COOLING PROPERTIES OF ASPHALT SURFACES

STUDY 2112, ORA 125-4197

Submitted to
Oklahoma Department of Transportation

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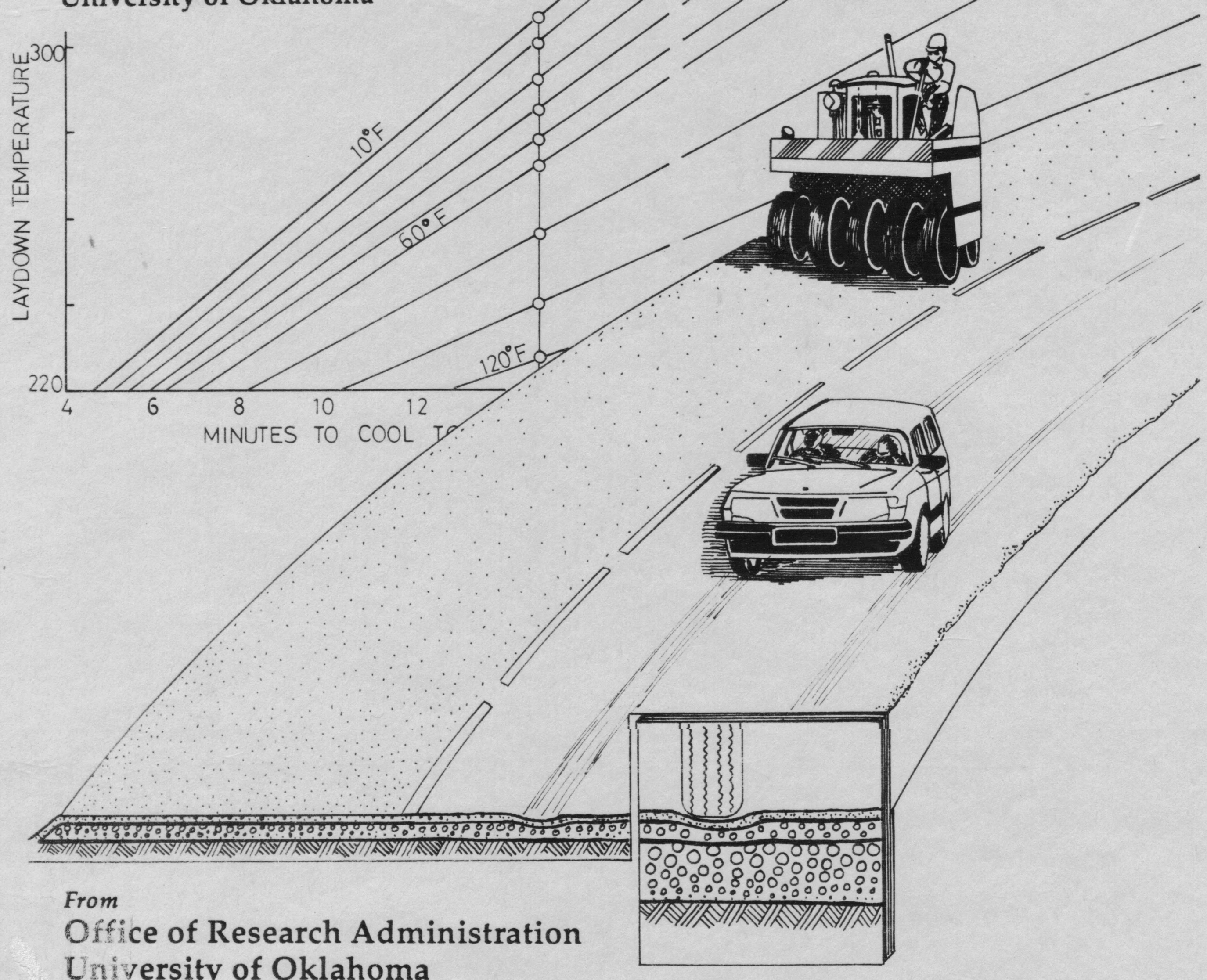

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16. ABSTRACT

Cooling properties of hot mix asphalt (HMA) are important to transportation agencies and contractors in a surfacing or resurfacing operation. The cooling rate of an HMA overlay dictates how soon a roadway can be opened to traffic without having any potentially serious consequences on the pavement performance. The ease or difficulty of compacting HMA paving mixtures by rolling is influenced by the viscosity-temperature characteristics of the asphalt cement and the temperature of the mix during compaction. Thus, knowing the cooling rate of HMA provides the contractor information such as the extent of time within which breakdown rolling must be completed to ensure quality of the pavement and also when a roadway can be opened to traffic following a surfacing/resurfacing job without any detrimental consequences.

A telephone interview was conducted with selected DOTs. From the interviews, it became evident that although several DOTs do not specify a certain temperature range, they do suggest, based on their experiences, that it is preferable to open a roadway to traffic when the HMA temperature is below 140°F. This temperature is close to the 150°F reported in the Synthesis of Highway Practice by the National Cooperative Highway Research Program (NCHRP). HMA thickness and wind velocity have been rated by the DOTs as the most significant factors that influence the cooling rate of HMA.

A finite difference computer code provided in the reference as well as a general purpose finite element program ABAQUS were used to compute the time needed by a HMA layer to cool to 150°F. In this work, the time to cool to various given average mat temperatures was computed for various laydown (200-300°F) and base temperatures (50-120°F). Some field data was collected from a site on I-35 near its intersection with State Highway 51. The field data compares favorably with that obtained from the numerical model predictions for similar conditions. Therefore, the results reported here can be used, with proper engineering judgement, to determine the time required to open the road to traffic.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Cooling properties of hot mix asphalt (HMA) are important to transportation agencies and contractors in a surfacing or resurfacing operation. The cooling rate of an HMA overlay dictates how soon a roadway can be opened to traffic without having any potentially serious consequences on the pavement performance. The ease or difficulty of compacting HMA paving mixture by rolling is influenced by the viscosity-temperature characteristics of the asphalt-cement and the temperature of the mix during compaction. The cooling rate of HMA becomes a very important factor with regard to the compactive effort needed to achieve the specified density. Thus, knowing the cooling rate of HMA provides the contractor information such as the extent of time within which breakdown rolling must be completed to ensure quality of the pavement and also when a roadway can be opened to traffic following a surfacing/resurfacing job without any detrimental consequences.

A telephone interview was conducted with selected DOTs. From the interviews, it became evident that although several DOTs do not specify a certain temperature range, they do suggest, based on their experiences, that it is preferable to open a roadway to traffic when the HMA temperature is below 140 F. This temperature is close to the 150 F reported in the Synthesis of Highway Practice by the National Cooperative Highway Research Program (NCHRP). HMA thickness and wind velocity have been rated by the DOTs as the most significant factors that influence the cooling rate of HMA.

A finite difference computer code provided in the reference as well as a general purpose finite element program ABAQUS were used to compute the time needed by a HMA layer to cool to 150°F. In this work, the time to cool to various given average mat temperatures was computed for various laydown (200-300°F) and base temperatures (50-120°F). Some field data was collected from a site on I-35 near its intersection with State Highway 51. The field data compares favorably with that obtained from the numerical model predictions for similar conditions. Therefore, the results reported here can be used, with proper engineering judgement, to determine the time required to open the road to traffic.

Chapter I

INTRODUCTION

1.1 BACKGROUND AND NEED

Cooling properties of hot mix asphalt (HMA) surfaces are important to transportation agencies for various reasons. For example, the cooling rate of an HMA overlay dictates how soon a roadway can be opened to traffic without suffering any potentially serious consequences on the pavement performance. In many state roadways in Oklahoma where the traffic is rather heavy it is desirable to reduce the time between an overlay or surfacing operation and opening the roadway to traffic. This is particularly important for two lane highways and urban roadways where interruptions in normal traffic flows may have many detrimental effects. A premature opening of a roadway to traffic after an HMA surfacing or resurfacing operation can seriously impact the pavement performance. Excessive rutting, fatigue cracking and surface deterioration in the form of spalling or raveling can all occur as a result of premature traffic flow on HMA surfaces. For example, a rutting depth of as much as 2.5 in. within several months of HMA placement has been reported in the literature due to the urgency of prematurely opening a lane to traffic after the completion of rolling [Dickson and Corlew, 1972]. According to an AASHTO [1991] report, an overlay thickness of less than 2 in. is very susceptible to premature failure because of the potential inability to compact to an adequate density before it cools below the minimum compaction temperature [AASHTO, 1991]. It is particularly difficult to obtain the desired density on thin lifts in cool weather because of the rapid heat loss [AASHTO, 1991].

An understanding of cooling rate of an HMA overlay under various environmental conditions is important to the contractor in a surfacing or resurfacing operation. This information will provide a contractor an estimate of the desired time to apply the "breakdown rolling" to ensure the quality of the pavement. It has been reported by Foster [1970] that the initial or breakdown rolling usually produces most of the density. Compaction is the single most important factor that affects the ultimate performance of a HMA pavement [AASHTO, 1991]. An adequate compaction of the mix increases the fatigue life, strength and stability of HMA pavements, and decreases permanent deformation (rutting) and low-temperature cracking [AASHTO, 1991].

The ease or difficulty of compaction of any given dense graded asphalt-concrete paving mixture by rolling during construction is influenced by the viscosity-temperature characteristics of the asphalt-cement and the temperature of the mix during compaction [McLeod, 1966]. If the paving mixture becomes too hard due to low temperature, the pavement will have low density. Consequently, higher air voids may cause it to deteriorate at a faster than normal rate, resulting in curtailed service life. McLeod [1966] reported that an increasing resistance to compaction is due to increasing viscosity of the binder as the mix temperature falls. Therefore, the cooling rate of HMA becomes a very important factor with regard to the compactive effort needed to achieve the specified density [McLeod, 1966]. The rate of cooling of asphalt concrete surfaces is a complex problem which can be influenced by many factors including the thermal properties, density, thickness and initial temperature of the mix, as well as environmental factors such as ambient temperature, wind velocity, solar flux and base or subgrade moisture contents [Corlew and Dickson, 1968; Foster, 1970; Beagle, 1966]. Thus, for field applications, it is important to quantify the influences of these factors on the cooling rates of HMA surfaces. Numerical models, in conjunction with field data, may be an important tool in such efforts.

1.2 GOALS AND OBJECTIVES

The primary objective of the proposed research was to conduct a comprehensive survey of literature on the cooling properties of HMA and review the standards and practices followed by various state DOTs, particularly those having environmental factors similar to Oklahoma. Specifically, information was gathered to seek answers to the following questions:

(1) What HMA temperature range is acceptable or desirable before opening a roadway to traffic ?

(2) How long does it take to obtain this temperature in the field after a surfacing or resurfacing operation?

(3) Could the important factors (influencing the cooling rates of HMA) be quantified?

1.3 STUDY TASKS

To accomplish the aforementioned objectives the following tasks were identified and pursued:

Task 1 : Review of literature.

Task 2 : Telephone interviews with selected DOT personnel from several states who are experienced with HMA surfacing/resurfacing operations and the associated standards and practices. The following DOTs were included in the information collection process: Georgia, Florida, Arizona, Texas, Nevada, Arkansas, and New Mexico because of their climatic similarities to Oklahoma.

Task 3 : Analysis of information collected.

Task 4 : Comparison of state practices.

Task 5 : Modification of an existing numerical model to predict the cooling rate of HMA under some specific weather conditions (similar to Oklahoma weather)

Task 6 : Conclusions and recommendations

Chapter II

COOLING OF HOT-MIX ASPHALT

2.1 COOLING PROCESS

The physical problem of hot mix asphalt (HMA) cooling involves the transient flow of thermal energy from the HMA layer or mat to its surroundings. Since thickness of the mat is much smaller compared to its length and width, for practical purposes, only the heat flow in the vertical dimension is considered to dominate the cooling process [Dickson and Corlew, 1970]. HMA loses its temperature to the two contact surfaces: the upper surface and the lower surface, as shown in Fig. 2-1. At the upper surface of the HMA mat, heat is lost to the atmosphere by a combination of convective transport and radiative emittance of the asphalt surface. Convective heat losses are dictated by the wind velocity, due to its influence on the heat transfer coefficient. Radiative heat emittance from the asphalt surface is dominated by the product of its total emittance, the Stefan-Boltzmann constant and surface temperature to the fourth power. In addition, radiant energy from the sun impinges on the asphalt surface and a portion of this energy is absorbed by the asphalt [Dickson and Corlew, 1970]. At the lower asphalt surface, thermal energy is lost to the base (or existing pavement in case of an overlay) by the process of thermal conduction. The magnitude of the thermal flux from asphalt to base is determined by the thermal conductivities and the temperature distributions in the two regions. The temperature distributions in both asphalt and base vary with time as heat is lost from the asphalt and gained by the base [Dickson and Corlew, 1970].

Dickson and Corlew [1968] demonstrated both experimentally and analytically that the heat loss to the base exceeds the loss to the atmosphere. This means that asphalt temperatures decrease more rapidly near the base than near the surface. In a similar study, Beagle [1966] observed that the greatest heat loss is caused by transmission to the base. This was found to be true regardless of the thickness of mix used. It may be noted that thicknesses of 2.5, 5, 7.5 in. were considered in Beagle's study. According to Corlew and Dickson [1968], the greatest heat loss would occur at the lower surface of the mix for most actual paving operations. A study by Schaub [1968] confirmed this observation that the HMA mat lost heat more readily to the base than to the air.

2.2 FACTORS INFLUENCING THE COOLING RATE

2.2.1 Laydown Temperature

Asphalt mixes are usually produced from the plant at temperatures between 270 °F and 325 °F. Depending on environmental conditions and the hauling length, the mixture can lose between 5 °F and 25 °F from the plant to the paving site. As the initial mix laydown temperature is increased, the time available for compaction is also increased.

To demonstrate the effect of laydown temperature on the cooling rate of HMA surfaces, Fig. 2-2 shows a plot of laydown temperature versus time to cool to 175 °F for a 2 in. lift at a 50 degree °F base temperature. It is important to note that the data in Fig. 2-2 was replotted by Foster [1970] from the curves prepared by Corlew and Dickson [1968]. It is obvious that the laydown temperature is an important variable in determining the time available to apply rolling before the mat cools so much that it cannot be compacted effectively any more. For example, at a laydown temperature of 280 °F, it will take more than 15 min. for it to cool to 175 °F. However, if the laydown is delayed by truck or paver for some reasons so that the laydown temperature becomes 225 °F, it will cool to 175 °F in about 7 min.; this is less than half the time of the laydown temperature at 280 °F. It is observed from Fig. 2-6 that the effect of laydown temperature is more significant when a mat thickness is small and base temperature is low. Thus, when conditions are favorable for shortening the time of an HMA surface to cool to 175 °F, an increase in the mix laydown temperature would be required to extend the time available for compaction.

2.2.2 Effect of Base Temperature

As noted earlier a portion of the heat in the asphalt mix is lost to the base layer. Heat is usually lost to the base more rapidly than lost to the air. Although atmospheric temperature and base temperature are interacting with respect to temperatures near the upper and lower surfaces, base temperature is controlling for temperatures near the lower surface of HMA, and atmospheric temperature is controlling for temperatures near the upper surface of HMA. Base temperature was selected by Dickson and Corlew [1970] as the other principal variable, and air temperature and solar flux fitted the base temperature as given in Table 2-1.

All other factors being equal, an increase in the base temperature decreases the rate of cooling of the mix. This increase in base temperature allows more time for the compaction to achieve the desired density level in the mix.

It has been reported that a moist base layer can significantly increase the cooling rate of the new asphalt overlay [Dickson and Corlew, 1972]. Heat is lost from mix to moisture, turning water into steam and increasing the rate of heat transfer. The presence of moisture may cause the mix to cool quickly and reduce the time available for compaction. Therefore, ODOT and other DOTs (namely, Georgia, Florida, Arizona, Texas, Nevada, Arkansas, New Mexico) prohibit the paving of HMA on the wet surface [ODOT, 1988].

Fig. 2-3 illustrates the effect of base temperature on the time required for a 2 in. mat to cool to 175 $^{\circ}$F. A 10 degree change in base temperature would result in a very small (about one min.) change when the laydown temperature is of the order of 280 $^{\circ}$F.

2.2.3 Effect of Wind Velocity and Solar Flux

As might be expected, a change in wind velocity has greater effect on the temperature near the upper surface of the mix than near the lower surface. Also, the effect of wind velocity is more significant on a thin mat than on a thick mat. Fig. 2-4 illustrates the effect of wind velocity on time required for a 2 in. mat placed on a 50 $^{\circ}$F base to cool from 280 $^{\circ}$F to 175 $^{\circ}$F. It indicates that a 20 knot wind (about 22.2 mph) reduces the time by only 2 min. (from 15 to 13 min.)

The solar constant is the radiant energy flux incident upon a surface normal to the sun's radiation. According to Robinson [1966], solar-radiant flux incident on the earth's surface on a clear day may vary from 40 to 300 Btu /hr ft^2, depending on solar altitude. The relationships among solar flux, air temperature and base temperature are presented in Table 2-1.

The amount of radiant energy available from the sun (solar flux) is a function of many variables, including the position of the sun above the horizon, the elevation above sea level of the paving project, the amount of turbidity in the air, and the degree of cloud cover. The amount of solar flux is more important in terms of its effect on base temperature than its effect on mix temperature [Corlew and Dickson, 1968].

Similar to the effect of wind velocity on HMA temperature, the radiant energy from the sun has a pronounced effect on the temperature of the mix near the upper surface than on the temperature of the mix near the lower surface. Corlew and Dickson [1968] reported that a decrease in solar radiation from 350 to 0 Btu /hr ft^2 decreases the elapsed time to reach 200 $^\circ$F from about 25 min. to about 16 min. for a point 0.25 in. into the mix from the upper surface. Although solar-radiant flux plays only a minor role in the cooling of hot-mix asphalt concrete, the overall effect of solar radiation is two-fold. It affects both the rate of cooling on the upper surface of the mix and the initial base-temperature distribution prior to laying the asphalt. The effect of solar radiation on initial base-temperature distribution is undoubtedly of much greater consequence than its effect after the mix is placed [Dickson and Corlew, 1970].

2.2.4 Effect of Mat Thickness

Fig. 2-5 shows a plot of cooling curves for 1.5 and 2 in. mats illustrating the importance of mat thickness on time available for rolling or compaction of an HMA overlay. For the same laydown temperature and base temperature, the contractor will have considerably longer rolling time in a 2 in. mat than in a 1.5 in. mat. For a 280 $^\circ$F laydown temperature, the time difference is about 5 min.

Fig. 2-6 shows that for a laydown temperature of 250 $^\circ$F and a base of 40 $^\circ$F, an 1 in. thick mat will cool from 250 $^\circ$F to the 175 $^\circ$F compaction cutoff point in less than 4 min. For a 2 in. thick mat, under the same mix and base temperature conditions, it will take about 10 min. for the material to cool to 175 $^\circ$F. Doubling the lift thickness from 1 to 2 in. increases the time available for compaction from 4 to 10 min. If the layer depth is 4 in., the time to cool changes to about 29 min., a significant increase in available compaction time under similar temperature conditions.

2.3 CESSATION REQUIREMENTS

2.3.1 Influence of Temperature of Mix on Compaction

A mix of higher laydown temperature is easier to compact than a mix of lower temperature during laying. However, if the initial temperature of the mix is too high, the mix may be tender and difficult to compact until the mix temperature decreases and the viscosity of the asphalt cement increases. If the mix temperature is too low, an increased amount of compactive effort will be needed to obtain the required density. Adequate density may never be achieved if the laydown temperature is too low (e.g., below 175 $^{\circ}$F).

Difficulty in compacting any given dense graded asphalt-concrete paving mixture (by rolling during construction) can be contributed by many factors. The viscosity-temperature characteristics of the asphalt-cement, the temperature of the mix during compaction, the gradual increase of stability and density of the mix as rolling proceeds, the rate of cooling of the mix behind the spreader, and the use of low rather than high viscosity asphalt-cement all affect compaction effectiveness [McLeod, 1966]. Compaction of a HMA paving mixture to the specified density (by rolling during construction) is facilitated when the viscosity of the asphalt-cement is low, and becomes more difficult when the viscosity is high. For example, the viscosity at a laydown temperature of 275 $^{\circ}$F, the temperature at which the mix often leaves the spreader, is about 5 poises, whereas at about 135 $^{\circ}$F, the temperature at which rolling often ceases, its viscosity is about 5,000 poises. Consequently, this mixture is 1,000 times more viscous at 135 $^{\circ}$F than at 275 $^{\circ}$F [McLeod, 1966]. For a given compactive effort the temperature of compaction can have an important influence on the air voids content, and therefore on the density of a paving mixture. For example, compacting a particular mixture at 150 $^{\circ}$F results in an air void value 4 times as large as that resulting from compaction at 275 $^{\circ}$F. The principal difference between the paving mixture at 150 and 275 $^{\circ}$F is the much higher viscosity in the lower temperature mix.

During the construction stage the temperature of the paving mixture is normally within the range of 275 to 325 $^{\circ}$F as it leaves the mixing plant, and ends between 100 and 150 $^{\circ}$F, when final rolling is completed. In the long service stage of its existence, the maximum temperature attained at the pavement surface seldom exceeds 140 $^{\circ}$F and ordinarily remains at the highest temperature for less than two hours on any one day [McLeod, 1966].

2.3.2 Minimum Temperature Requirements

Currently, construction involving bituminous materials such as HMA surfaces needs to be stopped when the temperature and environmental factors fall below a certain value. For example, ODOT's 1988 specification [ODOT, 1988] states that for asphalt cement construction the minimum ambient temperature is 60 $^{\circ}$F and the minimum base temperature is 70 °F. Also, the base or existing pavement surface needs to be sufficiently dry. Likewise, Arkansas State Highway and Transportation Department [AHTD, 1993] suggests that hot mix asphalt materials not be mixed or placed when the surface temperature is below 40 °F or when there is frost in the base or subgrade. However, Foster [1970] suggests that a more logical requirement would be to stop placing HMA when conditions are such that the contractor will not have a reasonable time to compact the pavement before it cools to a temperature where it cannot be compacted effectively. Corlew and Dickson [1968] developed a mathematical model of the heat loss from a mat that considers laydown temperature, mat thickness, air temperature, base temperature, wind velocity, and solar flux. The model was used to produce cooling curves for mat thicknesses from 0.5 to 8 in., laydown temperatures from 225 to 300 °F, and a range of environmental conditions. The model was checked with field measurements, and there was agreement between the actual conditions and the model predictions [Corlew and Dickson, 1968; Foster, 1970]. The mathematical model shows that laydown temperature and mat thickness are far more important in determining how fast the mat will cool than the environmental conditions.

To prepare cessation requirements based on a reasonable time to apply the breakdown rolling, one needs information on (1) the rate of cooling of the mat; (2) a reasonable time for applying breakdown rolling; and (3) the temperature below which breakdown rolling is not effective in producing a good quality compaction. A method to establish more realistic cessation requirements was suggested by Foster [1970], based on Corlew and Dickson's [1968] study. According to this study paving may be permitted when the contractor would have a reasonable time to apply rolling while the mats temperature is adequate for compaction and would stop paving when there is not enough time. The suggested cessation requirements show that a requirement based on a single limiting air temperature is not adequate to ensure that paving is permitted only when conditions are satisfactory. Laydown temperature and mat thickness must be considered as well as the environmental factors should be taken into account in establishing HMA specifications. The data provided by Foster [1970] shows the need to apply breakdown rolling as quickly as possible to ensure the quality of the pavement.

The Florida Department of Transportation (FDOT) includes the effects of lift thickness on the minimum air temperature requirements in their specifications [FDOT, 1991]. FDOT specifications [FDOT, 1991] state that the mixture be spread only when the air temperature is 40 °F and above for layers greater than 1 in. in thickness and 45 °F and above for layers 1 in. or less in thickness. The Georgia Department of Transportation (GDOT) proposes a more detailed minimum air temperature requirements based on lift thickness [GDOT, 1993]. GDOT [GDOT, 1993] recommends that the placement of HMA mix be in accordance with the following specifications:

Lift Thickness	Minimum Temperature
1 in. or less	55 $^{\circ}$F
1.1 to 2 in.	45 $^{\circ}$F
2.1 to 3 in.	35 $^{\circ}$F
3.1 to 4 in.	30 $^{\circ}$F
4.1 to 8 in.	Contractor's Discretion

2.3.3 Cut-Off Temperature

To achieve adequate compaction of HMA pavement, the temperature of the mat must be sufficiently high for the period of time necessary to complete rolling. It is generally agreed that compaction of the mix should take place above a certain temperature, and some researchers [Minor,1966; LeClerc, 1967] have indicated that the temperature should be above 200 $^{\circ}$F. If the paving mixture becomes too hard due to low temperature, it will result in a low density. The resulting higher air voids will cause the pavement to deteriorate at a faster than normal rate, seriously curtailing its the service life [McLeod, 1966].

A survey was conducted by Foster [1970] to collect information on the time, temperature, and number of passes applied in breakdown rolling. Replies were received from 25 states, as given in Table 2-2. The data in Table 2-2 indicates that breakdown rolling ranges from 1 to 7 passes and averages about 3 passes. Also, it indicates that the average minimum time to complete breakdown rolling was 9 min. (3 min. before the first pass and 6 min to apply rolling). A roller pass is defined as the entire roller going over a given spot in the lane. The reasonable times to apply breakdown rolling selected by the National Asphalt Pavement Association (NAPA) Quality Improvement Committee were 15 min. for thick lifts and 8 min. for thinner lifts [Foster, 1970].

The respondents in the Table 2-2 indicated that on the average breakdown rolling was completed by the time the mat had cooled to 223 $^{\circ}$F. This temperature appears to be too high when the cooling curves and time for rolling are considered. Also, such a high cut-off temperature is not believed to be warranted. Kilpatrick and McQuate [1967] show a curve of density versus average breakdown temperature. Reportedly, the density did not increase much when the average breakdown temperature was below 200 °F. It should be noted that this value (temperature) was the average, not the value at the end of breakdown rolling. The NAPA Quality Improvement Committee suggested a 175 °F cut-off temperature for HMA jobs. AASHTO [1991] also suggests a minimum compaction temperature of 175 °F because it was found that below this temperature the internal friction and cohesion of the mix increase to the point that little density gain is achieved with the application of additional compactive effort. From his investigation of HMA compaction, Parker [1960] concluded that final rolling of dense graded asphalt-concrete should be completed by the time when the temperature of the mix has decreased to 175 °F. According to this study, rolling at temperatures below 175 °F is of little benefit to the density of pavements. From laboratory studies and observations on the compaction of pavements, Nijboer [1948] also concluded that rolling below a temperature of about 175 °F is not effective. Parker [1960] and Nijboer [1948] were working with paving mixtures containing high viscosity asphalts in the 85/100 and 60/70 penetration ranges.

The Texas Department of Transportation [TDOT, 1982] requires that all rolling be completed before the temperature of the mixture drops below 175 °F. The Arizona Department of Transportation [ADOT, 1987] suggested that initial and intermediate compaction be accomplished before the temperature of the asphalt concrete falls below 200 °F. In addition, ADOT recommends that steel wheel compactor be used in the vibratory mode when the temperature of the asphalt concrete falls below 180 °F. The Florida Department of Transportation [FDOT, 1991] specifies that regardless of the rolling procedure used, the final rolling must be completed before the internal pavement temperature has dropped below 175 °F.

2.4 COOLING RATE OF PAVING MIXTURE

Because of the increasing resistance to compaction due to increasing viscosity of the binder as the mix temperature drops, the rate at which a paving mixture cools behind the spreader becomes a very important factor with regard to the compactive effort needed to achieve the specified density [McLeod, 1966]. Fig. 2-7 represents the rate of cooling of a typical layer of paving mixture behind the spreader. The cooling curve shows how rapidly an ordinary layer of paving mixture cools off behind a spreader when the ambient air temperature is 86 °F. As the mix left the spreader its temperature was 275 °F. In 30 min., the temperature had cooled to 175 °F, and in 50 min to 150 °F. Fig. 2-8, taken from

Serafin and Kole [1962], shows that a normal layer of paving mixture loses heat much more rapidly behind the spreader during cold weather construction, when the ambient air temperature is 40 to 50 °F. Although the mix temperature was 280 °F as it left the spreader, it cooled to 175 °F in about 12 min., and to 150 °F in less than 20 min.

Beagle [1966] demonstrated experimentally the dependency of temperature on location within the depth of the mix as well as on time for single-lift construction of 2.5, 5, and 7.5 in. compacted thickness. According to experimental data [Beagle, 1966], the decrease in temperature with time was highest for the 2.5 in. thickness and lowest for the 7.5 in. thickness; and for the prevailing environmental conditions (subgrade temperatures 66 to 74 °F and air temperature 66 to 110 °F), the decrease in temperature with time for all lift thicknesses was greatest near the lower surface of the lift. Schaub [1968] also reported that the temperature at the mid-point of the mix decreased from 200 to 160 °F in 40 minutes at the West Virginia Route 54 near Beckley.

The heat loss due to the transmission of heat to the subgrade is many times greater than the heat loss due to ambient temperature [Beagle, 1966]. For example, Fig. 2-9 shows that the initial loss of temperature at the subgrade was 150 °F [Beagle, 1966]. This was due to transmission of heat to the subgrade. The initial loss of temperature at the surface was 30 degrees. This was due to the ambient temperature. The stabilized base studied by Beagle [1966] was a hot plant mix of bank run gravel and asphalt cement having a penetration of 85 to 100. It may be noted that the initial laydown temperature was 280 °F for this 12 in. lift. There was a gradual increase in temperature in the subgrade and decrease in temperature in the HMA. It took 200 min. to cool to 220 °F at a depth of 6 in.. Similarly, Fig. 2-10 shows a family of curves which illustrate the change in the temperature vs time for a 15 in. lift. The initial laydown temperature was 295 °F for this 15 in. lift. It took 365 min. to cool to 230 °F at a depth of 6 in..

The Asphalt Institute has proposed the cooling rate of HMA under varying conditions of mix temperature, lift thickness and base temperature, as shown in Fig. 2-11. It is observed from Fig. 2-11 that it takes approximately 15 min. for a 1.5 in. mat to cool to 185 °F given a mix temperature of 300 °F.

2.5 STATE PRACTICE

Telephone interviews were conducted with selected DOT personnel from several states who are experienced with HMA surfacing/resurfacing operations and the associated standards and practices. The following DOTs were included in the information collection process: Georgia, Florida, Arizona, Texas, Nevada, Arkansas, and New Mexico because of their climatic similarities to Oklahoma. An attempt was made to seek answers to the following questions:

1 What criteria are used in the DOT to determine when a lane should be opened to traffic after an AC surfacing or resurfacing operation ? (AC strength, AC temperature, AC density, penetration, etc)

2 How important is sufficient cooling before opening a roadway to traffic after HMA laying? (significant, moderate, not important)

3 To what temperature should a lane be cooled before it is opened to traffic after a surfacing or resurfacing operation?

4 At what depth is the temperature measured?

5 How long does it usually take a 2 in. lift at a laydown temperature of 270 $^{\circ}$F and ambient temperature of 80 $^{\circ}$F to reach the desired temperature for opening the roadway to traffic?

6 What factors influence the cooling time, and how important each factor is? (ambient temperature, HMA thickness, density, moisture content of existing surface, wind velocity, solar flux etc.)

7 What method and what type of tool is used in measuring the HMA temperature in the field ?

8 Is there a method used to speed up the cooling process (such as spreading water) and what are its consequences (rutting, cracking, etc.)?

9 What is the minimum base temperature and ambient temperature for an acceptable HMA surfacing job ?

The results gathered from the phone interviews are presented in Table 2-3. Some respondents indicated that the temperature was not included in the specifications but it had become a part of the "practice" of the DOTs. For example, several DOTs (namely, Texas, New Mexico, Arizona, Florida) do not specify a temperature when a lane could be opened to traffic but, based on their experiences, they do suggest that it is better when the HMA temperature is below 140 °F. This value (140 °F) is close to that reported by Hughes [1989] 150 °F in Synthesis of Highway Practice National Cooperative Highway Research Program.

The Georgia Department of Transportation (GDOT) has used temperature criteria to determine when a lane should be opened to traffic after an AC surfacing or resurfacing operation. GDOT also requires HMA temperature to be dropped below 140 °F (surface temperature) before opening a lane to traffic. In GDOT experience, 1 to 2 hours are needed for a 1.5 in. lift at a laydown temperature of 270 °F to cool to 140 °F with an ambient temperature of 80 °F .

In view of Table 2-3, it is observed that HMA thickness and wind velocity have been rated as the most significant factors that influences the cooling rate of HMA.

Table 2-1 Relationship of Base Temperature, Air Temperature, and Solar Flux [Corlew and Dickson, 1968]

Base Temperature (degree °F)	Air Temperature (degree °F)	Solar Flux (Btu /hr ft^2)
10	10	50
20	20	50
30	30	50
40	40	50
50	50	50
60	60	50
80	70	100
100	80	200
120	90	200

Table 2-2 Survey on Breakdown Rolling [Foster, 1970]

Condition	Surface Binder, Leveling		Hot-Mix Asphalt Base	
	Range	Avg.	Range	Avg.
Time-laydown to first pass, min.				
Normal	0.5 to 15	6	----	----
Minimum practicable	0.5 to 8	3	----	----
Temperature, deg. °F.				
At start of rolling	225 to 300	273	200 to 300	265
At end of rolling	130 to 275	223	130 to 260	214
Roller passes for breakdown	1 to 7	3.1	1 to 6	3.4
Time required to apply rolling, min.				
Normal	3 to 60	11	3 to 120	21
Minimum practicable	2 to 10	6	2 to 90	15

Table 2-3 Survey from Selected States

State	Criteria used to open a lane	Degree of importance	Temperature open to traffic	Depth temperature is measured	Time to reach desired temperature
GA	temperature	most important	140°F	surface, for 1.5 in. lift	1-2 hrs
FL	no standard, usually open to traffic after 1 day		usually below 130°F	surface	5 hrs
AR	no standard	important			
NV	no standard engr. judgement, open when density achieved	very important	mid-mat temp. below 180°F	mid-mat, not measured as a rule. no temp. taken during normal construction	1-2 hrs
TX	AC strength, AC temp.	significant	below 140°F	surface	2-3 hrs
NM	no standard	importance depends on ambient temp.	no specification, acceptable if below 140°F	measured at surface but want 140°F @ 2 in. below	it depends on thickness, wind, sun, and ambient temp.
AZ	no standard, engr. judgement	not critical, because of the sun and air; it never cools sufficiently	below 140°F	contractor's discretion, any method	1-3 hrs
OK	time surface temp. ambient temp.	important	surface temp. 100-120°F	surface	2 hrs

Table 2-3 Survey from Selected States (continued)

State	What factors influence the cooling time	Method used in measuring HMA temperature	Method to speed cooling process	Minimum base temperature
GA	#1 HMA thickness #1 ambient temp. base temp. is of some importance	dial-tap thermometer	sometime use water, steam can be hazardous to surrounding traffic	air 55°F for 0-1" 1-2", air 45F 2-3", air 35F 3-4", air 30F
FL	#1 HMA thickness #2 ambient temp. #3 density	not always taken since 24 hrs usually gives sufficient cooling. flat dial, lays on surface of HMA	none	no standard, should be 40°F
AR	#1 wind, #2 HMA thickness solar flux and base temp. are of some importance	none	none	
NV	#1 wind #2 base temperature	none no temp. taken during construction	water is used sometimes on open-graded friction course with no noticed consequences	50°F for base < 1", air 55°F 1-2", air 45°F 2-3", air 35°F
TX	#1 ambient temp. #2 wind velocity #3 HMA thickness	IR gun (infrared) or conventional thermometer	water is used occasionally on intersections. no consequences noted	50°F for base

Table 2-3 Survey from Selected States (continued)

State	What factors influence the cooling time	Method used in measuring HMA temperature	Method to speed cooling process	Minimum base temperature
NM	thickness, wind ambient, sun	IR gun (infrared)	water used in open-graded friction course in high traffic areas, when time limitations are in effect; no water used on dense-grade	conventional : air 45°F wind chill 35°F polymer added : air 55°F wind chill 45°F
AZ	ambient, wind	contractor's choice	no	base @ 65°F rubber-ACFC asphalt base @ 80°F
OK	#1 wind #2 sun #3 ambient	surface thermometer	water sprayed on ramp from adjacent lane, not preloading the ramp	50°F ambient on open grade friction course.

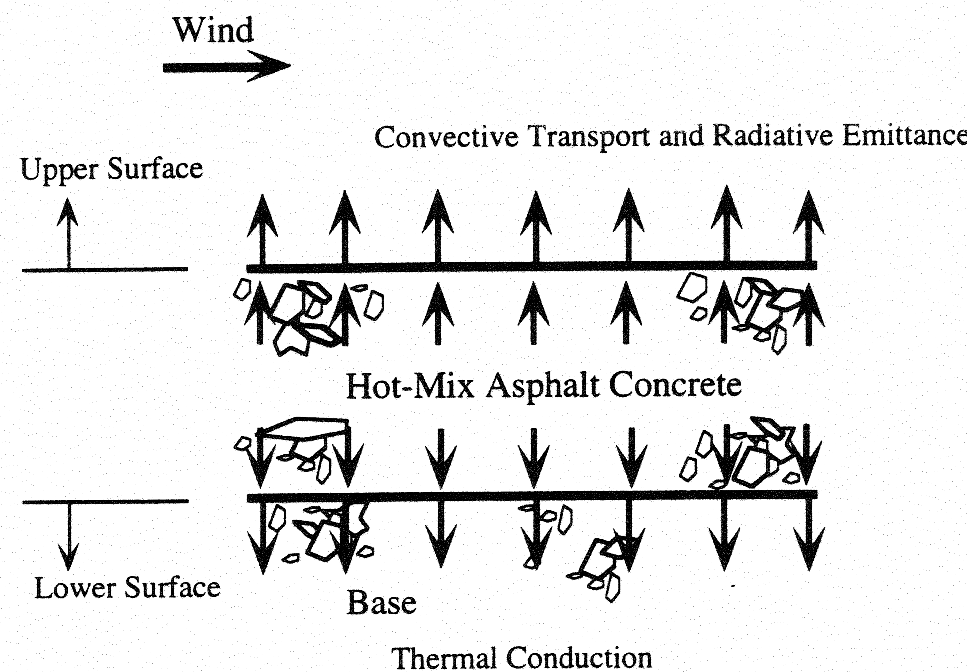


Fig. 2-1 Cross Section of Hot-Mix Asphalt Concrete Indicating Directional Flow of Thermal Energy

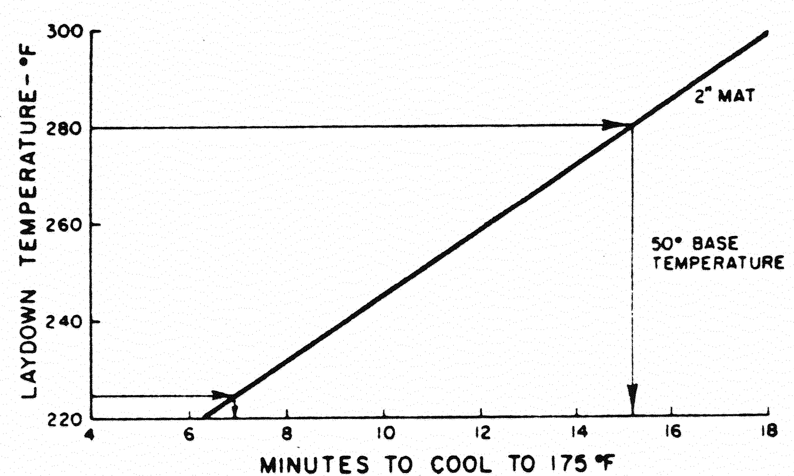


Fig. 2-2 Effect of Laydown Temperature [Corlew and Dickson, 1968]

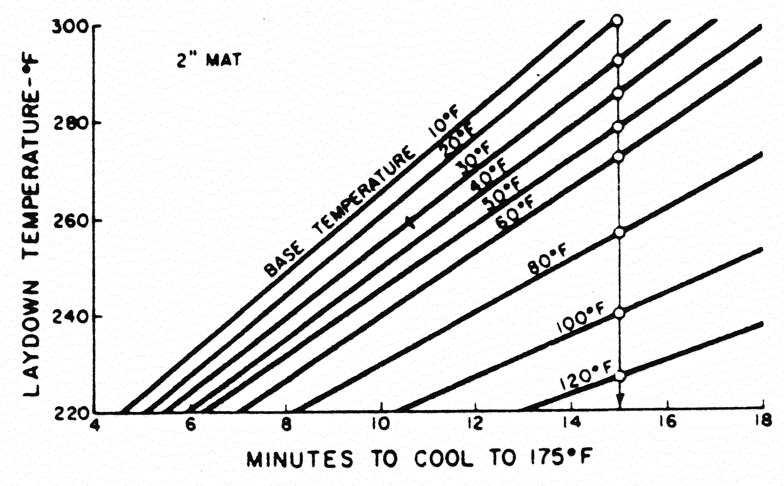


Fig. 2-3 Effect of Base Temperature [Corlew and Dickson, 1968]

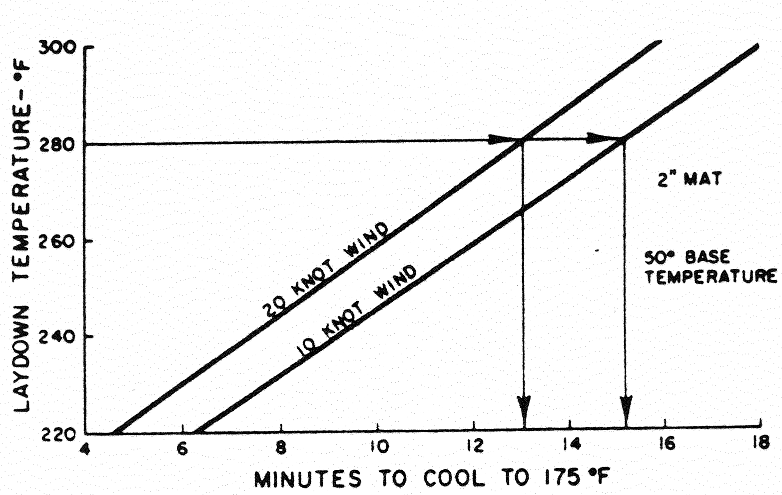


Fig. 2-4 Effect of Wind Velocity [Corlew and Dickson, 1968]

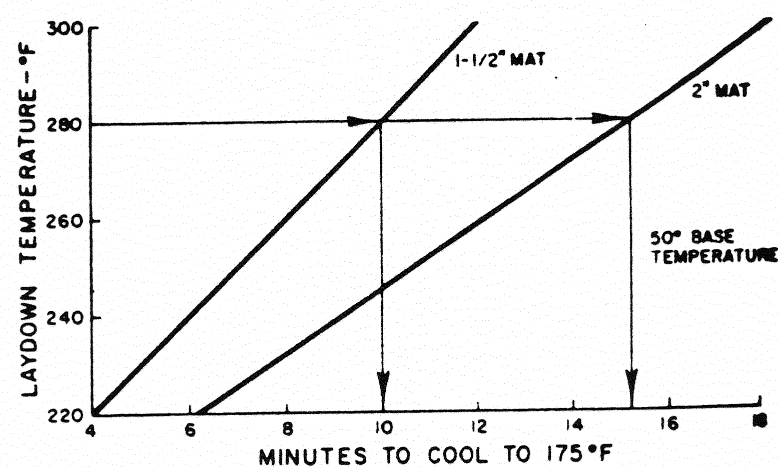


Fig. 2-5 Effect of Mat Thickness [Corlew and Dickson, 1968]

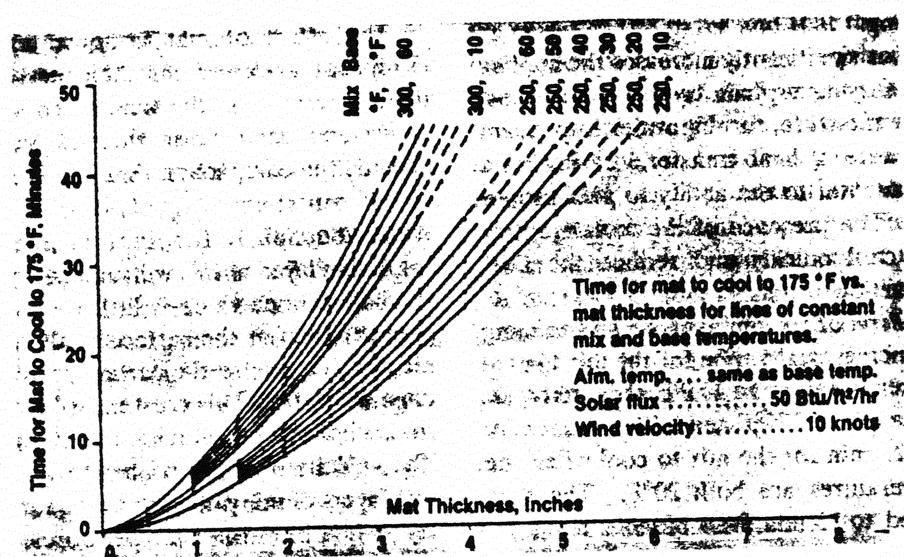


Fig. 2-6 Time for Mat to Cool to 175 F vs. Mat Thickness for Lines of Constant Mix and Base Temperatures [Dickson and Corlew, 1970]

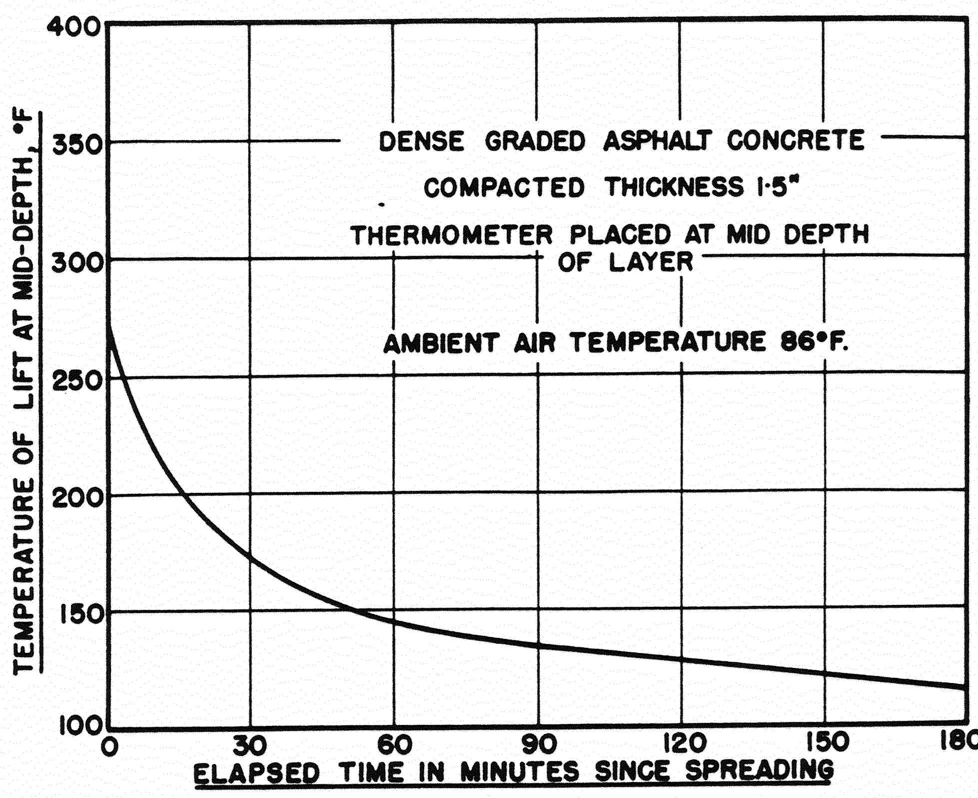


Fig. 2-7 Cooling Rate of Hot-Mix Asphalt [McLeod, 1966]

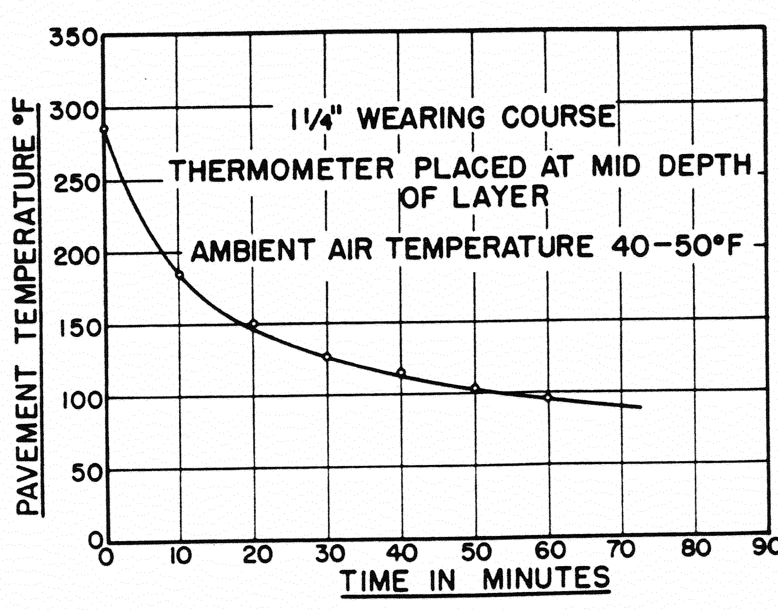


Fig. 2-8 Cooling Rate of Hot-Mix Asphalt [Serafin and Kole, 1962]

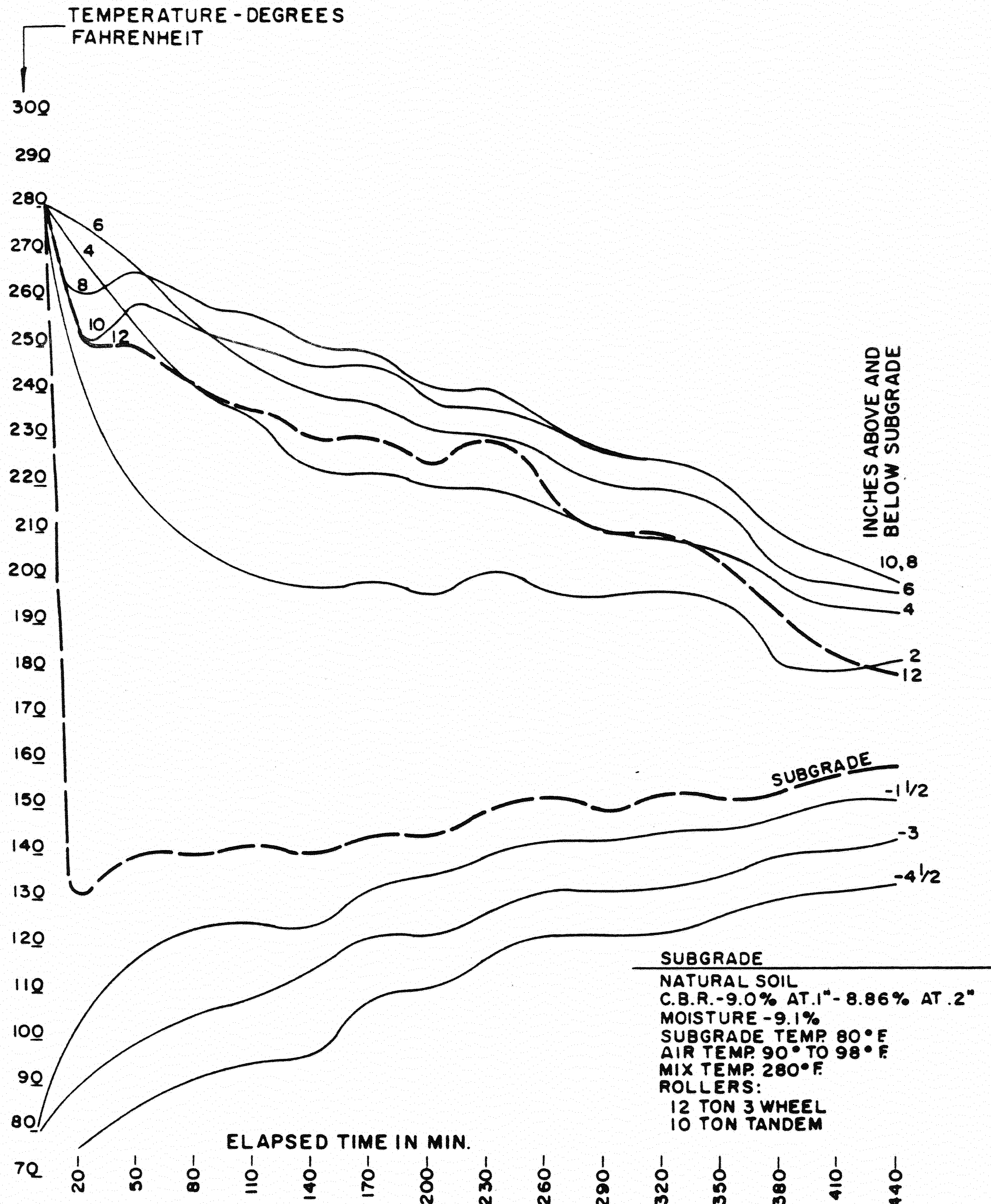


Fig. 2-9 Cooling Temperatures During Application of Hot Plant Mix Stabilized Base (Single Lift 12 inches Compacted Thickness) [Beagle, 1966]

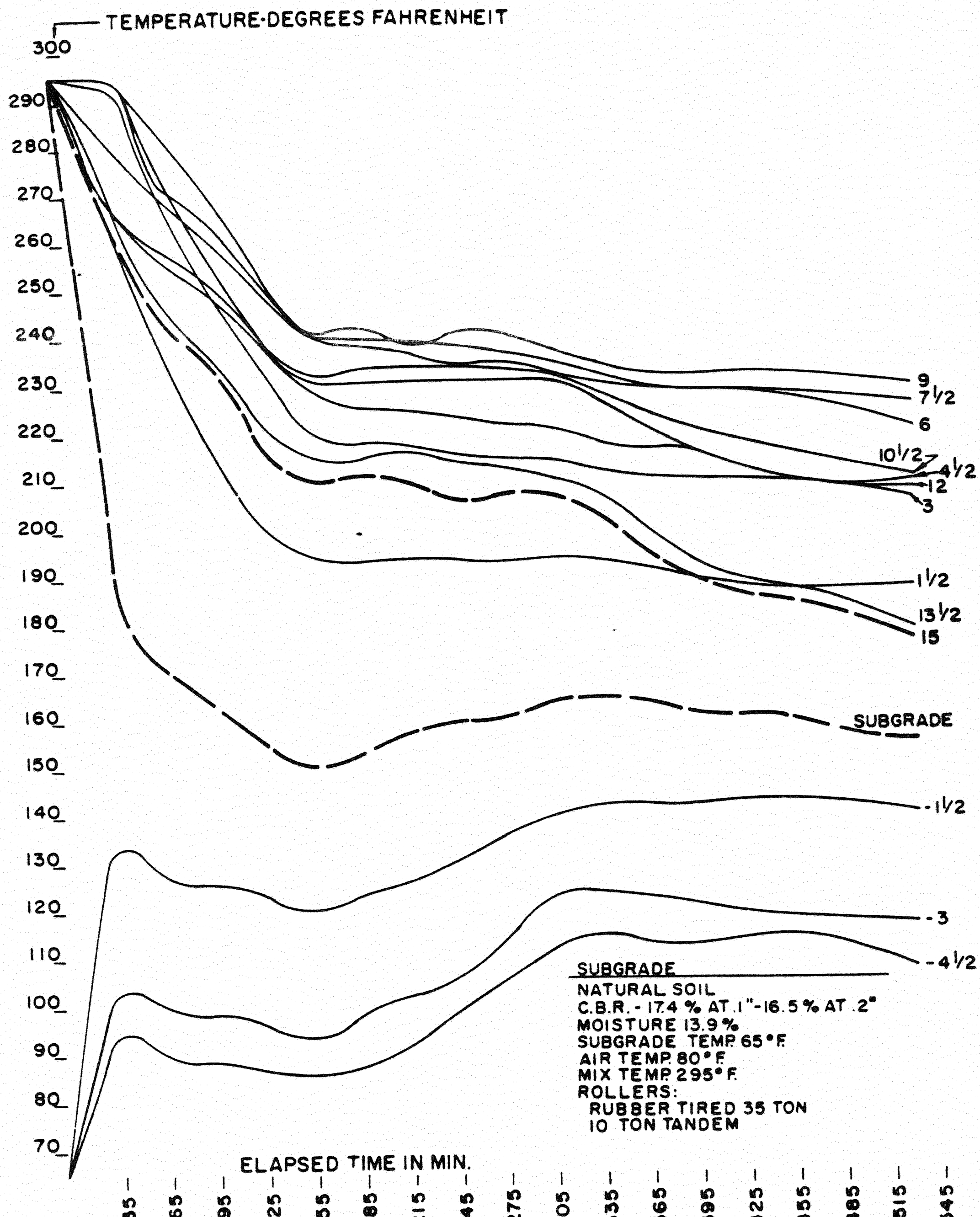
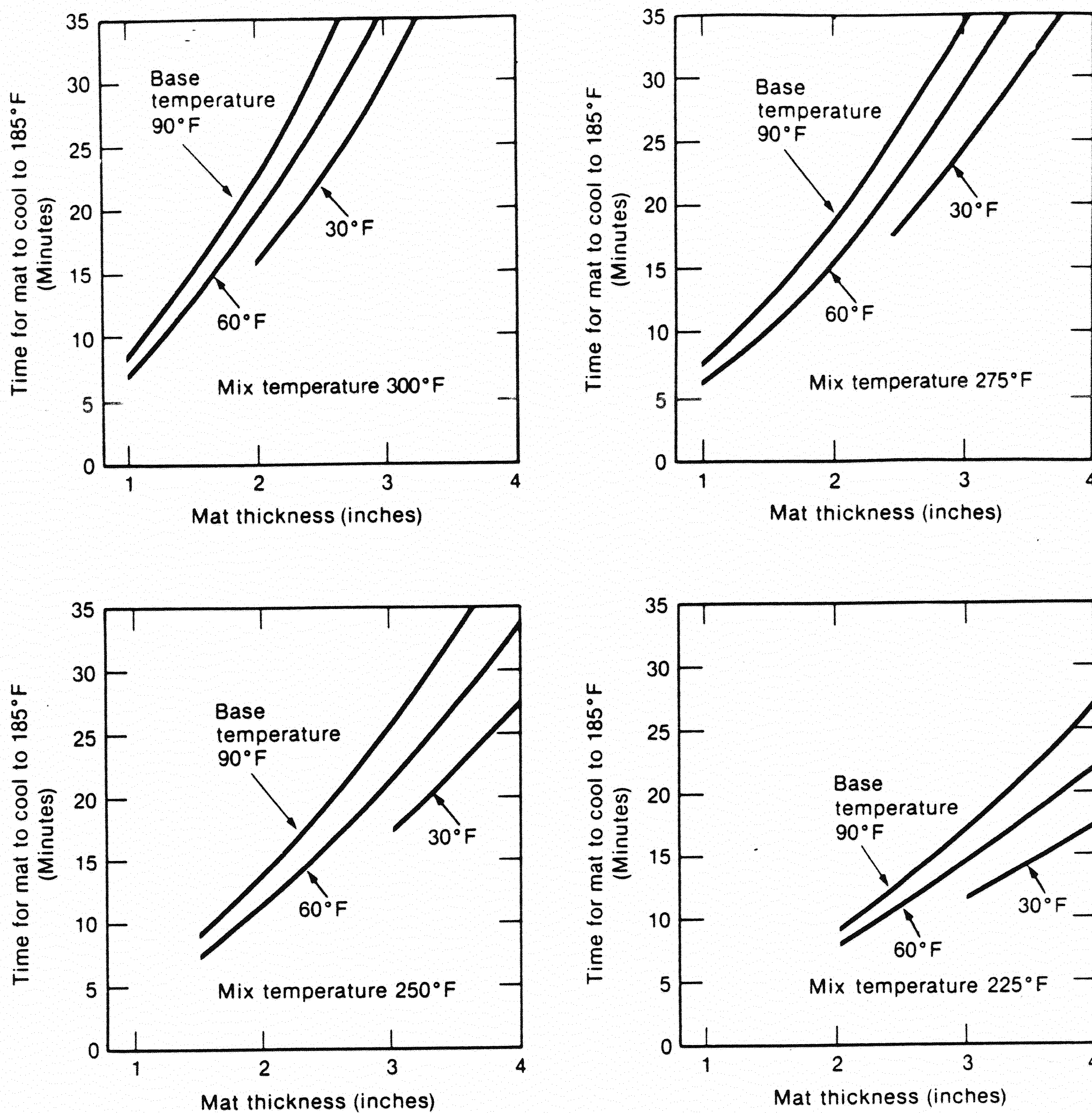


Fig. 2-10 Cooling Temperatures During Application of Hot Plant Mix Stabilized Base (Single Lift 15 inches Compacted Thickness) [Beagle, 1966]



Times for asphalt to cool to 185°F.

Wind velocity—10 knots. Atmospheric temperature—same as base.

Note: "Base Temperature" is the temperature of the surface upon which the asphalt mat is placed.

*185°F is the temperature of the mat measured ¼ to ½ inch below the mat surface. The average temperature of the entire mat thickness when this temperature is reached, is approximately 175°F.

On a subgrade (base temperature) of 30°F, placing of thicknesses less than those shown on the curves is not recommended.

(Conversion: 1 inch = 25mm, $^{0}C = 5/9\,[^{0}F - 32]$)

Fig. 2-11 Time Allowed for Compaction, Based on Temperature and Thickness of Mat and Temperature of Underlying Base [Asphalt Institute, 1983]

Chapter III

NUMERICAL MODELING AND FIELD EXPERIMENTATION

3.1 FINITE DIFFERENCE COMPUTER SOLUTION

3.1.1 Governing Equation

The one-dimensional transient flow of energy in the HMA was proposed by Corlew and Dickson [1968] as:

$$\frac{\partial T_m}{\partial t} = \alpha_m \frac{\partial^2 T_m}{\partial y^2} \tag{1}$$

where

T_m = temperature of the mix,

α_m = thermal diffusivity of the mix,

t = time, and

y = vertical dimension.

The corresponding equation for base is given by

$$\frac{\partial T_B}{\partial t} = \alpha_B \frac{\partial^2 T_B}{\partial y^2} \tag{2}$$

where

T_B = base temperature, and

α_B = thermal diffusivity of base.

The finite difference method can be applied to solve Eqs. 1 and 2 using an incremental approach. The detailed solution is well documented in the reference [Corlew and Dickson, 1968] and only a brief discussions provided in the following Sections.

3.1.2 Numerical Solution

There are five basic elements in the numerical solution for the idealized problem shown in Fig. 3-1. The five equations for these elements are given in Eqs. 3, 4, 5, 6, and 7. An energy balance over the upper surface element of HMA generates an equation for the surface temperature after an increment of time, Δt, as follows :

$$T_1(t+\Delta t) = T_1(t)\left[1-\frac{2\alpha_m \Delta t}{\Delta y^2}(N_{Bi}+1)\right] + \frac{2\alpha_m \Delta t}{\Delta y^2}(T_2(t) + N_{Bi}T_a) + \frac{2\alpha_m \Delta t}{k_m \Delta y}(aH_s - \varepsilon\sigma T^4_{1(t)}) \tag{3}$$

where

T_1	=	temperature, $^{\circ}$F, at surface of HMA (or element 1) at time t,
$T_1(t+\Delta t)$	=	temperature, $^{\circ}$F, at surface of HMA at time $t+\Delta t$,
$T_2(t)$	=	temperature, $^{\circ}$F, at element 2 at time t,
α_m	=	thermal diffusivity of HMA, ft^2/hr ,
Δt	=	incremental time, hr,
Δy	=	thickness of incremental element, ft,
N_{Bi}	=	Biot number, dimensionless,
T_a	=	atmospheric temperature, $^{\circ}$F,
k_m	=	thermal conductivity of HMA, Btu/ hr/ ft / $^{\circ}$F,
a	=	total absorptance of HMA, dimensionless,
H_s	=	solar energy on HMA surface, Btu /hr ft^2,
ε	=	total emittance of HMA surface, dimensionless,
σ	=	Stephan Boltzmann constant, 1.714×10^{-9} Btu/ft^2 hr R^4.

Similarly, the energy balance over an interior element (such as element 3) is given as:

$$T_3(t+\Delta t) = T_3(t) + \frac{\alpha_m \Delta t}{\Delta y^2}\left[T_4(t) - 2T_3(t) + T_2(t+\Delta t)\right] \tag{4}$$

The equation of the incremental element of the mix adjacent to the upper surface of the base (element 10) is given by:

$$T_{10}(t+\Delta t)= T_{10}(t) + \frac{\alpha_m \Delta t}{\Delta y^2}\left[T_{b1}(t) -2T_{10}(t)+T_9(t+\Delta t)\right] \tag{5}$$

The equation of the incremental element of the base adjacent to the lower surface of the mix can be expressed as:

$$T_{b1}(t+\Delta t)= T_{b1}(t) + \frac{\alpha_B \Delta t}{\Delta y^2}\left[T_{b2}(t) -2T_{b1}(t)+T_{10}(t+\Delta t)\right] \tag{6}$$

Finally, an energy balance over an element within the base yields an equation as shown below:

$$T_{b3}(t+\Delta t)= T_{b3}(t) + \frac{\alpha_B \Delta t}{\Delta y^2}\left[T_{b4}(t) -2T_{b3}(t)+T_{b2}(t+\Delta t)\right] \tag{7}$$

The foregoing equations (3 to 7) provide the basis for setting up the computer program. The FORTRAN computer code is given in Dickson and Corlew [1970].

3.2 DISCUSSION OF RESULTS

An effort was made in this study to use the computer code provided in the reference [Dickson and Corlew, 1970] to compute the time for HMA to cool to 150 °F. It is important to note that, in the past, the cooling rate of HMA has been focused on allowing time for compaction. Thus, figures for predicting the time for HMA to cool to 175-185 °F had been reported in the past such as those shown in Figs. 2-3, 2-4, and 2-11. In this work, the time for a HMA layer to cool to 150 °F for various laydown and base temperatures was computed. The time required to open a roadway to traffic can be determined from these data. A typical Oklahoma sunny day (125 Btu /hr ft^2) with a normal wind velocity of 10 Knots (11.1 mile/hr) was selected in this study.

The following HMA properties used in this study were:

density = 140 pcf,
heat capacity = 0.22 Btu/lb/°F,
thermal conductivity = 0.7 Btu/ hr/ ft /°F,

thermal diffusivity = 0.02227 ft^2/hr,

wind velocity = 10 knots (11.1 mile/hr), and

solar flux = 125 Btu /hr ft^2.

The average temperatures of the mat were computed in this study. It is realized that the temperature in the middle of the mix would not be the average temperature. Temperature at specific depth in the mix does not correlate with the average temperature because the location in the mat where the average temperature changes is compacted with time [Dickson and Corlew, 1972].

The time to cool to 150 $^{\circ}$F for 1.5 and 3 in. lifts for various base and laydown temperatures is presented in Fig. 3-2 and 3-3, respectively. It is observed from Figs. 3-2 and 3-3 that the cooling time for an HMA to reach 150 $^{\circ}$F is 28 min. for the 1.5 in. lift and 100 min for the 3 in. lift . These results are based on a 280 $^{\circ}$F laydown temperature and 90 $^{\circ}$F base temperature. The results obtained in this study compare well with those reported in the literature. For example, McLeod [1966] reported that for a dense graded asphalt concrete with a compacted thickness of 1.5 in. it requires 52 min. to cool to 150 $^{\circ}$F for a laydown temperature of 270 $^{\circ}$F (refer to Fig. 2-7). Serafin and Kole [1962] stated that for a 1.25 in. wearing course it needs 18 min. to cool to 150 $^{\circ}$F in an ambient air temperature 40 - 50 $^{\circ}$F. The thermometers were placed at mid layer depth in the studies by McLeod [1966] and Serafin and Kole [1962].

3.3 FIELD EXPERIMENTATION

To verify the model discussed in the previous Sections, an attempt was made in this study to include some field measurements to determine the cooling rate of HMA. The field measurements were performed on September 7, 1994 for project No. IM 35-4 (152) 172. The site is located near milepost 174.7 on State Highway I-35 (north bound, inside lane) near Stillwater, Oklahoma. The properties of the HMA mix are presented in Table 3-1. Figs. 3-4 and 3-5 show the mix plant visited and the hauling truck used by the contractor for transporting HMA from the plant to the construction site, respectively. Figs. 3-6 and 3-7, respectively, illustrate the paver and pneumatic-tired roller in action. Fig. 3-8 shows the research crew measuring the surface and mid-depth temperatures.

The following data was used for the two field measurements conducted in this study, as given in Tables 3-2 and 3-3.

1 plant mix temperature varying from 300 to 350 $^{\circ}$F,

2 laydown temperature varying from 275 to 280 $^{\circ}$F,

3 ambient temperature during measurement varying from 74 to 82 $^{\circ}$F,

4 cloudy day with wind velocity approximately 5 mph (south), and

5 lift thickness 1.5 in.

In view of Tables 3-2 and 3-3 , the time to cool to 150 $^{\circ}$F is approximately 26.5 min. for location No. 1 and 21 min. for location No. 2. These results are in close agreement with the results predicted by the numerical model as discussed in the previous Section (Sec. 3.2) with a 28 min. cooling time for the similar conditions.

3.4 APPLICATION OF A FINITE ELEMENT PROGRAM ABAQUS IN PREDICTING THE COOLING PROPERTIES OF ASPHALT SURFACES

In recent years, the finite element (FE) method has become a powerful tool to analyze boundary value problems having complex geometric and boundary conditions. An effort was made in this study to use the general FE program ABAQUS [ABAQUS, 1992] to compare the results with those obtained from the finite difference (FD) analysis and field measurements. In the FE analysis, a 2-dimensional heat transfer idealization was utilized, and boundary conditions similar to those in the field were adopted. During the resurfacing of existing pavements, the surface of the old roadway is scarified to a certain depth of the surface material throughout the entire width of the pavement. The shoulder on either side of the pavement is quite often left untouched. Thus, in this study the pavement section shown in Fig. 3-9 was adopted to model this field condition. The width and the depth of the pavement were 12 feet and 1.5 in., respectively. The new HMA layer was placed in the 1.5 in. excavation. Initially, the shoulder and the base were assumed to have ambient temperature (in this case ambient temperature is equal to base temperature) and then the HMA layer at the laydown temperature was added. The temperature distributions throughout the pavement layers are computed at different times.

It may be noted that in the FE analyses, two properties, radiation and conductivity were used. The surface elements were assumed to have radiation properties which are related to heat transfer from the HMA to the air. The heat transfer within the base layer was only by conduction. The effect of solar flux and wind velocity were neglected.

Initially, it was mandatory to determine the depth of the layer which was effective/influential in contributing to the cooling of HMA. As a result of this investigation, the bottom of the layer in the FE analysis was set to coincide with this depth. For this purpose, the parameters used were base and laydown temperatures, 120 $^{\circ}$F and 300 $^{\circ}$F, respectively. For a 1.5 in. thick HMA with a base of 12 in. or a 3 in. thick HMA with a base of 10.5 in., this depth turned out to be 13.5 in. The width of the shoulders adjacent to the 12 feet pavement were taken as 4 feet on either side, as shown in Fig. 3-9. Note that the example cites a two lane highway, but only one lane is resurfaced at a time to keep the traffic open in the other lane. It was observed from temperatures along the width that the temperature variation is insignificant across the width but it became somewhat significant outside the pavement and only within 3 feet from the pavement. For purposes of calculation that width was taken as 4 feet (refer to Fig. 3-9).

There is a large temperature gradient between the boundary of HMA surface and base, and surface layer and shoulder. Thus, to analyze and capture the behavior of this situation a finer mesh was used for these areas. As the distance from these boundaries increases, the temperature gradient is reduced and the variation of temperature becomes negligible. Thus, a coarser mesh was provided away from these boundaries, as shown in Fig. 3-10.

An effort was also made to investigate the variation of temperatures along the width of the pavement at the surface and the existing base, and through the depth along the center line when the maximum HMA temperature reached 150 $^{\circ}$F. The time to cool to 150 $^{\circ}$F for 1.5 and 3 in. lifts for various base and laydown temperatures is presented in Figs. 3-11 and 3-12, respectively. The results of FD analyses from Section 3.1 were compared with those obtained from FE analyses, as presented in Figs. 3-13 and 3-14. It should be noted that the intent of the comparisons in Figs. 3-13 and 3-14 is to show the relative closeness and not to judge the appropriateness or the suitability of each program. Fig. 3-13 depicts the 1.5 in. lift to have the cooling time of 30 min. as the dividing line. Below 30 min., the FD analysis yielded a longer time than that of the FE analysis but the reverse was true beyond 30 min. Similar behavior was obtained for the 3 in. lift, according to Fig. 3-14, but the dividing line occurs at 80 min.

Two common cases of the base temperatures of 70 $^{\circ}$F and 90 $^{\circ}$F were considered for a laydown temperature of 280 $^{\circ}$F. As the vertical distance from the surface increases downward, there is a decrease in temperature, as shown in Figs. 3-15 and 3-16. There is a heat transfer from the surface to the base and, thus a loss of temperature in the HMA and a gain of temperature in the base was observed. From both contours, it was observed that at the depth of 4.5 in for a base temperature of 70 $^{\circ}$F and a layout temperature of 280 $^{\circ}$F there was an increase in temperature to 91.5 $^{\circ}$F (a 21.5 $^{\circ}$F gain). Likewise, for a base temperature of 90 $^{\circ}$F and layout temperature of 280 $^{\circ}$F there was an increase to 114 $^{\circ}$F (a 24 $^{\circ}$F gain).

The results obtained from the FE analyses indicated that there are large variations through the depth and the temperatures are nearly constant over the width of the pavement. Also, this study confirmed that dissipation of heat is quicker through conduction to the base rather than radiation to the air which explains the lowest temperature at the bottom and the highest temperature on the surface.

Table 3-1 Composition of Paving Mixtures

percent passing	Job Formula	JMF Tolerances
3/4"	100	0
1/2"	98	± 7
3/8"	90	± 7
No. 4	54	± 7
No. 10	30	± 4
No. 40	14	± 4
No. 80	7	± 4
No. 200	4.8	± 2
% Asphalt Cement (PMAC-1C)	5.1	± 0.4
Mix Temp. @ Discharge from Mixer, °F	325	± 20
Optimum Roadway Compaction Temp., °F	305	
Test of Asphalt Cement :		
Penetration @ 25 °C	67	
Viscosity @ 60 °C	10,276	
Compacted Wt. 106.9 lbs./sq yd/1" thickness		

Table 3-2 Field Measurements at Location No. 1

Temp. at 1/2" (°F)	Temp. at surface (°F)	time (minutes: seconds)
275	------	0, at 8:31 A.M. air 78 °F
215	210	2:00*
195	205	6:32
150	115	20:34
150	115	21:53
150	110	26:30
125	104	38:27
120	104	152:00
106	104	314:00

* The time period from zero to two minutes is the stabilization of the thermometer

Table 3-3 Field Measurements at Location No. 2

Temp. at 1/2" (°F)	Temp. at surface (°F)	time (minute: second)
275	------	0, at 10:28 A.M., air 80 °F
215	------	2*
200	175	4:10
175	170	7:57
175	170	10:30
170	150	12:00
168	150	14:57
162	150	16:47
154	150	19:04
150	149	21:00
140	130	25:07
125	115	29 :03
125	115	30:19

* The time period from zero to two minutes is the stabilization of the thermometer

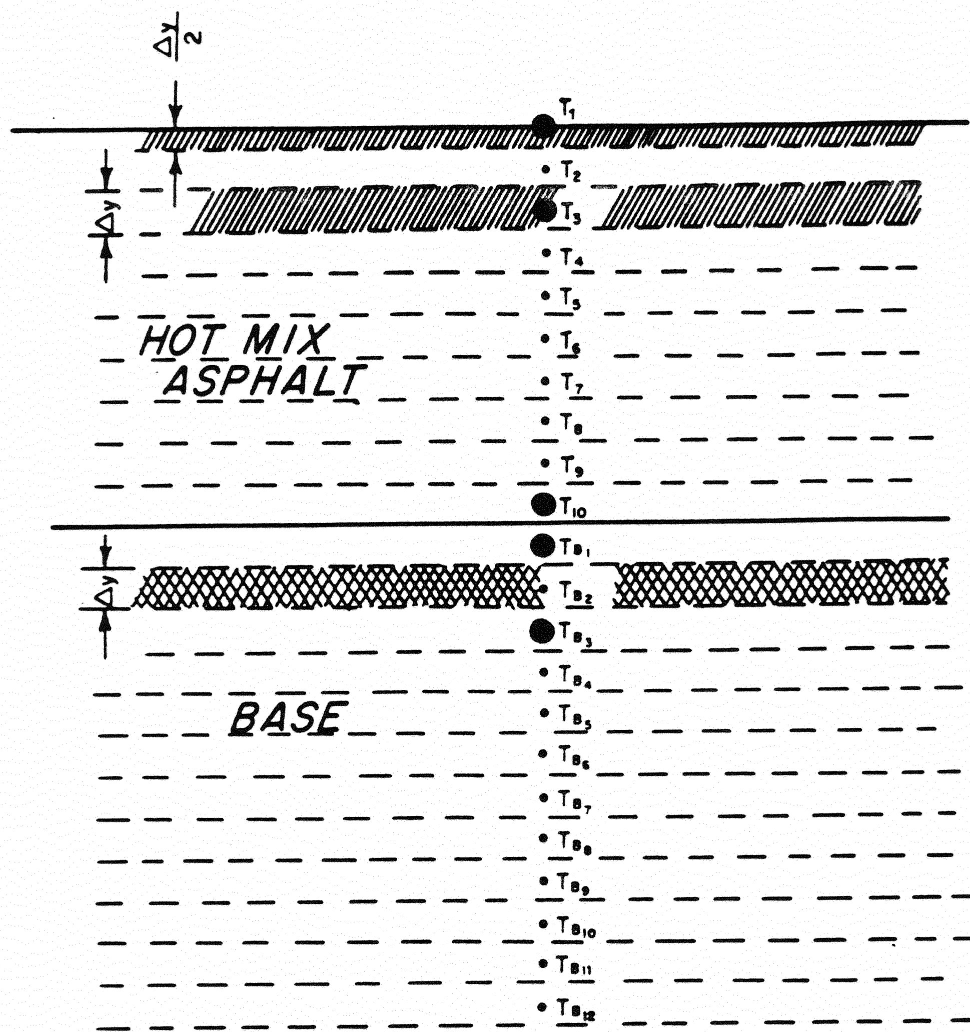


Fig. 3-1 Typical Incremental Elements in Numerical Solution [Corlew and Dickson, 1968]

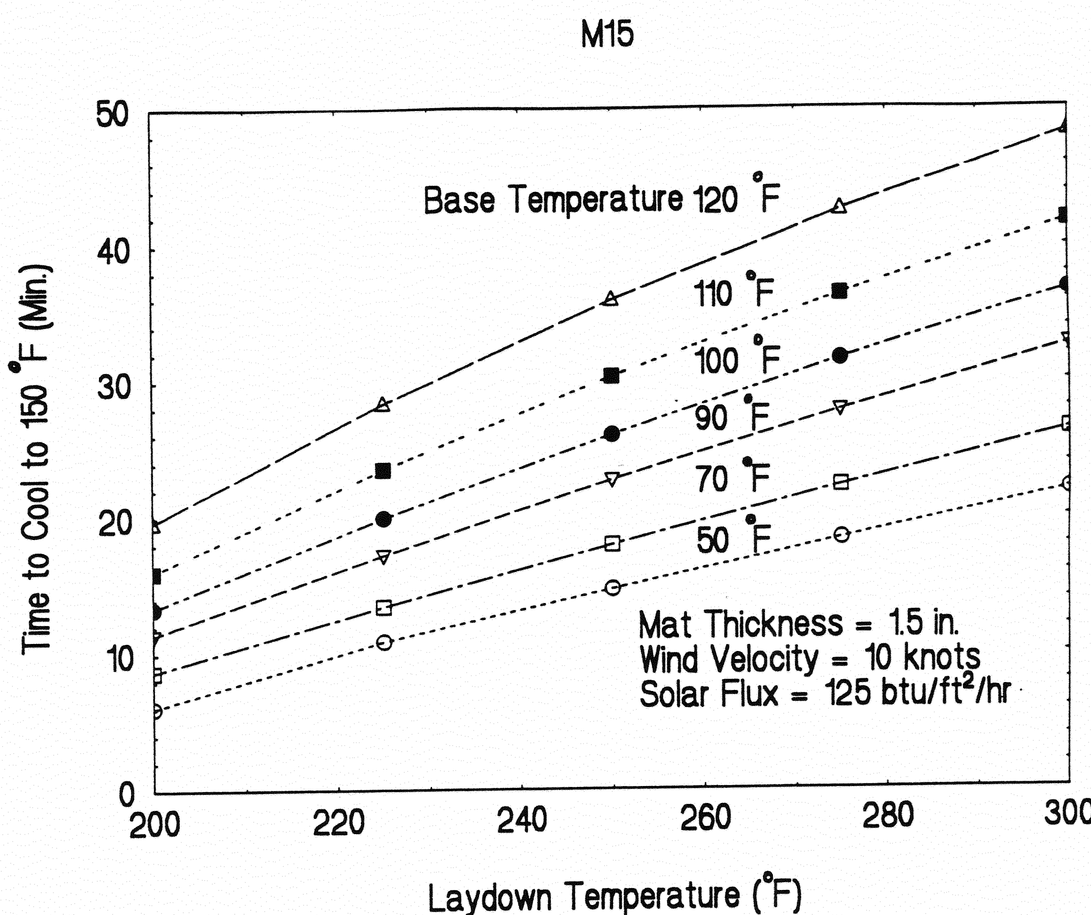


Fig. 3-2 Cooling Rate of Hot-Mix Asphalt (1.5 in. lift)

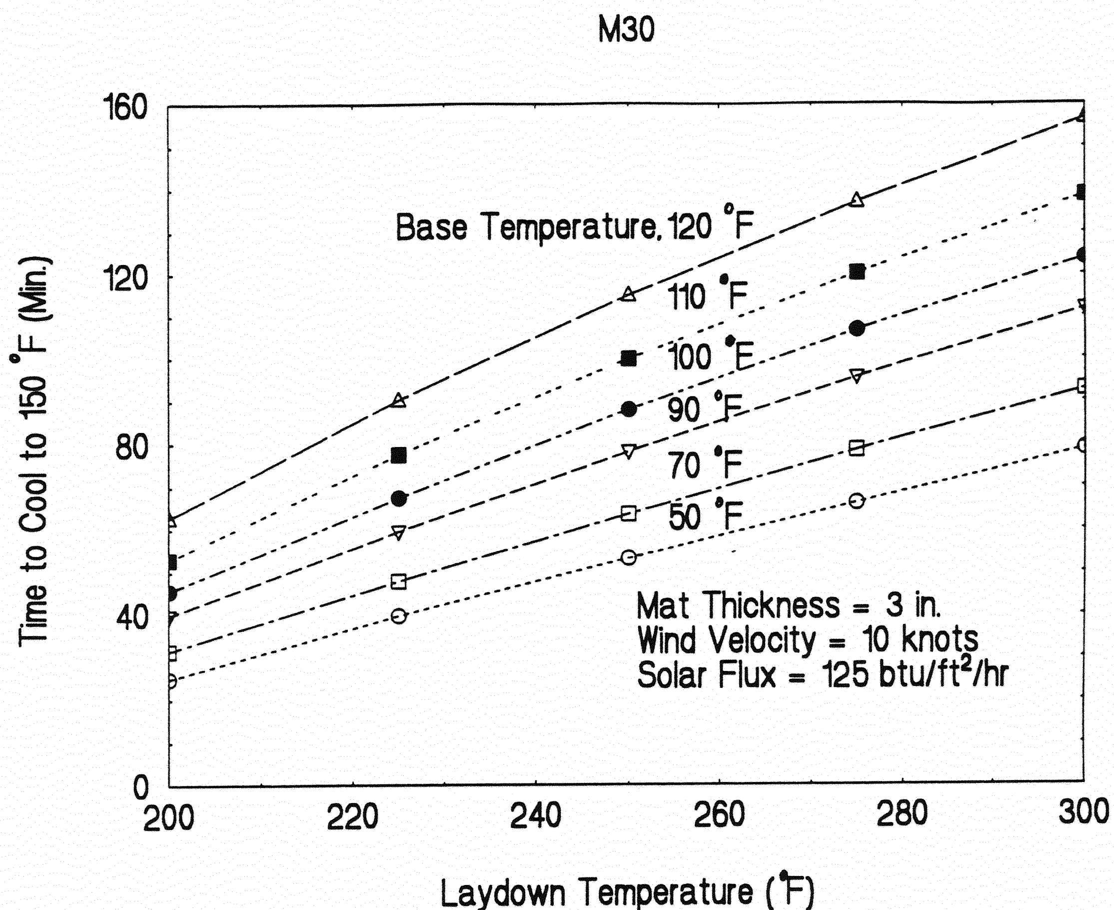


Fig. 3-3 Cooling Rate of Hot-Mix Asphalt (3 in. lift)

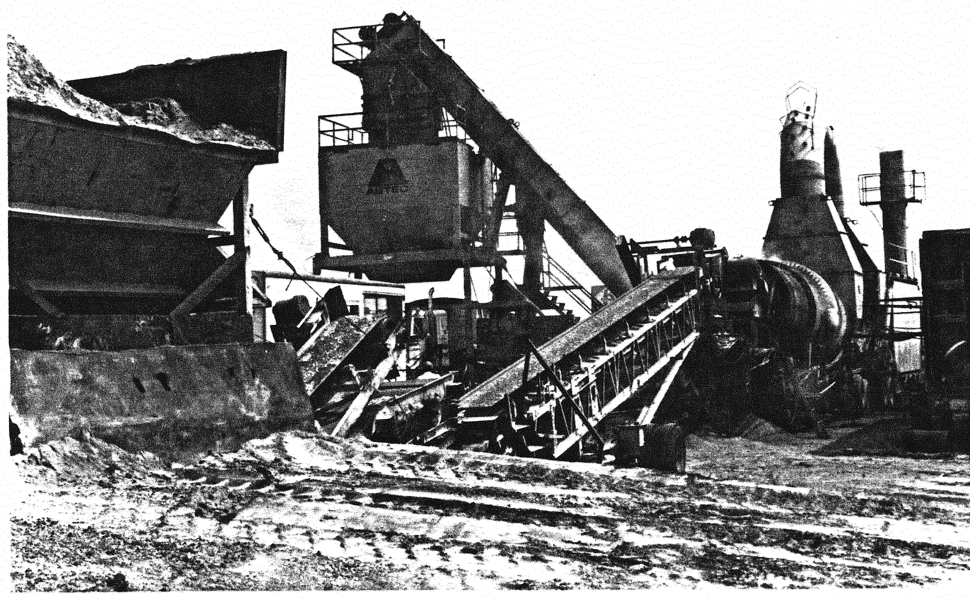


Fig. 3-4 HMA Mixing Plant

Fig. 3-5 Hauling Truck for Transporting HMA from the Plant to the Construction Site

Fig. 3-6 Paver in Action

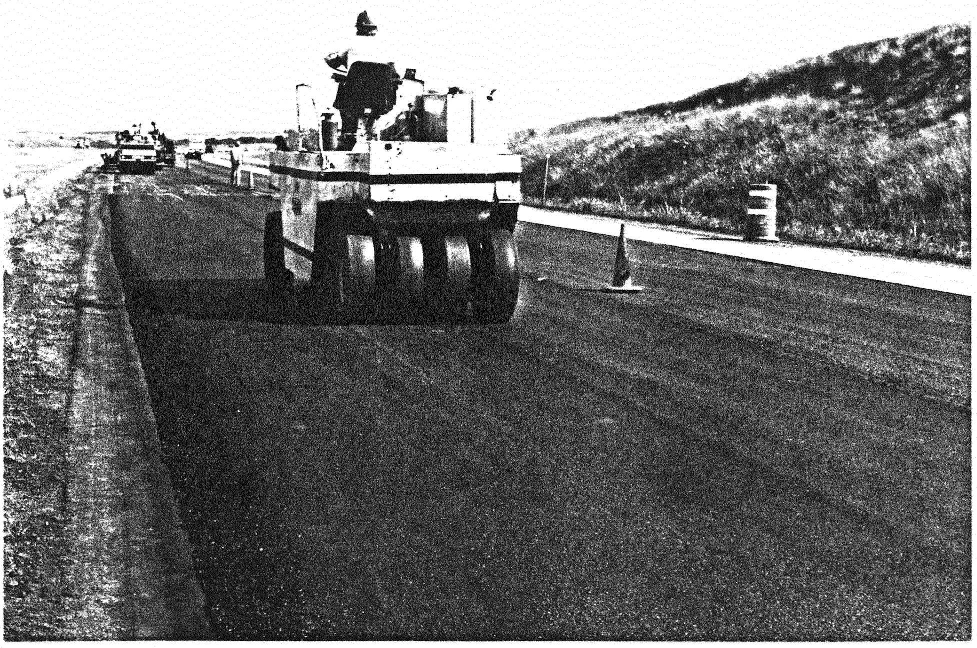


Fig. 3-7 Pneumatic-Tired Roller Compaction of Hot-Mix Asphalt Concrete

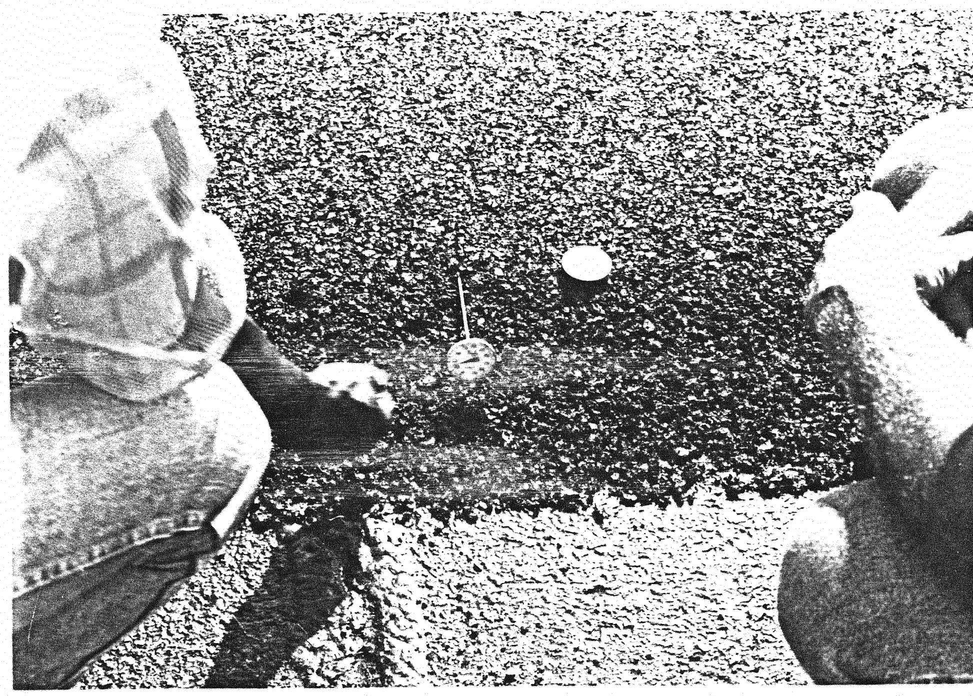


Fig. 3-8 Measurement of Surface and Mid-Depth Temperatures at the Site

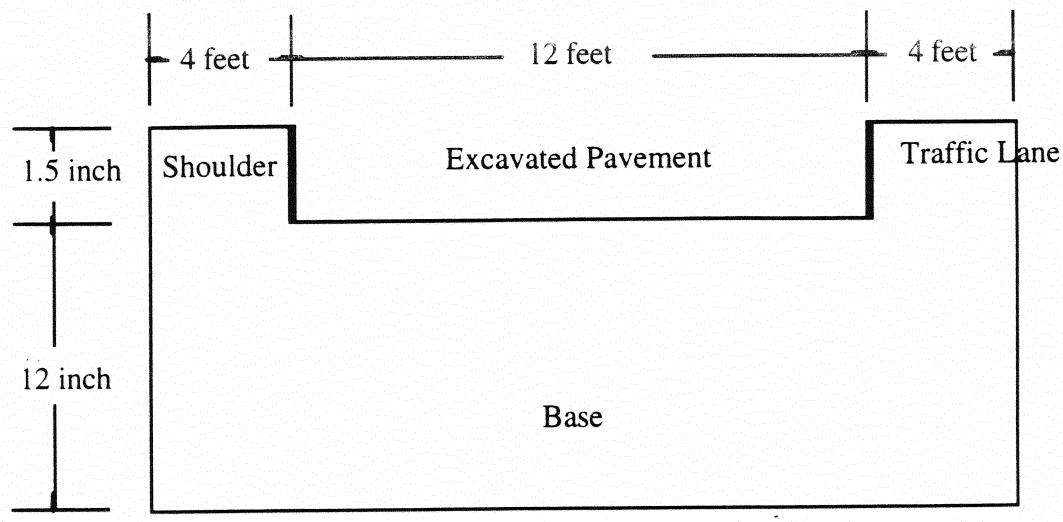


Fig. 3-9 Finite Element Idealization

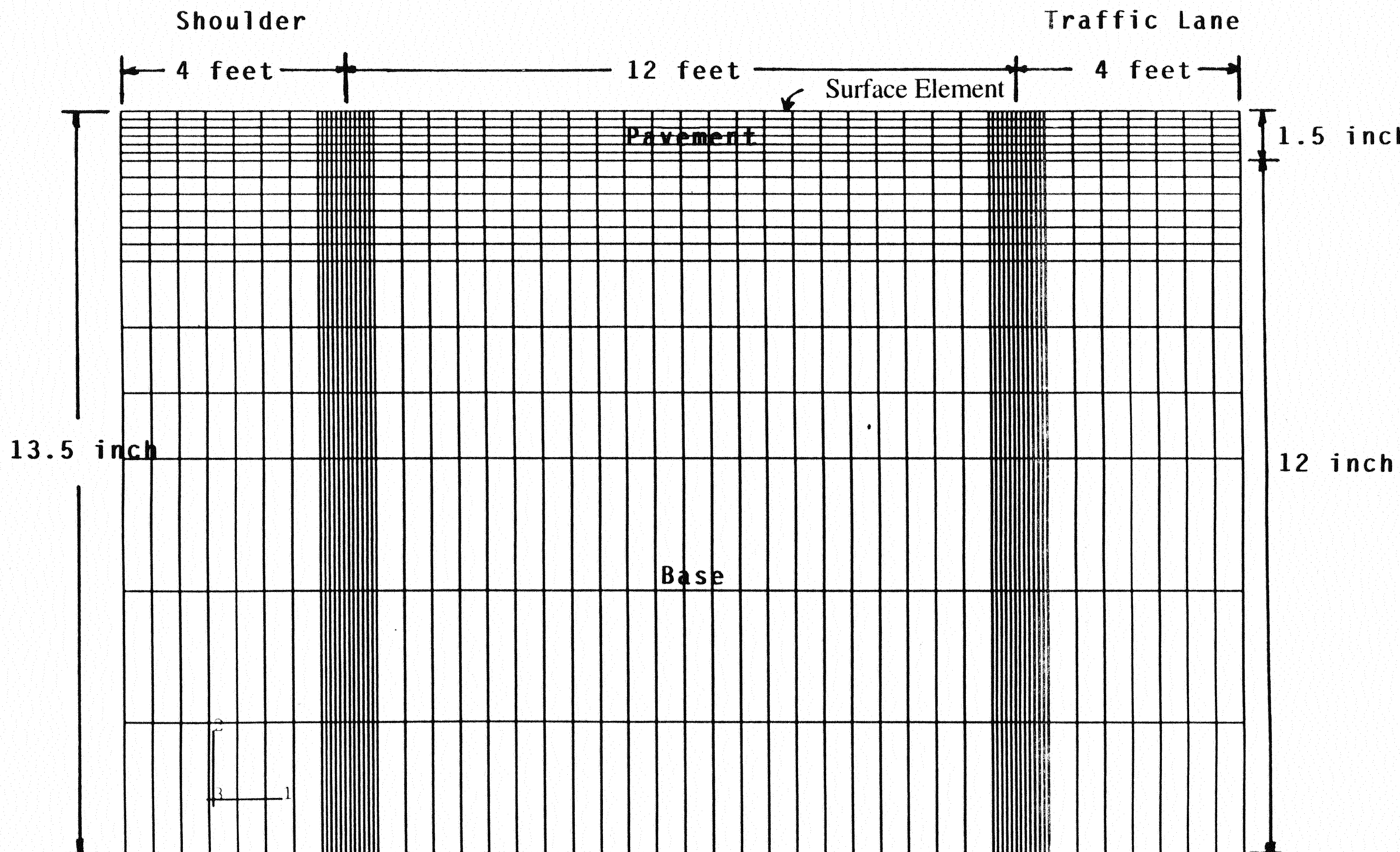


Fig. 3-10 Typical Finite Element Mesh for ABAQUS

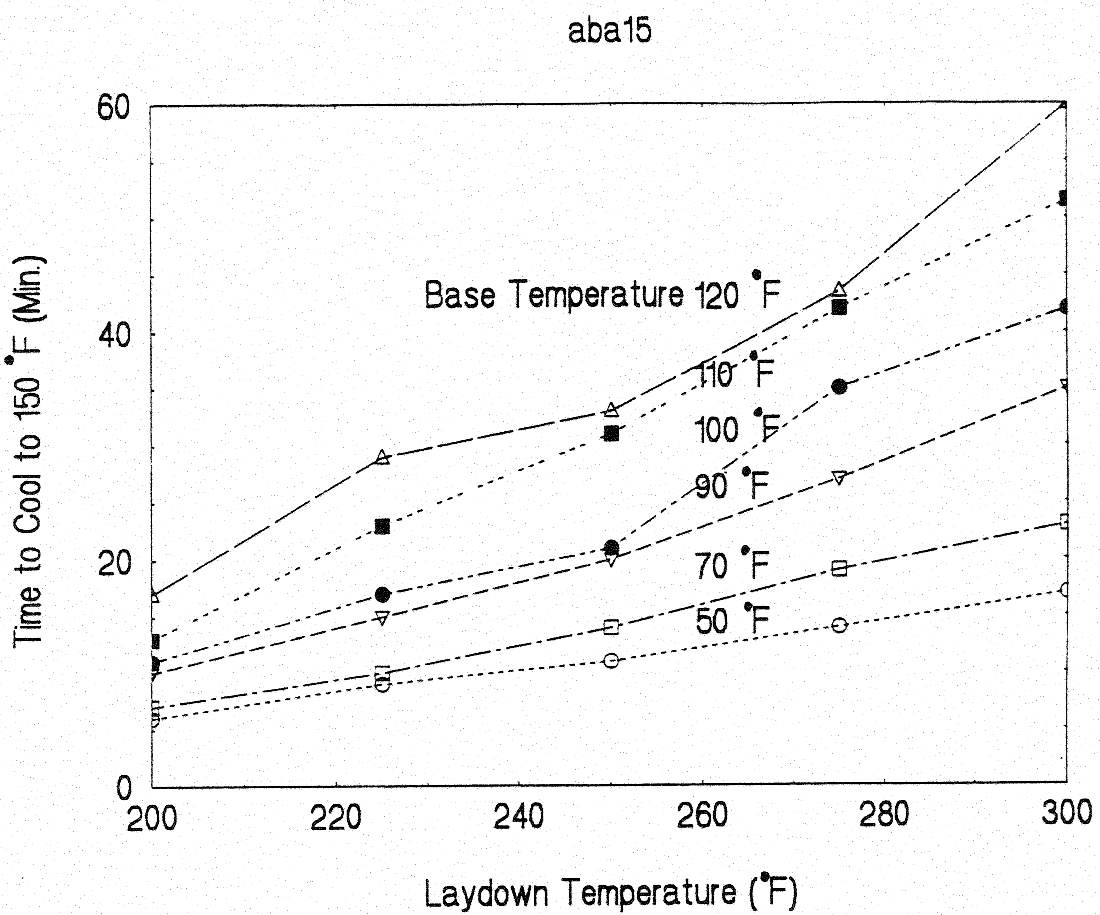


Fig. 3-11 Cooling Rate of Hot-Mix Asphalt Using Finite Element Program ABAQUS (1.5 inch lift)

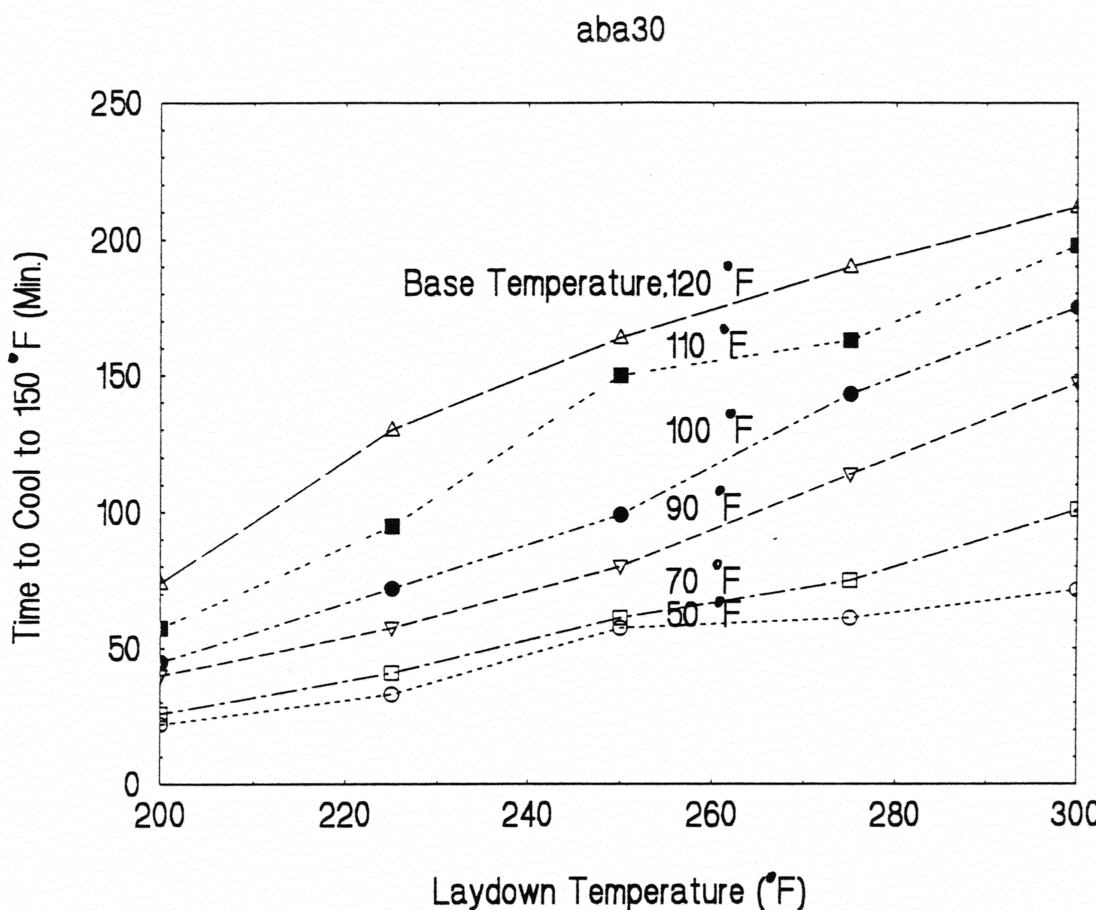


Fig. 3-12 Cooling Rate of Hot-Mix Asphalt Using Finite Element Program ABAQUS (3 inch lift)

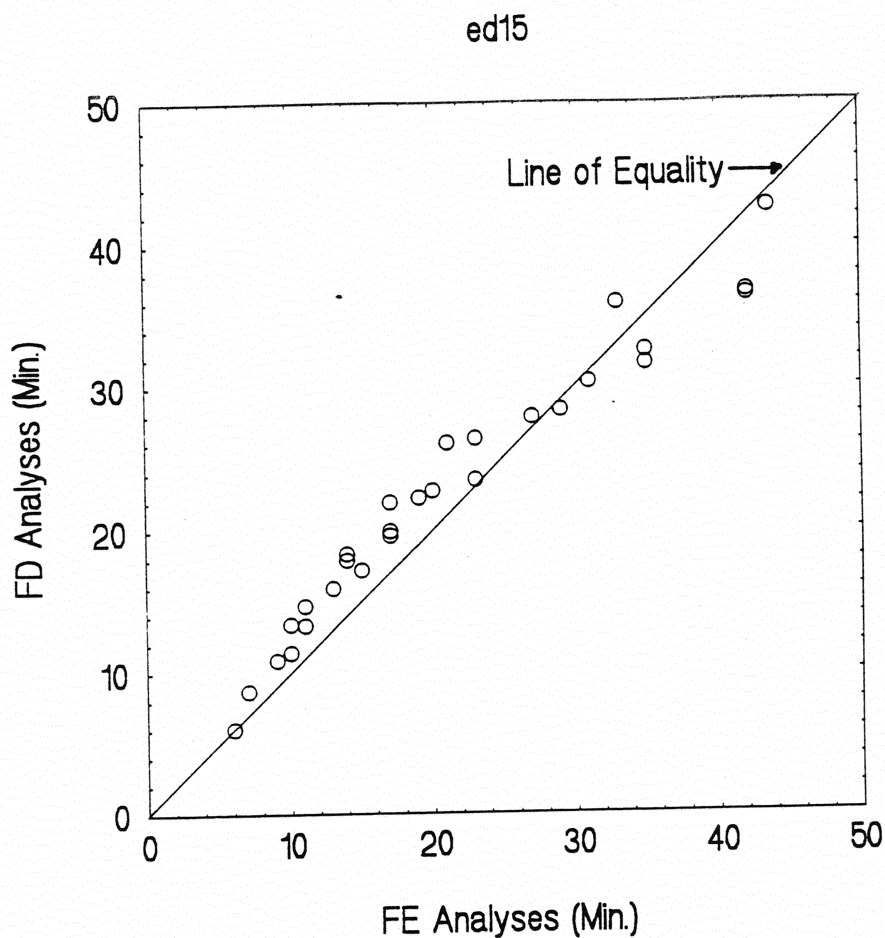


Fig. 3-13 Comparison of Time Required to Cool to 150 °F Between Finite Element (FE) Analyses and Finite Difference (FD) Analyses (1.5 inch lift)

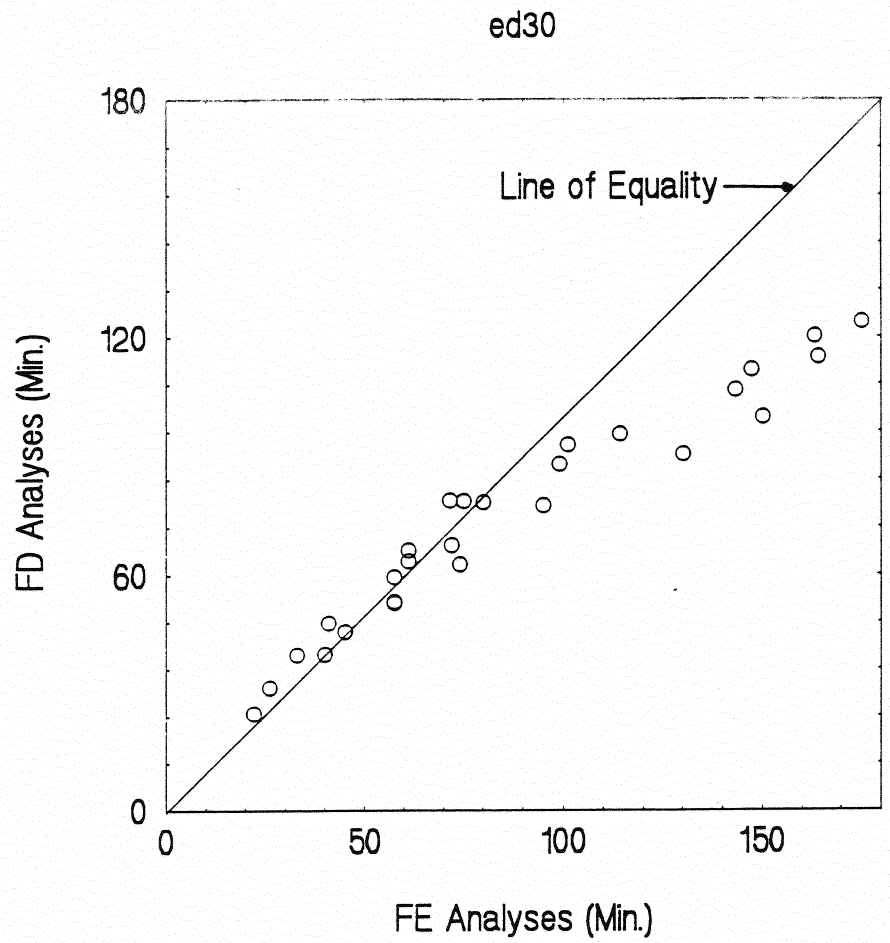


Fig. 3-14 Comparison of Time Required to Cool to 150 °F Between Finite Element (FE) Analyses and Finite Difference (FD) Analyses (3 inch lift)

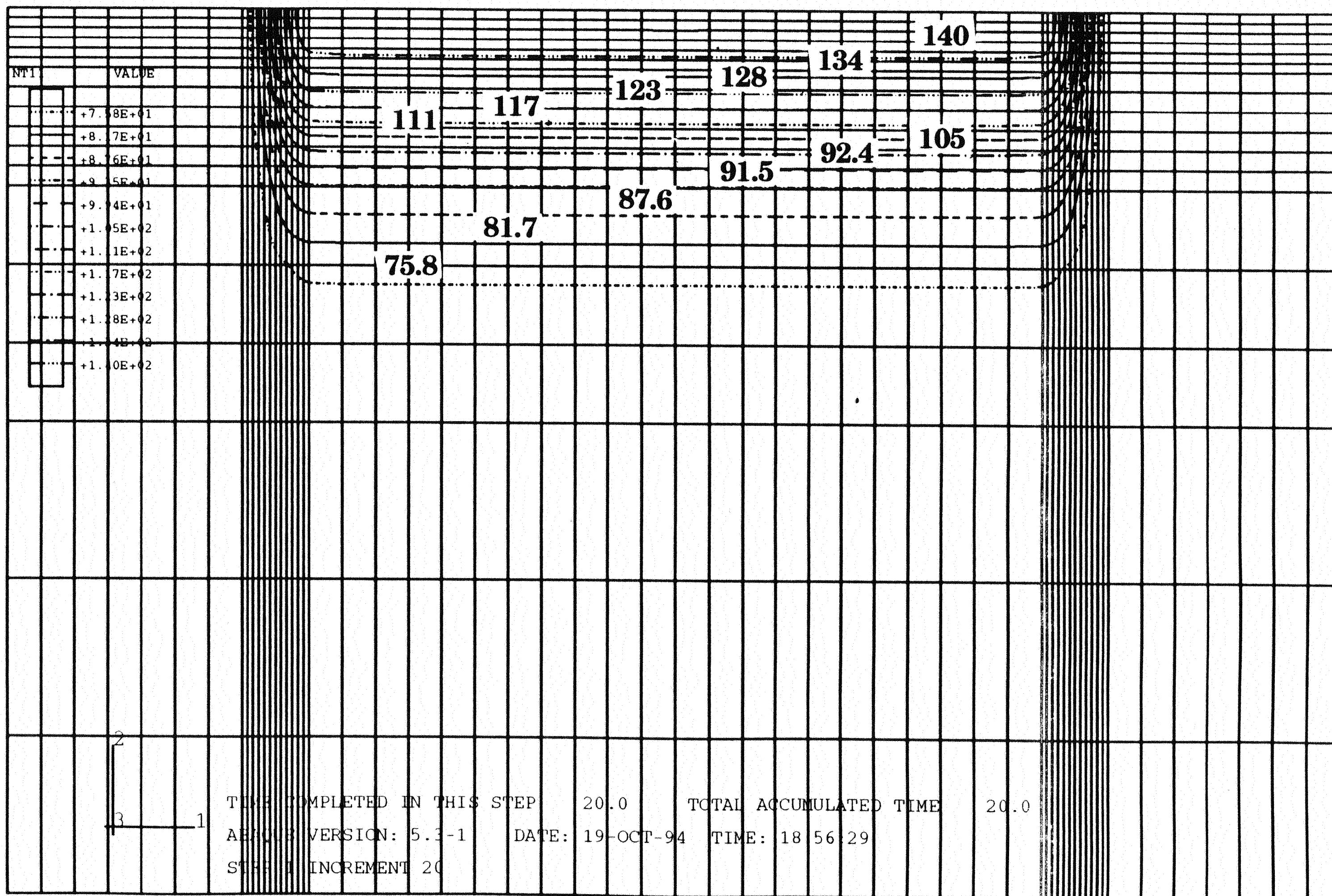


Fig. 3-15 Temperature Contour for a Base Temperature of 70 °F and a Laydown Temperature of 280 °F at Time 20 Minutes

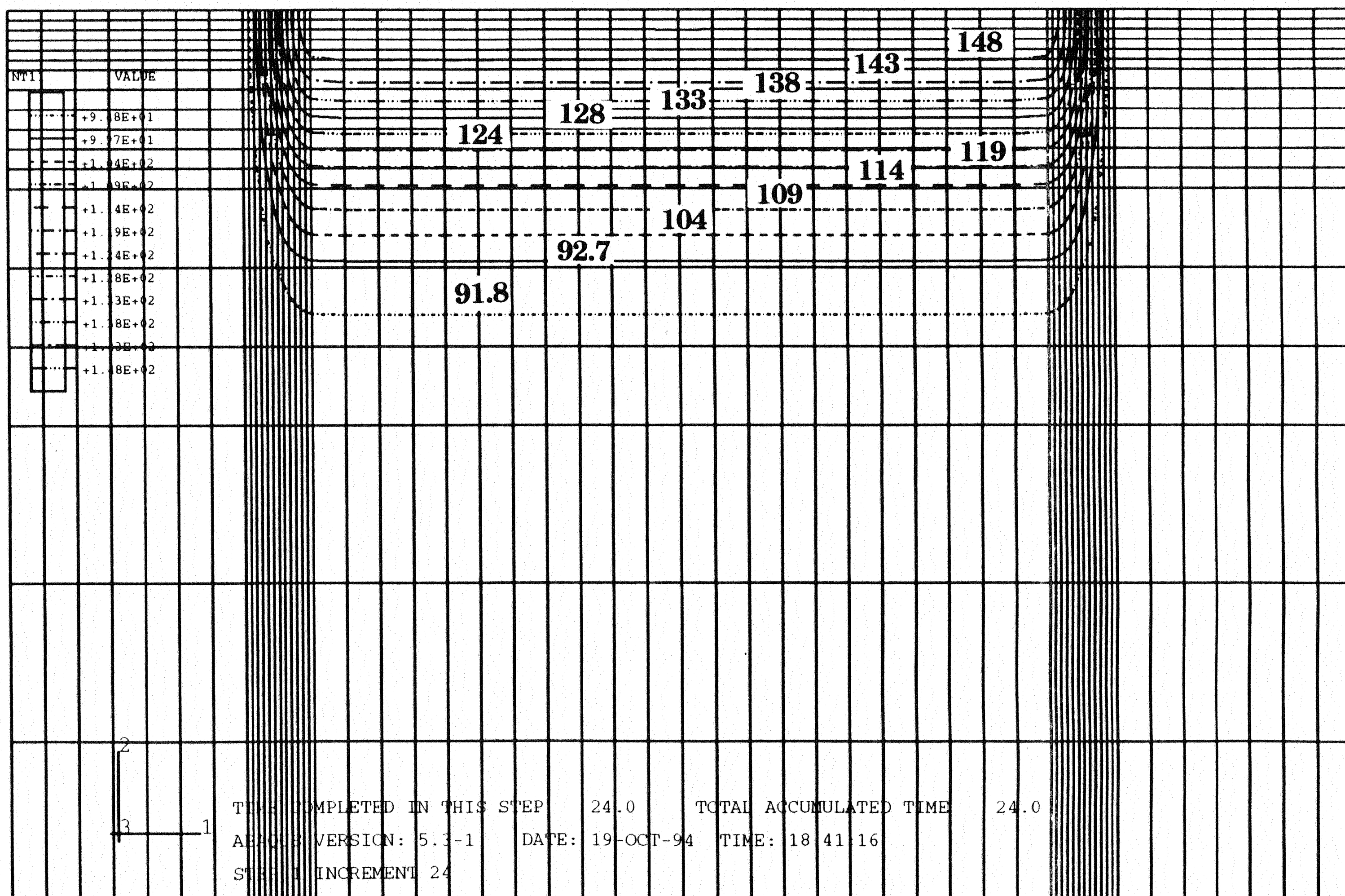


Fig. 3-16 Temperature Contour for a Base Temperature of 90 °F and a Laydown Temperature of 280 °F at Time 24 Minutes

Chapter IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 SUMMARY

Cooling properties of hot mix asphalt (HMA) are important to transportation agencies and contractors in a surfacing or resurfacing operation. The cooling rate of an HMA overlay dictates how soon a roadway can be opened to traffic without having any potentially serious consequences on the pavement performance. The ease or difficulty of compaction of the HMA paving mixture (by rolling during construction) is influenced by the viscosity-temperature characteristics of the asphalt-cement and the temperature of the mix during compaction. If the paving mixture becomes too hard due to low temperature, the pavement is likely to attain a low density. Consequently, higher air voids may cause it to deteriorate at a faster than normal rate resulting in seriously curtailed service life. It has been reported that an increasing resistance to compaction is due to the increasing viscosity of the binder as the mix temperature falls. The cooling rate of HMA becomes a very important factor with regard to the compactive effort needed to achieve the specified density. Thus, knowing the cooling rate of HMA provides the contractor, among others, the extent of time within which breakdown rolling must be completed to ensure the quality of the pavement and when a roadway can be opened to traffic following a surfacing/resurfacing job without any detrimental consequences.

HMA loses its temperature to the two contact surfaces: the upper surface and lower surface. At the upper surface of the HMA mat, heat is lost to the atmosphere by a combination of convective transport and radiative emittance of the asphalt surface. At the lower asphalt surface, thermal energy is lost to the base by the process of thermal conduction. In general, heat is lost to the base more rapidly than it is lost to the air.

In general, researchers have concluded noted that density does not increase much by rolling compaction when the average HMA temperature is below 175 $^{\circ}$F. AASHTO and several DOTs suggest a minimum compaction temperature of 175 $^{\circ}$F. It is reported that below this temperature the internal friction and cohesion of the mix increases to the point that little density gain is achieved with the application of additional compactive effort.

From the telephone interviews, it become evident that although several DOTs (namely, Texas, New Mexico, Arizona, Florida) do not specify a specific temperature range, they do suggest, based on their experiences, that it is preferable to open a roadway to traffic when the HMA temperature is below 140 °F. This temperature is close to the 150 °F reported in the Synthesis of Highway Practice by the National Cooperative Highway Research Program (NCHRP). HMA thickness and wind velocity have been rated by the selected DOTs as the most significant factors that influence the cooling rate of HMA.

An effort was made in this study to use the finite difference computer code provided in the research report by Corlew and Dickson [1968] to compute the time needed by a HMA layer to cool to 150 °F. In this work, the time to cool to various given average mat temperatures was computed for various laydown (200-300 °F) and base temperatures (50-120 °F). Some field data was collected from Interstate I-35 near Stillwater, Oklahoma. The field data compares favorably with that obtained from the numerical model prediction for similar conditions. The time required to open a roadway to traffic can be estimated from Figs. 3-2 and 3-3 of this report.

4.2 CONCLUSIONS

From the information obtained and the analysis of the results presented in the preceding chapters, the following observations and conclusions are made:

1 It is generally agreed that with a normal mix the ability to increase HMA density becomes more difficult when the mix temperature is below 175 °F. Therefore, several DOTs and agencies have set a cut off temperature of 175 °F for compactive rolling.

2 Asphalt mix temperature decreases more rapidly near the base than near the surface.

3 Asphalt mix temperature is normally within the range of 275 to 325 °F as it leaves the mixing plant.

4 Data obtained from the the phone interviews and the literature search suggest that HMA temperature should be below 140 - 150 °F before opening a lane to traffic.

5 HMA thickness and wind velocity have been rated as the most significant factors that influence the cooling rate of HMA by the selected DOTs.

6 The two field results (26.5 and 21 min. for the mat to cool to 150 °F) are close to that predicted by the FD model (28 min. cooling time) for the similar conditions.

7 It was observed that the 1.5 in. lift to have the cooling time of 30 min. as the dividing line. Below 30 min., the FD analysis yielded a longer time than that of the FE analysis but the reverse was true beyond 30 min. Similar behavior was obtained for the 3 in. lift but the dividing line occurs at 80 min.

4.3 RECOMMENDATIONS

The following recommendations are made for further studies:

1 The figures (Figs. 3-2 and 3-3) developed in this study are for a given wind velocity (10 knots) and solar flux (125 Btu /hr ft^2). Inasmuch as wind velocity has been rated as one of the most significant factor, it is desirable to establish similar figures with different wind velocity and solar flux.

2 A more accurate numerical model can be developed to quantify various factors which influence the cooling characteristics influence the cooling characteristics of asphalt surfaces. This numerical model may be used to develop nomographs including various environmental factors and HMA properties. Such nomographs can be readily used by contractors and ODOT in HMA jobs. Findings from such studies would help ODOT in upgrading its standards and practices, resulting in improved performance of HMA surfaces.

3 The two field data collected in this study show some degree of dissimilarity. Therefore, more data from others site will enhance the findings of the present study. Also, additional field data are required to investigate the different environmental conditions and application scenarios.

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