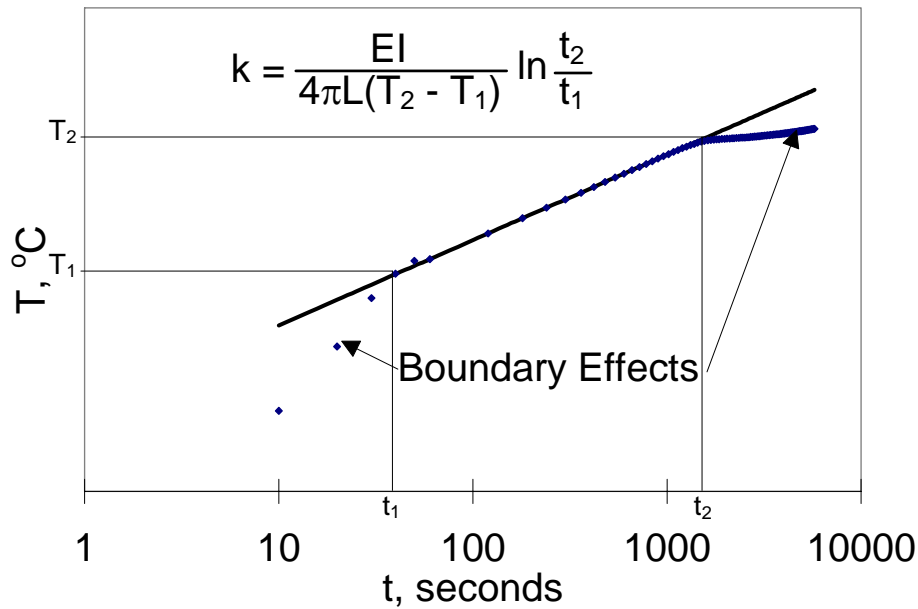$$k = \frac{EI}{4\pi L(T_2 - T_1)} \ln \frac{t_2}{t_1}$$

FIG. 7--Thermal probe time-temperature curve.

Although this probe had not yet been calibrated using a thermal test standard, the thermal conductivity values fell within the range of values reported in the literature (Table 1).

Effect on Asphalt Pavement Cooling Rates

Pavement cooling computer simulations were conducted for the thermal diffusivity and thermal conductivity values determined in this project. For the purposes of comparison, the specific heat was held constant at 920 J/kgK (0.22 Btu/lb°F), the value recommended by Corlew and Dickson (p. 114), and the thermal diffusivity values were calculated from the thermal conductivity values modeled in the sensitivity analysis and the specimen densities (Equation 2). The ranges of both the thermal diffusivity and thermal conductivity values measured for this study represented a tripling of the cooling rate of a 40 mm (1.6 in.) lift and a quadrupling of the cooling rate of a 100 mm (3.9 in.) lift. The model used in the sensitivity analysis indicated that decreasing the temperature from 140 to 70°C (284 to 158°F) resulted in a 20 percent increase in the cooling rate for the dense-graded mix, and between a 50 and 80 percent increase in the cooling rate for the SMA mix.

Although this analysis was based on a fairly simple pavement cooling model, the method was verified as an adequate predictor of pavement cooling rates by Corlew and Dickson. Many of the pavement properties that were assumed to be constant probably were not, but the purpose of this analysis was to gain a preliminary understanding of the impact that various thermal properties have on pavement cooling rates. The range of cooling rates predicted by this analysis indicate a need for further study of these properties and how they relate to late season hot-mix asphalt paving.
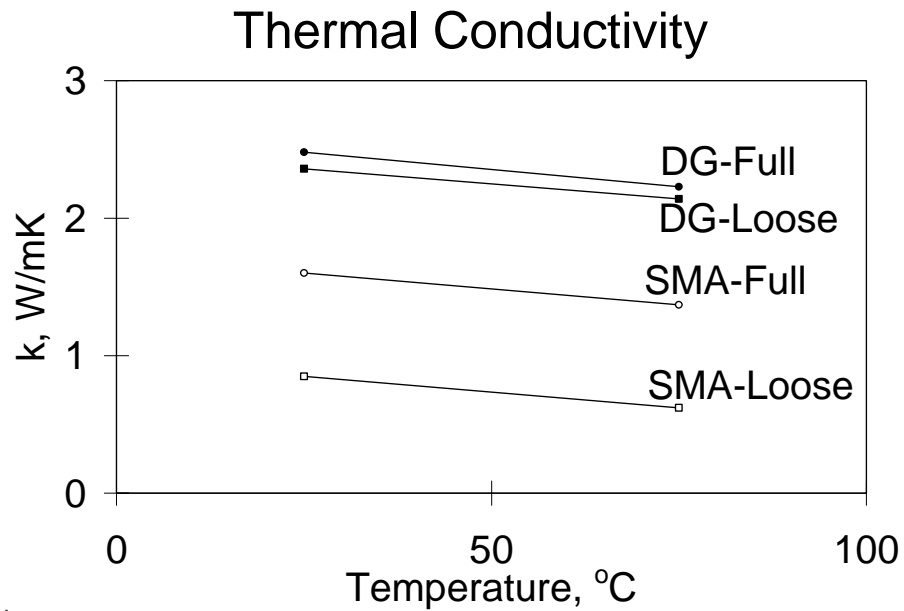
Thermal Conductivity

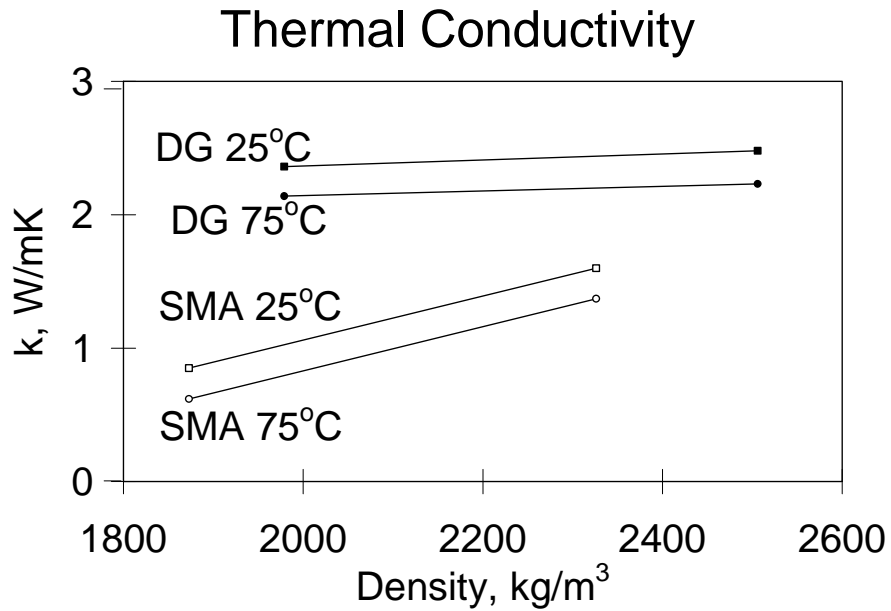FIG. 8--Variation of thermal conductivity with temperature.

Thermal Conductivity

FIG. 9--Variation of thermal conductivity with density.

TABLE 1--Reported thermal properties for asphalt concrete.

k, W/mK	Cp, J/kgK	a x 10^6, m^2/s	Source
0.76	------	-----	Turner and Malloy [10]
0.80 – 1.06	850 – 870	0.37 – 0.53	Jordan and Thomas [6]
1.21	920	0.59	Corlew and Dickson [1]
1.21 – 1.38	840 – 1090	------	Tegeler and Dempsey [3]
1.49	------	------	Kersten [11]
0.85 – 2.32	------	------	O'Blenis [15]
2.28 – 2.88	------	1.15 – 1.44	Kavianipour [15]

CONCLUSIONS

1. The ranges of thermal diffusivity and conductivity values determined by the slab cooling method agree with the range of values reported in the literature.

2. The ranges of thermal diffusivity and thermal conductivity values correspond to a significant variation in pavement cooling rates.

3. Thermal conductivity values calculated from the measured thermal diffusivity values and assumed values of density (2000 kg/m^3) and specific heat (900 J/kgK) agree with the measured thermal conductivity values.

4. Thermal diffusivity values determined by the slab cooling method should be suitable for use in the adverse weather paving tool.

RECOMMENDATIONS

The following steps should be taken to verify the effects of asphalt thermal properties on hot-mix asphalt pavement cooling rates and to further the development of an adverse weather paving tool:

1. Develop a test method and apparatus for measuring the temperature at several depths in behind-the-paver hot-mix asphalt lifts.

2. Calibrate the slab cooling and thermal probe methods using thermal reference standards which have thermal conductivity and thermal diffusivity values comparable to those reported for asphalt concrete.

3. Conduct a complete test program to determine the variation in hot-mix asphalt thermal conductivity, thermal diffusivity, and specific heat values resulting from the temperature and density changes that occur throughout the compaction process.

4. Incorporate measured thermal diffusivity values into the adverse weather paving tool.

5. Locate the appropriate sources of expert information for development of the expert system.

6. Test pre-release versions of the adverse weather paving tool for field verification and software improvements.

7. Develop a training program for implementation of the final version of the adverse weather paving tool.

ACKNOWLEDGMENTS

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