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Calcool: A multi-layer Asphalt Pavement Cooling Tool for Temperature Prediction During Construction

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The temperature at which compaction takes place is an important factor in the construction of asphalt concrete pavements. In cold climates, rapidly cooling mats can contribute to poor compaction. Under warm paving and high traffic demand conditions, time of construction is a greater concern, and the compaction schedule should minimize the required time for construction. This research created a computer tool (CalCool), based on theoretical heat transfer considerations, for use by pavement designers and on-site construction crews to predict the pavement temperature during construction and modify designs or compaction procedures accordingly. A model validation study compared CalCool to several construction scenarios. The comparisons were favorable in the single-layer cases, but increased discrepancies were observed Fin the multi-layer cases. Future validation studies are needed to expand the data set beyond the two sites examined in this paper.

Keywords: Heat transfer; Asphalt; Construction; Calcool; Paving temperature; Compaction

INTRODUCTION

Background

Compaction of a newly laid hot mix asphalt mat is a critical component of the paving process. Compaction serves to achieve an optimum density so that the pavement will have sufficient bearing capacity and durability to withstand weathering. While factors such as aggregate particle shape and gradation, binder viscosity and filler material are known to affect the compaction process, the temperature of the mat at which compaction takes place is the most critical factor once construction has begun (Chadbourn *et al.*, 1998).

Two problems, described by Kari (1967), may arise during compaction. First, the mixture may be

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*Corresponding author. E-mail: timmx010@umn.edu overstressed, a condition that often occurs when the mixture is too warm. In the overstressed case, the mat lacks the stability to support the weight of compaction and the asphalt spreads laterally from beneath the roller. Second, the mixture can be understressed, a condition occurring when the mixture is too cool. In this instance, the roller does not create shear forces sufficient to increase density. In either case, the optimum density is very difficult to achieve and mixture performance problems may develop.

For cold climates the understressed condition is more prevalent, especially when paving very early or late in the construction season. Construction practices, such as the lag time between the paver and roller, often do not change significantly to account for the environmental conditions contributing to a rapidly cooling mat. Consequently, air voids after compaction can be as high as 16% (Chadbourn *et al.*, 1998) while target air voids are typically from 7 to 9%.

A different problem arises in warmer climates. Faced with increasing traffic demands on roads and highways, it is imperative that compaction begin as soon as possible after the mat is placed to help minimize the overall time of the paving process. However, there must be enough stability to avoid the overstressed condition.

Part of the solution to the cold and warm climate compaction problems is to determine the temperature profile of the mat during the paving process and adjust the compaction time frame accordingly. Figure 1 shows schematically how the compaction time frame is determined from pavement temperatures. Under different sets of conditions, the compaction time frame may shift along the time scale and may expand or compress, depending on the rate of cooling.

Following the seminal work of Corlew and Dickson (1968) a number of one-dimensional solutions to the pavement cooling phenomenon has been developed to predict rates of cooling during compaction (Jordan and Thomas, 1976; Daines, 1985; Luoma *et al.*, 1995). More recently, the one-dimensional solution to the pavement cooling phenomenon was implemented in a Windows$^{\text{TM}}$-based computer program, PaveCool (Chadbourn *et al.*, 1998; Voller *et al.*, 1998). This program was designed to address the cold climate scenario and took into consideration the following factors in determining the thermal gradient during compaction:

- Time of year
- Time of day
- Degree latitude
- Cloud cover
- Ambient temperature
- Lift thickness
- Existing base material type, pertinent thermal properties, and temperature
- Hot mix material type, pertinent thermal properties and initial temperature

While PaveCool and its predecessors (Corlew and Dickson, 1968; Jordan and Thomas, 1976; Daines, 1985; Luoma *et al.*, 1995) are useful tools for cold temperature paving, they are somewhat limited in that they only considers one asphalt pavement lift. However, in multiple-lift paving operations, previously laid and compacted lifts may act as residual heat sources and slow the overall cooling of the newly placed lift. Therefore, an analysis that considers the complexity of a multi-layer operation is warranted. Additionally, PaveCool does not address construction time optimization problems that arise when paving multiple lifts in warm ambient conditions.

Objectives

The primary objective of this research was to develop and implement a multi-layer solution to the pavement heat transfer problem. The intention was to provide designers and on-site construction crews with a computer tool to determine the pavement temperature profile throughout the duration of the paving operation. In this way, an optimal compaction time frame could be found to minimize construction delays and improve compaction efficiency.

Scope

This research built on previous work contributing to the PaveCool program. The numerical algorithm was extended from the single layer case to the multi-layer

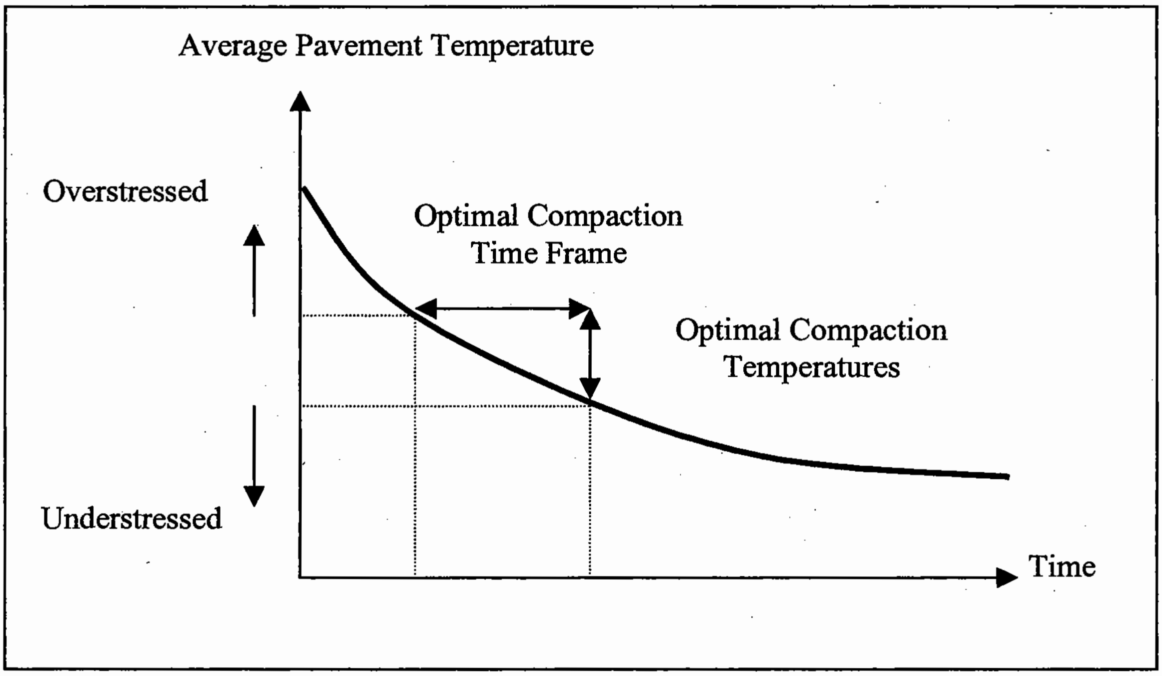


FIGURE 1 Pavement cooling curve and compaction time frame.

so that a maximum of nine pavement lifts could be simulated in a new program, CalCool. This paper describes in detail the governing equations and numerical algorithms employed in solving the multi-layer case. Comparisons between the model and *in situ* temperatures were done to validate the model. Single layer comparisons were conducted in Minnesota and several multi-layer comparisons were done in California.

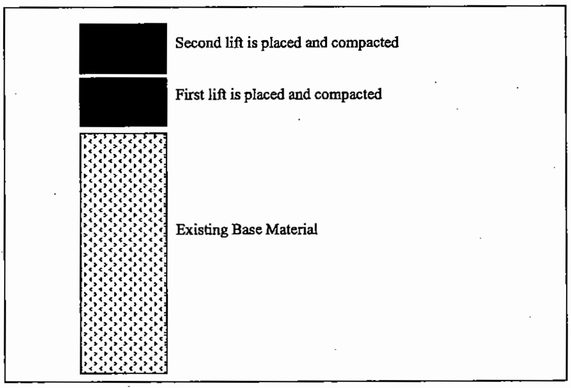


FIGURE 2 Two-lift paving process (one-dimensional schematic).

THERMAL MODEL

Multiple Lift Paving Process

Consider a two-lift paving process as shown schematically in Fig. 2. Ideally, the first lift is placed, allowed to cool below the overstressed temperature threshold, and compaction occurs between the over-stressed and understressed temperature limits. To minimize the overall construction time, the second lift is placed immediately after the first lift reaches the understressed temperature threshold and compaction begins when the temperature in the second lift falls below the overstressed threshold. Figure 3 illustrates this concept for a hypothetical two-lift pavement.

Establishing the threshold temperatures for a particular asphalt mixture is critical in effectively using information such as in Fig. 3. Establishing threshold temperatures was beyond the scope of the project since the primary focus was to determine the temperature profile with time in a multi-layer pavement. However, previous research has been

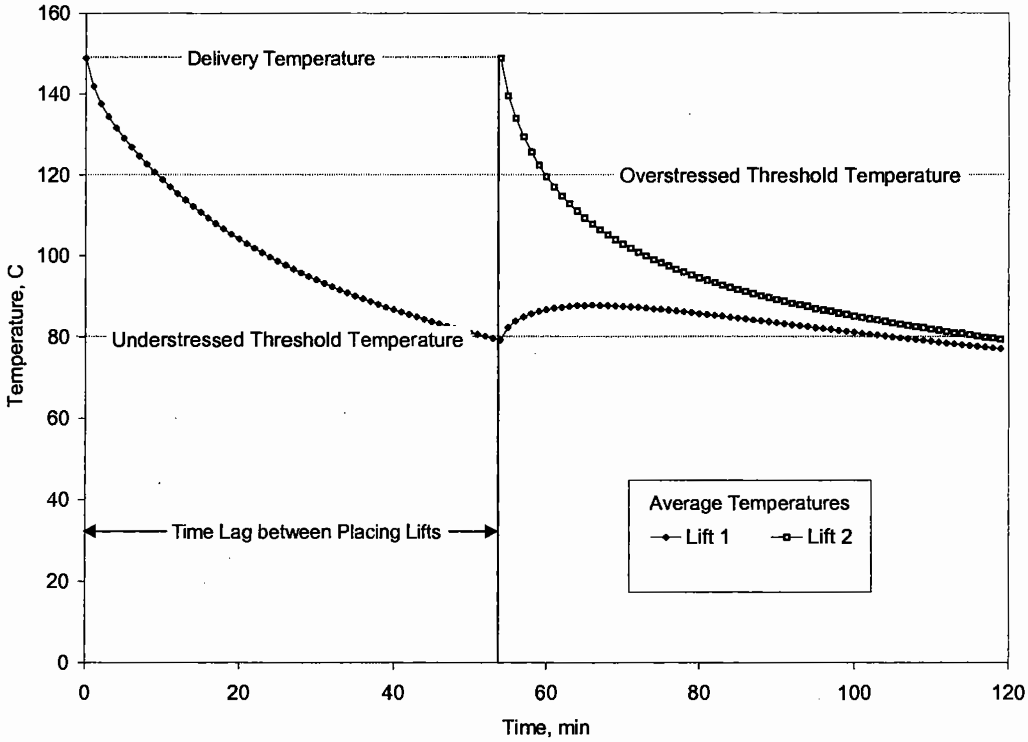


FIGURE 3 Temperature vs. time for two-lift paving process.

done to link compaction effectiveness to temperature. DeSombre *et al.* (1998) recommended starting compaction at 125°C for a PG 58–28 mixture and 115°C for a PG 52–34 mixture. Corlew and Dickson (1968) have suggested ceasing compaction when mixtures drop below 80°C.

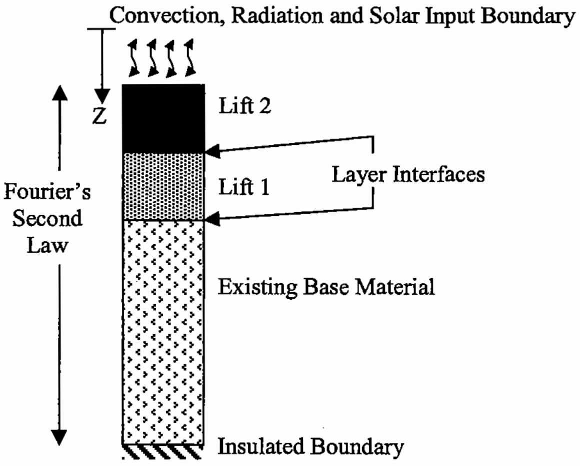


FIGURE 4 One-dimensional heat transfer in a pavement structure.

Numerical Solution

Heat Conduction and Boundary Conditions

Figure 4 illustrates one-dimensional heat transfer in a pavement structure. Within the pavement cross-section, heat transfer occurs by conduction as described by Fourier's second law:

$$\rho C\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{1}$$

where k is the thermal conductivity (W/m K), T the temperature (K), t the time (s), C the specific heat (J/kg K), ρ the density (kg/m^3), z the depth (m), positive downward.

At the bottom and top of the pavement structure, special boundary conditions can be employed to simulate the field condition. The bottom of the pavement structure is often assumed to be perfectly insulated (i.e., heat flux equals zero). Chadbourn *et al.* (1998) and Corlew and Dickson (1968) demonstrated how to incorporate convection, radiation and solar input at the pavement surface. The following heat flux equations (Eqs. (2) and (3)) represent the boundary conditions at the surface and bottom, respectively:

$$q = h(T_a - T_p) - k\frac{\partial T}{\partial z} + \alpha H_s + \varepsilon\sigma(T_a^4 - T_p^4) \quad (2)$$

$$q = 0 \quad (3)$$

where q is the heat flux(W/m^2), h is the convective heat transfer coefficient (W/m^{2}K), T_a is the ambient temperature (K), T_p is the pavement surface temperature (K), α is the total absorbency of asphalt (unitless), H_s is the net solar flux at the surface (W/m^2), ε is the total pavement emittance (unitless), and σ is the Stefan–Boltzmann constant (W/m^{2}K^4).

Finite Difference Solution

As done by Corlew and Dickson (1968) and Chadbourn *et al.* (1998), the above equations were solved using the finite difference method. Figure 5 illustrates a one-dimensional pavement structure, divided into control volumes, over which the numerical solution may be applied. Note the presence of a special node that is placed at the surface of the lift being paved. The surface node was used in the original PaveCool program and was based on work by Patankar (1991) to improve temperature predictions at the surface.

The key to the multi-layer solution is that the surface node is placed within the existing grid, as shown in the figure, and the system of simultaneous equations is solved from the surface node to the bottom of the pavement structure. This was done to eliminate the need to regrid the problem as additional pavement lifts are added during the simulated construction process. Essentially, the system of equations is only solved for the nodes that are "active" in the pavement structure.

The system of simultaneous equations (Eqs. (4)–(6)) was developed by discretizing Eq. (1) and considering a heat balance over an internal control volume as pictured in Fig. 6(a). In other words, the heat balance is expressed as the heat flowing into the central (p) control volume across the northern boundary minus the heat flowing out of the control volume across the southern boundary equals the rate of heat increase in the control volume, or:

$$\text{Heat flowing in} = k_n\left(\frac{T_n - T_p}{\delta z_n}\right) \quad (4)$$

$$\text{Heat flowing out} = k_s\left(\frac{T_p - T_s}{\delta z_s}\right) \quad (5)$$

$$\text{Rate of heat increase} = \Delta z_p \rho_p C_p\left(\frac{T_p - T_p^{\text{old}}}{\Delta t}\right) \quad (6)$$

where T is the temperature at new time step, T^{old} the temperature at old time step, $\Delta\ t$ the time increment, $\delta z_n = \Delta z_n/2 + \Delta z_p/2$, $\delta z_s = \Delta z_p/2 + \Delta z_s/2$, k_n is the thermal conductivity at the northern border of the control volume p, $k_s$is the thermal conductivity at the southern border of the control volume p, ρ_p the density of the central control volume, C_p the heat capacity of the central control volume, n the northern control volume, located above the central control volume, s the southern control volume, located below the central control volume, Δz_n the size of the northern control volume, Δz_s the size of the southern control volume, and Δz_p the size of the central control volume.

In the solution of the multi-layer cooling problem, it was assumed that only two conductivities existed, k_{asphalt} and k_{base}, although Δz was allowed to vary with the individual pavement lifts. Therefore, the heat balance equation for internal nodes, after grouping terms, is:

$$-a_n T_n + a_p T_p - a_S T_s = b_p \quad (7)$$

where:

$$a_n = \frac{2k}{\Delta z_n + \Delta z_p}$$

$$a_p = \frac{z_p \cdot \rho_p \cdot C_p}{\Delta t} + a_n + a_s$$

$$a_s = \frac{2k}{\Delta z_p + \Delta z_s}$$

$$b_p = \frac{\Delta z_p \rho_p C_p}{\Delta t}$$

At the interface between the surface and base layers, a geometric mean of the conductivities was used (Eq. (8)) for better accuracy:

$$k_{avg} = (\Delta z_{asphalt} + \Delta z_{base}) \cdot \left[\frac{\Delta z_{asphalt}}{k_{asphalt}} + \frac{\Delta z_{base}}{k_{base}}\right]^{-1} \qquad (8)$$

The special surface node, as shown in Fig. 6(b), does not have a control volume associated with it. Therefore, there is no rate of heat increase in the control volume, but it is subject to the boundary condition of Eq. (2). The first-order treatment of the heat balance expressed in Eq. (7) takes the following coefficients for the special surface node:

$$a_n = 0$$

$$a_p = a_s + h$$

$$a_s = \frac{2k}{\Delta z_s}$$

$$b_p = h(T_a) + \alpha H_s - \varepsilon\sigma(T_a^4 - T_p^{*4})$$

Note that the last term in the b_p equation, representing radiation, has not been linearized. Therefore, T_p* refers to the best estimate of the surface node temperature. In other words, a value is assumed and then the solution of the simultaneous equations must be iterated until this term converges, using the most recent T_p value for T_p*. Also, a higher order treatment of the surface node is possible, as described by Patankar (1991), and was used in determining the surface node coefficients. However, their explanation is beyond the scope of this work.

The bottom node also required special treatment. Since the bottom of the structure is assumed to be insulated, the a_s coefficient equals zero for the last node in the grid. The other coefficients for the bottom node are as specified immediately below Eq. (6).

The equations presented above, taken over the entirety of the pavement structure, form a tri-diagonal matrix that may be solved using a conventional tri-diagonal matrix algorithm or TDMA as described by Patankar (1981). Because the heat transfer at the pavement surface is modeled somewhat simplistically (i.e., no linearization of radiation boundary condition), it is necessary to iterate during a single time step as described above. However, only three to four iterations are necessary for convergence. Additionally, since the scheme is implicit in time, the solution is stable for larger time steps.

COMPUTER PROGRAM: CALCOOL

The numerical solution presented above was implemented in the computer program, CalCool. The main program window is pictured in Fig. 7, much of which is devoted to obtaining inputs from the user. An effort was made to simplify the inputs and eliminate the need for the analyst to enter such quantities as thermal conductivity and heat capacity. Rather, default values based on previous research (Kersten, 1949; Corlew and Dickson, 1968; Farouki, 1986; Atkins, 1997) were used for each of the pavement layers. Additionally, the program output is presented in either graphical or tabular form.

The program is meant for use as a pre-construction tool to aid designers in predicting the rate of cooling and specifying appropriate compaction timing. The

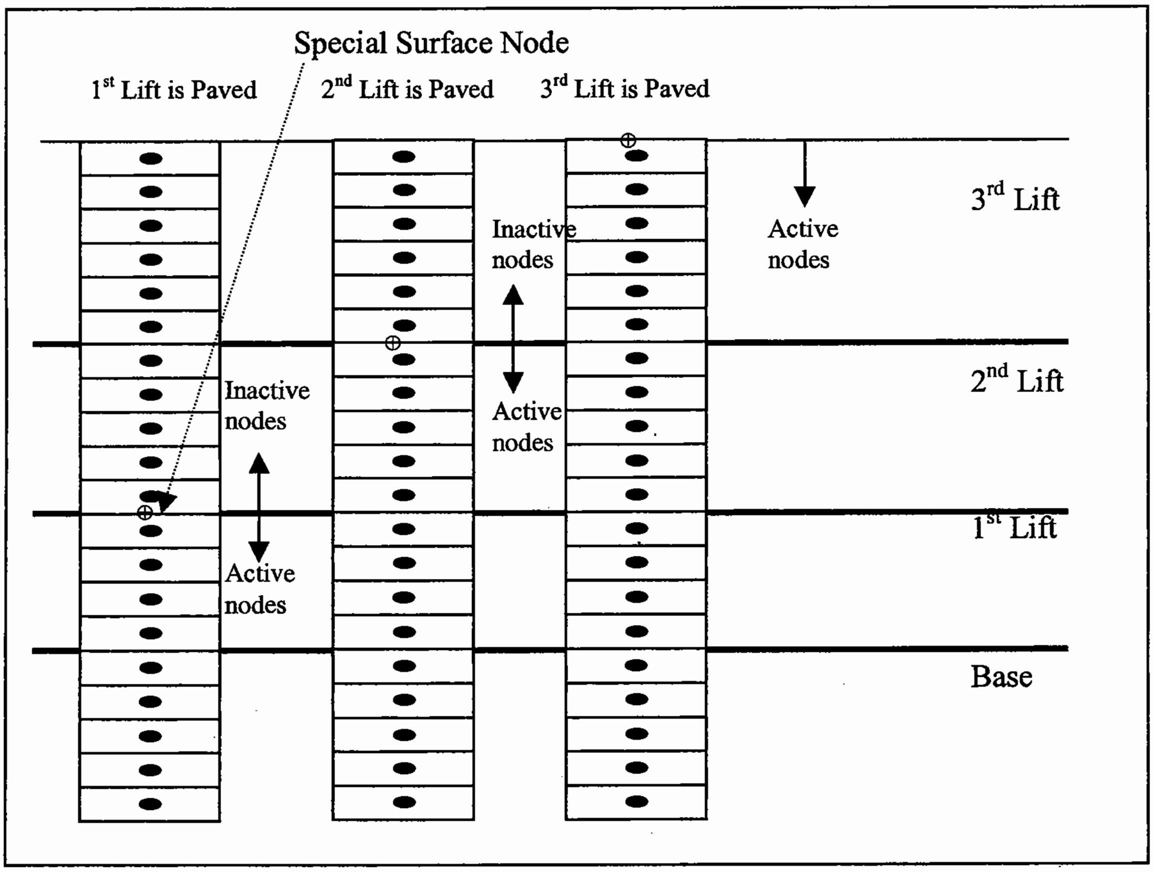


FIGURE 5 Discretized three-layer pavement structure for finite difference solution.

program may also be used on-site to aid construction crews in a similar fashion.

Program Inputs

The four input categories required to perform a cooling simulation are starting time, environmental conditions, existing surface and mix specifications, respectively. Each category will be described briefly.

Start Time

The time at which construction starts is specified so that the angle of the sun, and thus incoming solar radiation, may be calculated at the start of the simulation. As additional lifts are added during the simulation, the time is updated based upon the time elapsed during the simulation.

Environmental Conditions

The ambient temperature, average wind speed and cloud conditions at the start of paving of each individual lift are specified. These inputs pertain directly to the surface boundary conditions specified in Eq. (2). Entering different values for each lift enables simulation of changing environmental conditions during the paving operation. However, these inputs are assumed constant during the cooling of the individual lifts, respectively. The degree latitude of the job site is part of the angle of sun calculation mentioned above.

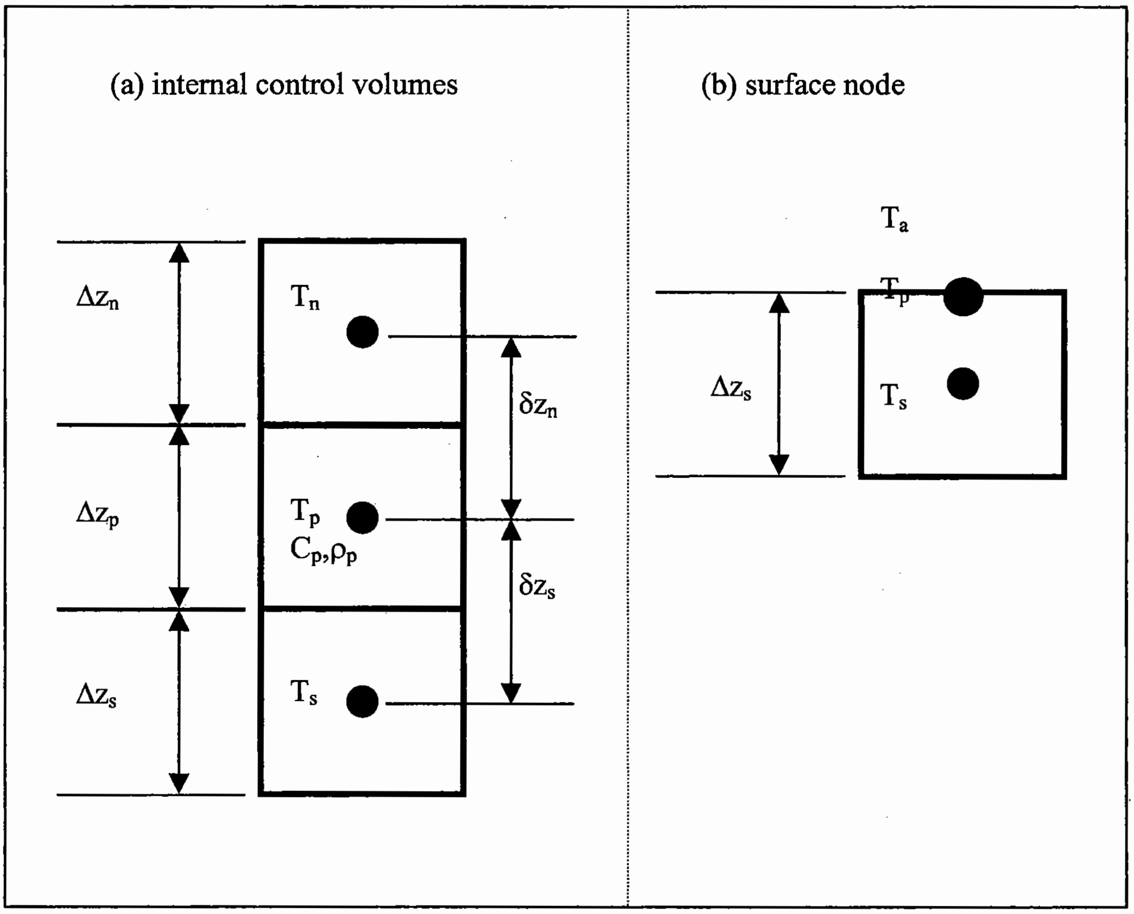


FIGURE 6 Finite difference control volumes.

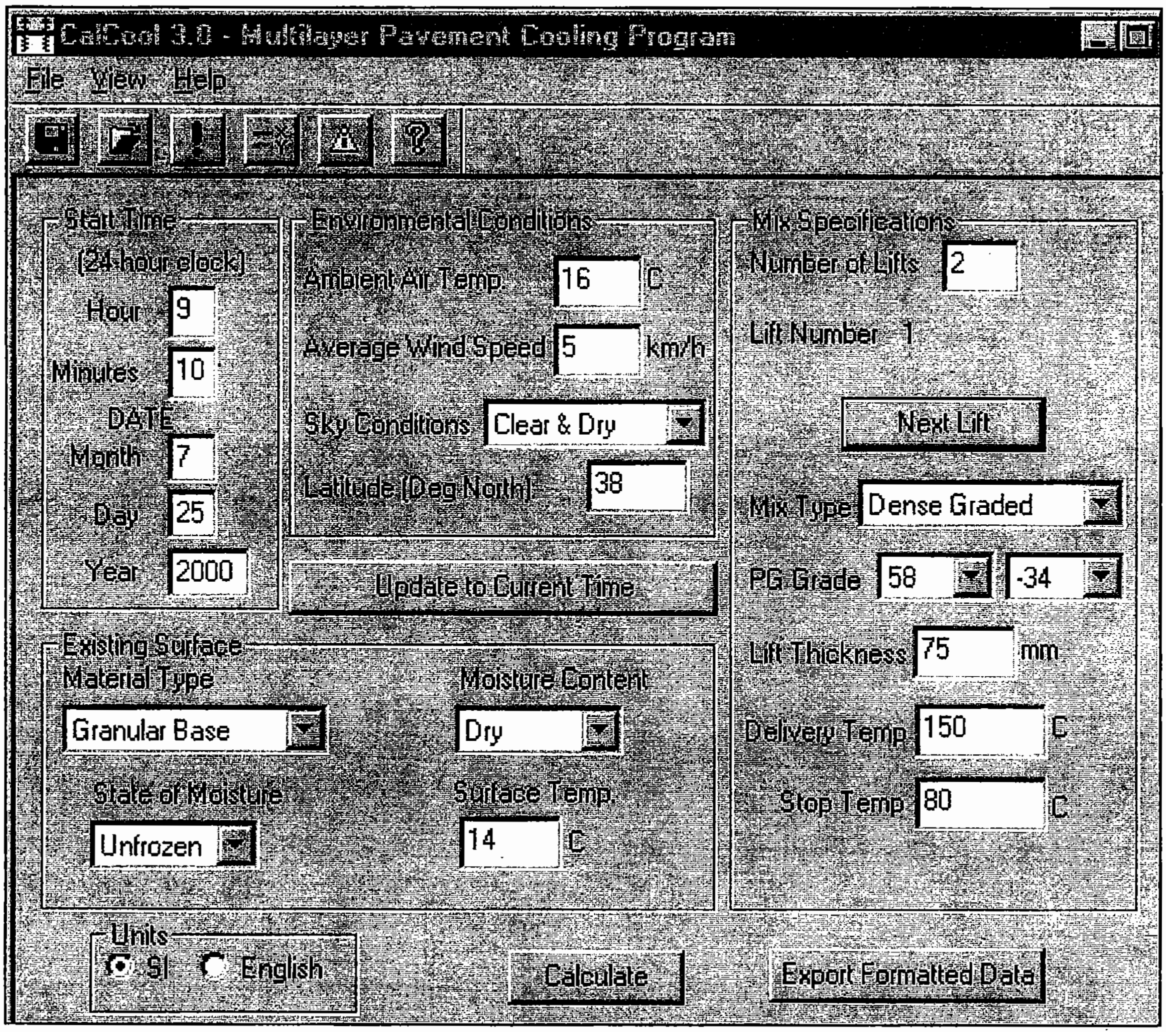
Existing Surface Conditions

Selecting a combination of existing base material, moisture content and state of moisture within the base automatically sets default values for the thermal properties required for simulation (i.e., thermal conductivity, specific heat and density). The default values in CalCool were based upon previous research (Kersten, 1949; Corlew and Dickson, 1968; Farouki, 1986; Atkins, 1997). The temperature of the existing material represents an initial equilibrium condition and is constant throughout the layer.

Mix Specifications

The analyst must input the number of total lifts that will be paved, up to nine, and it is assumed that they are paved in immediate succession. The mixture is specified according to gradation and binder. The gradation is related to the default thermal properties while the binder simply serves to better define the mixture. The default thermal properties (i.e., thermal conductivity and specific heat) are based on values measured by Chadbourn *et al.* (1998) which were similar to those reported by Kersten (1949), Kavianipour (1967), and Tegeler and Dempsey (1997). Only one asphalt mixture may be specified per paving operation.

The last three inputs are the lift thickness, delivery temperature and stop temperature, respectively. The delivery temperature is the temperature at which the hot-mix asphalt leaves the paver and can be thought of as the initial temperature. The stop temperature



Start Time
(24 hour clock)
Hour 9
Minutes 10
DATE
Month 7
Day 25
Year 2000

Environmental Conditions
Ambient Air Temp 16 C
Average Wind Speed 5 km/h
Sky Conditions Clear & Dry
Latitude (Deg North) 38

Mix Specifications
Number of Lifts 2
Lift Number 1
Mix Type Dense Graded
PG Grade 58 -34
Lift Thickness 75 mm
Delivery Temp 150 C
Stop Temp 80 C

Existing Surface
Material Type Granular Base
Moisture Content Dry
State of Moisture Unfrozen
Surface Temp 14 C

Units
● SI ○ English

FIGURE 7 CalCool main window—inputs.

signifies the temperature that the lift must be below before the next layer is added.

Program Outputs

During simulation, CalCool calculates the spatial average lift temperature with time for each of the individual lifts. The results are then plotted in the main window if graphical output was selected as shown in Fig. 8. Alternatively, the time to cool the individual lifts to the stop temperature in addition to the total time for the paving operation may be viewed in tabular form as shown in Fig. 9. Finally, the input and output data may be written to a formatted text-delimited file that can be opened, viewed and/or modified by commercial spreadsheet software.

MODEL VALIDATION

Single Layer Validation

A validation study was undertaken as part of the development of the original PaveCool program (Chadbourn *et al.*, 1998). Temperature data collected

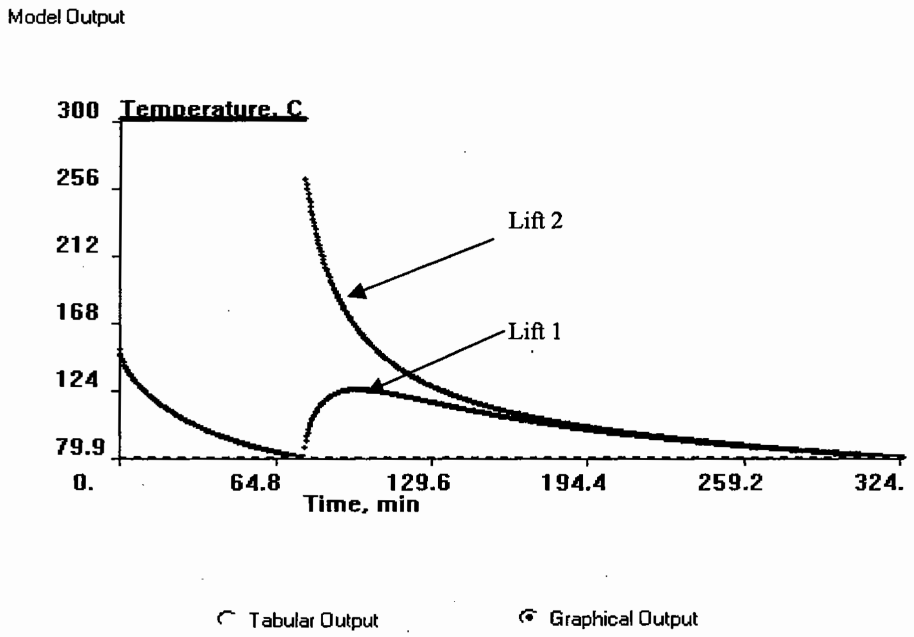
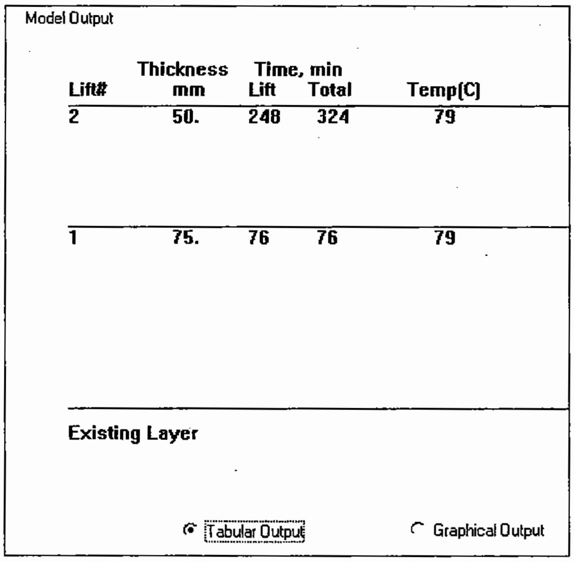


FIGURE 8 CalCool graphical output.

from the eight projects in Minnesota were compared against those calculated by PaveCool. These same data were used in comparison with CalCool. The temperature measurements were made by thermocouples embedded in the asphalt lift and spatial average temperatures were calculated using between four and six thermocouple sensors at various depths.


Model Output

Lift#	Thickness mm	Time, min Lift	Total	Temp(C)
2	50.	248	324	79
1	75.	76	76	79

Existing Layer

FIGURE 9 CalCool tabular output.

Since a single-layer simulation in CalCool is essentially identical to PaveCool, an in depth discussion of the single layer case is not warranted in this paper. However, a comparison of data at one site is shown in Fig. 10. The input parameters used in the simulation are shown in Table I. The agreement shown in Fig. 10 was typical among all the projects in the study. In general, agreement was better when as-constructed rather than designed lift thicknesses were used in simulation (Chadbourn *et al.*, 1998).

TABLE I Calcool Hwy 52 paving conditions

Input	Value
Date	July 12, 1996
Time	9:45 am
Air temperature	19.4 C
Wind speed	16 km/h
Existing surface	Dense graded HMA
Existing surface temperature	22.7 C
Cloud cover	Partly cloudy
Mix specification	Dense graded HMA
Lift thickness	64 mm

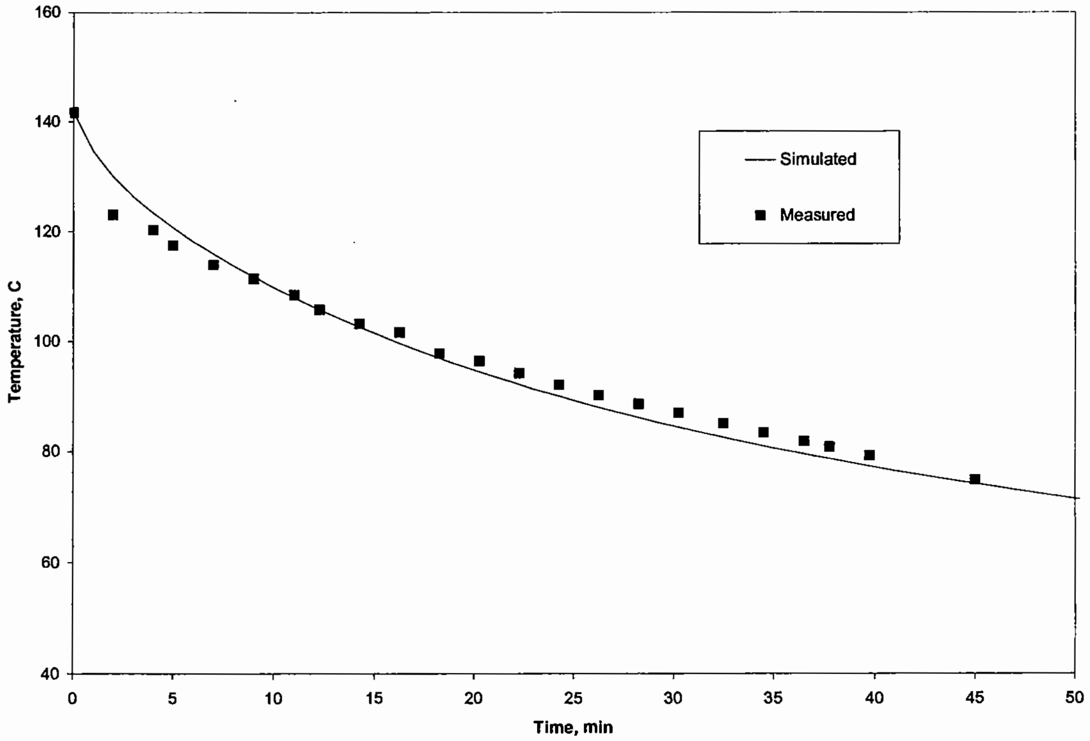


FIGURE 10 Average lift temperature comparison—Hwy 52, Rosemount, MN (Chadbourn *et al.*, 1998).

Multi-layer Validation

Multi-layer field validation of CalCool was done on two construction sites in California as part of a California Department of Transportation report on asphalt constructability (Lee *et al.*, 2000). In contrast to the single-layer validation, temperatures were only obtained at three points:

- Edge of the pavement at the bottom of the lift.
- 1 m from the edge at the pavement surface.
- 1 m from the edge of the pavement at mid-depth of the pavement lift.

The air temperature, wind speed and cloud cover were also recorded at each location. The frequency of recording data varied depending on the number of locations being monitored. Sampling of temperatures and wind speed continued until the lift temperature reached 50°C or 60°C.

Site 1: Lompoc

The first site was daylight construction on Route 1 in Lompoc in Santa Barbara County. The existing asphalt concrete was removed and new asphalt concrete was placed over the existing granular base in three lifts. Paving occurred over two days of which the first day could be considered a single-layer operation with multi-layer following on the second day.

The first lift of material on the existing granular base was a rich bottom (5.8% AR-8000) asphalt mixture with 19 mm maximum size coarse aggregate. The hot asphalt concrete was placed in a windrow by bottom dump trucks and the paver was waiting for the delivery of the hot asphalt mix. As a result delivery temperatures measured in the windrow were on average 155°C.

TABLE II Lompoc—day 1—single lift paving conditions

Input	Value
Date	October 7, 1999
Time	7:55 am
Air temperature	11 C
Wind speed	2.5 km/h
Existing surface	Granular base
Existing surface temperature	14.0 C
Cloud cover	Clear and dry
Mix specification	Dense graded HMA
Lift thickness	90 mm

An "anteater" was used to pick up the windrow and transfer it to the paver. The delivery temperature of the asphalt concrete was taken with a digital thermometer once the bottom dump truck placed the windrow. Temperatures were monitored over time at the same locations.

Tables II and III contain the paving conditions and Figs. 11 and 12 illustrate the temperature curves over the two days of paving at Lompoc, respectively. Since CalCool calculates average lift temperatures, it was decided to compare the mid-depth temperature measurement to the CalCool prediction.

TABLE III Lompoc—day 2—second and third lift paving conditions

Input	Value
Date	October 8, 1999
Second lift data	
Time	8:50 am
Air temperature	23 C
Wind speed	5.0 km/h
Existing Surface	Dense graded HMA
Existing surface Temperature	23.0 C
Cloud cover	Clear and dry
Mix specification	Dense graded HMA
Lift thickness	80 mm
Third lift data	
Time	11:22 am
Air temperature	32 C
Wind speed	0 km/h
Existing surface	Dense graded HMA
Existing surface Temperature	58.0 C
Cloud cover	Clear and dry
Mix specification	Dense graded HMA
Lift thickness	80 mm

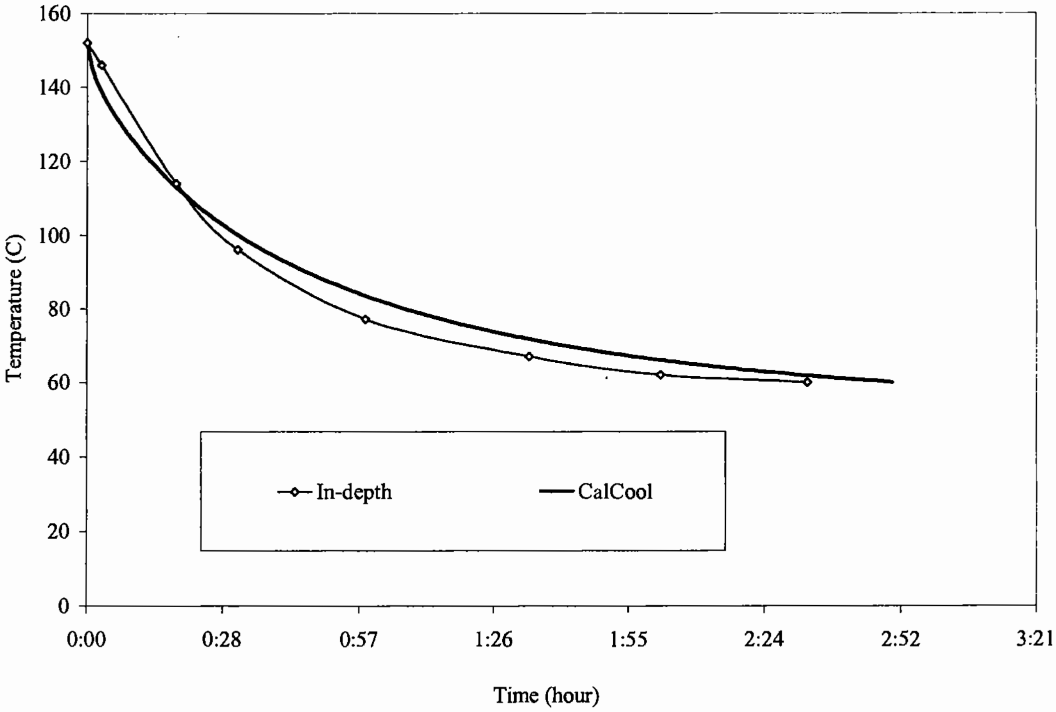


FIGURE 11 Lompoc—day 1—single lift.

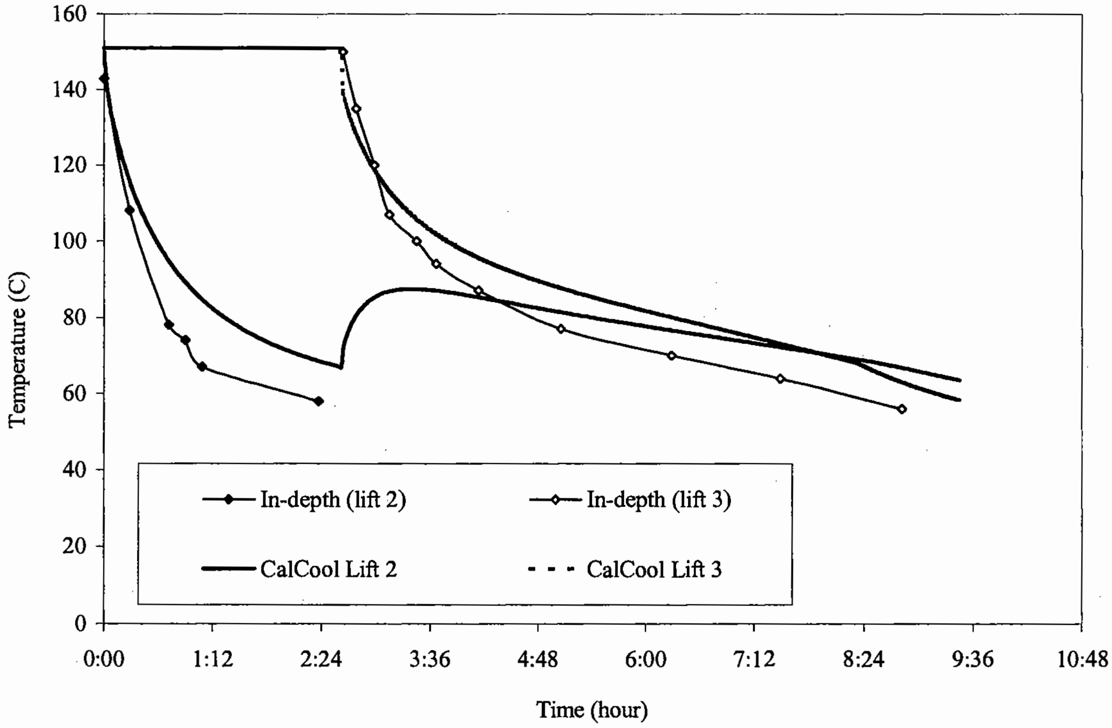


FIGURE 12 Lompoc—day 2—second and third lifts.

Good agreement between the measured and predicted cooling curves was observed for the first lift. CalCool tended to over-predict the pavement temperature for the second and third lifts, respectively. However, CalCool did capture the shape of the cooling curves and was within 10°C of the measured values. It is possible that comparing spatial averages directly, as done by Chadbourn *et al.* (1998), would improve the accuracy of the CalCool prediction.rather than using a single measurement in the pavement.

Site 2: San Leandro

The second site was on Marina Boulevard in San Leandro in Alameda County. Unlike the previous construction, this was done at night since this area is a main corridor for heavy truck traffic off of Interstate 880. Construction involved removing, on average, 318 mm of existing asphalt concrete and replacing it with 5.2% AR-8000 using 19 mm maximum size coarse aggregate. The first lift of asphalt concrete was placed over the existing granular base on the lane nearest the sidewalk and over Portland cement concrete on the adjacent lanes. The existing layers were wet due to heavy mist and rain. Three lifts of asphalt concrete were placed nearest the sidewalk lane and four lifts on the adjacent lanes. The data shown below pertain only to the first three lifts in both cases.

This project was true multi-lift construction as the lifts were placed one after the other in the same night. End dump trucks were used to deliver the hot asphalt mix. Unlike the Lompoc construction, delivery trucks were in line waiting for the paver. Since the length of construction was very short (about 245 m on the first day), the paver needed to maneuver around corners and backup to the start point after it reached the end. Therefore, delivery temperatures of the asphalt mix as a result were

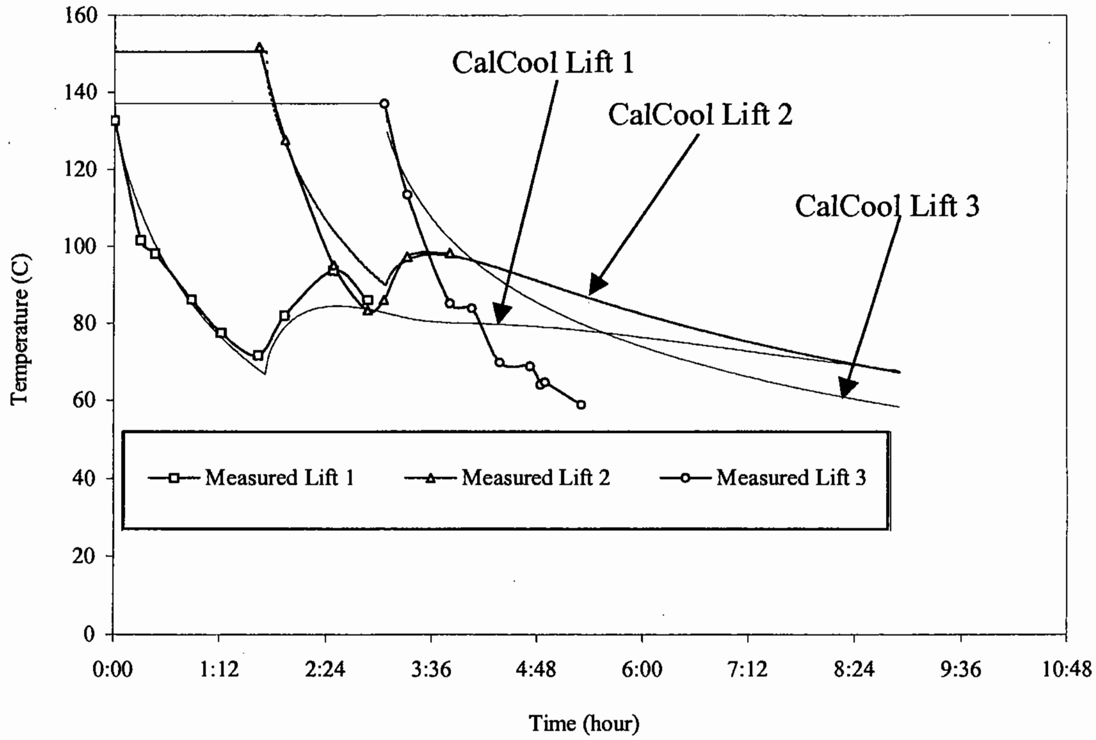


FIGURE 13 San Leandro—AC over granular base.

more variable and lower than the Lompoc construction. The average initial temperature measured of the hot asphalt mixture was 143.7°C. Initial temperature measurements were lower because they were taken behind the paver rather than from the truck or the windrow as was done in Lompoc.

The paving conditions for the AC over granular base and AC over PCC are listed in Tables IV and V, respectively. Figures 13 and 14 show the cooling curve comparisons between CalCool and the measured mid-depth temperature.

In general, the data compared more favorably for the AC over the granular base (Fig. 13) than the AC over PCC (Fig. 14). The CalCool predictions for lifts 1 and 2 in Fig. 13 fare reasonably, typically within 5°C and 10°C of the measured values. The third lift in Fig. 13 cooled more quickly than predicted by CalCool. Other confounding factors, such as rainy conditions, not accounted for in CalCool, could be the reason for the discrepancy.

The data shown in Fig. 14 have greater differences between the measured and predicted temperatures. While capturing the general shape of the cooling curves, CalCool under-predicts the temperature by as much as 20°C. Similar results were seen on some projects in the original PaveCool validation project (Chadbourn *et al.*, 1998).

It is important to note in Fig. 13 that at certain points in time the temperature of the underlying layers were greater than the newly placed layer. The phenomenon was both predicted by CalCool and measured *in situ* and has important implications regarding compaction. For example, a previously compacted lift thought to have cooled sufficiently to provide a stable construction platform for the next lift could undergo further compaction due to the elevated temperature. Consequently, the new lift may not undergo sufficient compaction since some of the compactive effort would be going into the layer placed previously. This phenomenon should therefore

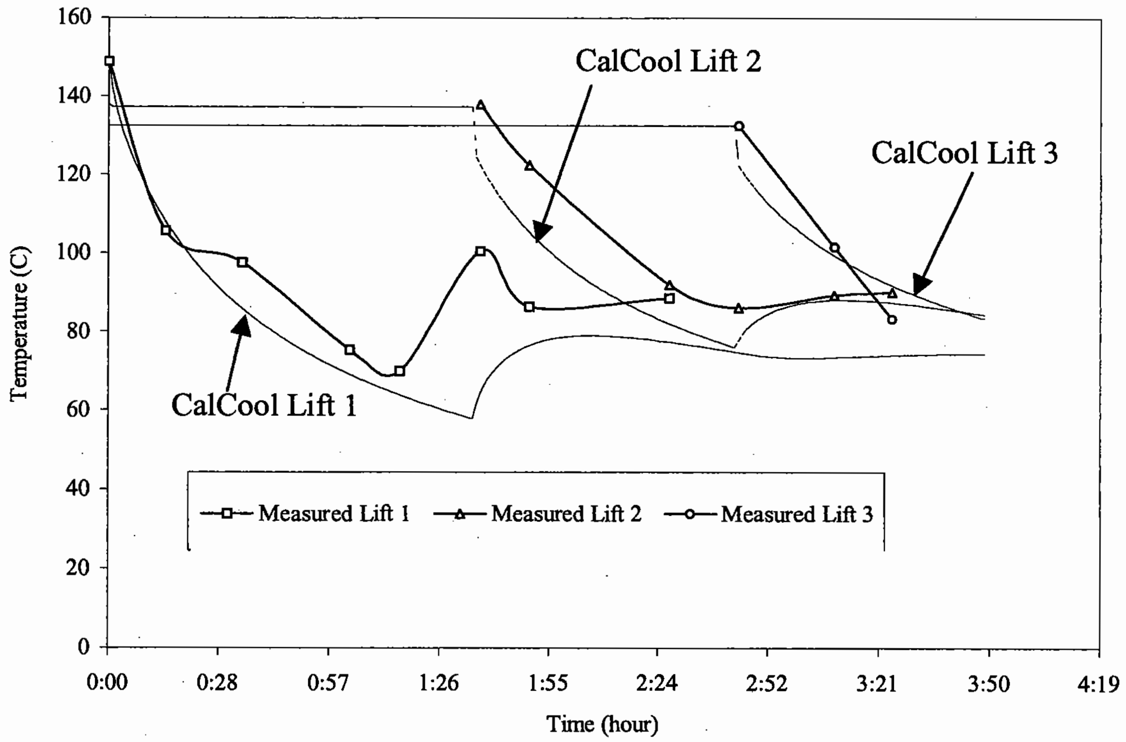


FIGURE 14 San Leandro—AC over Portland cement concrete (PCC).

be taken into consideration when planning and executing the compaction plan.

SUMMARY AND CONCLUSIONS

The temperature at which compaction takes place is an important factor in the construction of asphalt concrete pavements. In cold climates, rapidly cooling mats can lead to poor compaction that is detrimental to the overall structural capacity and durability of the pavement. In warm paving conditions, time of construction is a greater concern, and compaction should begin as soon as possible to minimize the required time for construction.

The objective of this research was to create a computer tool that pavement designers and on-site construction crews could use to predict the pavement temperature during construction and modify designs or compaction procedures accordingly. The result of this research was CalCool, a multi-layer pavement cooling tool based on theoretical heat transfer considerations. The program advanced previous work in this area by extending the single layer solution to multi-layer construction operations.

A model validation study was conducted to compare CalCool in single and multi-layer construction scenarios. The comparisons were favorable in the single-layer cases, but the multi-layer cases increased some discrepancies between the measured and predicted cooling curves. It is recommended that future validation studies use thermocouples imbedded in the pavement structure so that spatial averages may be determined and compared with the results of CalCool. Also, based upon the data from only two sites, it is difficult to state with certainty whether CalCool provides reliable multi-layer cooling predictions. Therefore, more validation studies are certainly needed. Despite the discrepancies, the data provided in this paper do suggest that CalCool gives reasonable temperature predictions in multi-layer paving operations.

TABLE IV San Leandro—AC over granular base—paving conditions

Input	Value
Date	July 17, 2000
First lift data	
Time	1:17 am
Air temperature	14 C
Wind speed	7.1 km/h
Existing surface	Wet granular base
Existing surface temperature	19.4 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	100 mm
Second lift data	
Time	2:55 am
Air temperature	16.4 C
Wind speed	5.8 km/h
Existing surface	Dense graded HMA
Existing surface temperature	58 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	100 mm
Third lift data	
Time	4:20 fam
Air temperature	16.3 C
Wind speed	16.3 km/h
Existing surface	Dense graded HMA
Existing surface temperature	77.6 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	91 mm

TABLE V San Leandro—AC over PCC—paving conditions

Input	Value
Date	July 17, 2000
First lift data	
Time	2:00 am
Air temperature	15.9 C
Wind speed	5.8 km/h
Existing surface	PCC
Existing surface Temperature	20.0 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	61 mm
Second lift data	
Time	3:37 am
Air temperature	15.8 C
Wind speed	4.0 km/h
Existing surface	Dense graded HMA
Existing surface temperature	81.1 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	76 mm
Third lift data	
Time	4:45 am
Air temperature	16.0 C
Wind speed	4.0 km/h
Existing surface	Dense graded HMA
Existing surface temperature	86.6 C
Cloud cover	Overcast
Mix specification	Dense graded HMA
Lift thickness	76 mm

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