

TWO-DIMENSIONAL FINITE DIFFERENCE TECHNIQUES APPLIED TO TRANSIENT TEMPERATURE CALCULATIONS IN HOT-MIX ASPHALT CONCRETE WINDROWS

J. W. Fishback, Exxon Company USA, Baton Rouge, Louisiana; and
P. F. Dickson, Department of Chemical and Petroleum-Refining Engineering,
Colorado School of Mines

Temperature is an important variable in the compaction of hot-mix asphalt concrete. This study calculates the change with time in average bulk temperature of hot-mix windrows of different sizes and initial temperatures considering the following environmental conditions: the base material temperature, the ambient temperature, the net absorbed solar radiation, and the wind velocity. The analytical solution of the mathematical model describing the windrow and its immediate surroundings cannot be obtained. Therefore, the approach used was a 2-dimensional transient heat balance model formulated by explicit finite-difference techniques in FORTRAN-IV. The results of the finite-difference solution were those readily predicted by the laws of heat transfer. The most significant variable affecting the cooling rates was the size of the windrow. Large windrows, having a lower surface-to-volume ratio than smaller windrows, were less affected by all environmental conditions and thus cooled more slowly. For the same initial temperature (300 F) under the same environmental conditions (the most severe case used was 10 F base temperature, 10 F ambient temperature, overcast day, and still wind), the temperature drop after 30 minutes was 67 F for a 2- by 1-ft windrow but only 24 F for a 6- by 3-ft windrow. The computer programs developed in the study may be used to calculate bulk temperature versus time curves for an almost limitless number of combinations of windrow sizes, initial temperatures, environmental conditions, and cooling times.

•THE PURPOSE of this study was to determine the average bulk temperature of windrows of hot-mix asphalt concrete as a function of time. The bulk temperature of the asphalt windrow is important because this is the effective input temperature of the hot-mix asphalt at the laydown machine. The average bulk temperature will vary considerably, depending on the environmental conditions to which the asphalt is exposed. The environmental conditions that most affect the bulk temperature of the asphalt and that were considered in this study are the base material temperature, the ambient temperature, the net absorbed solar radiation, the wind velocity, the size of the windrow, and the initial temperature of the windrow.

The success of a paving operation using hot-mix asphalt concrete depends significantly on the temperature of the asphalt when it is compacted into the road surface mat. Before the asphalt enters the paving machine to be laid down in a mat, it is sometimes dumped from trucks into long triangular windrows ahead of the paver, where it begins to cool before it can be used. If the temperature of the asphalt becomes too low, the asphalt viscosity will be so high that specified compaction densities cannot be obtained and a poor road surface will result.

The results of this study enable an asphalt contractor to predict the bulk temperature of an asphalt windrow under given environmental conditions at any time after dumping from the truck. If the actual temperature of the hot mix being fed to the laydown machines is known, he can decide in advance of starting the operation whether or not enough time exists to complete the paving operation.

Previous studies of temperature effects in hot-mix asphalt concrete have been concerned with the effect of temperature on compactibility in the final mat (1). Experimental work has also been conducted to measure temperature changes as a function of time at given positions in the mat (1).

A logical next goal was a mathematical analysis of heat transfer in asphalt windrows to allow prediction of bulk asphalt temperatures in advance of paving jobs. Previous studies have assumed that the laydown temperature is approximately that of the hot-mix plant. When hot mix is dumped in windrows rather than directly into the laydown machine, this assumption will not in all cases be true. The results of this study provide the means to predict effective laydown temperature based on windrow cooling.

STATEMENT OF THE PROBLEM

As noted earlier, the purpose of this study was to determine the average bulk temperature of windrows of hot-mix asphalt concrete as a function of time under different environmental conditions. The problem was to mathematically model the windrow system and its immediate surroundings to achieve the stated purpose. This mathematical model must include realistic boundary conditions that can be calculated accurately from easily measurable physical quantities. The analytical mathematical solution of the simultaneous, 2-dimensional, nonlinear, unsteady-state partial differential equations that result from the energy balances in this problem cannot be obtained. Therefore, finite-difference mathematical solutions must be calculated. The problem, in finite-difference form, must be solved with a digital computer and with a node size small enough to closely approximate the real situation yet within the storage capacity of the computer and within reasonable expenditures of computer time.

APPROACH TO THE PROBLEM

The approach used to calculate a feasible and reasonably accurate solution to the problem of heat losses from an asphalt windrow was a 2-dimensional transient mathematical heat-balance model of the windrow formulated by explicit finite-difference techniques in FORTRAN-IV for computer solution on a PDP-10 computer.

The necessary theoretical considerations were first incorporated into the solution; these included applications of Fourier's law for conduction effects, Newton's law of cooling (or heating) for convection effects, Nusselt-type heat transfer correlations to predict the convection heat transfer coefficient, the Stefan-Boltzmann law for radiative effects, and empirical expressions for incident solar flux.

The asphalt windrow model was then divided into a grid system of specific nodes, as shown in Figure 1. Overall transient energy balances were developed for each of 8 different types of nodes. The type of node depends on the combinations of boundary conditions to which the windrow is subjected at various locations throughout the windrow.

The overall transient energy balances were then converted from the differential form, for which an analytical solution is mathematically unobtainable, to the finite-difference form, for which iterative approximate solutions can be obtained with digital computers. The change in temperature of each node with time was used to calculate the change in average bulk temperature of the windrow as a function of time.

Finally, the computer program model was executed with various combinations of values of important variables such as base temperature, ambient temperature, net absorbed solar radiation, wind velocity, size of windrow, and initial temperature of windrow, as shown in Table 1. The average bulk temperatures of the windrow at 10, 20, and 30 minutes after it is dumped onto the base material were calculated and plotted in Figures 2 through 5. These figures illustrate the effect of each significant variable independent of the others and indicate permissible paving conditions that can be used readily by asphalt contractors.

Figure 1. Schematic cross section of asphalt windrow and base material with typical nodal system overlay for finite-difference analysis indicating various modes of thermal energy transfer at a given node.

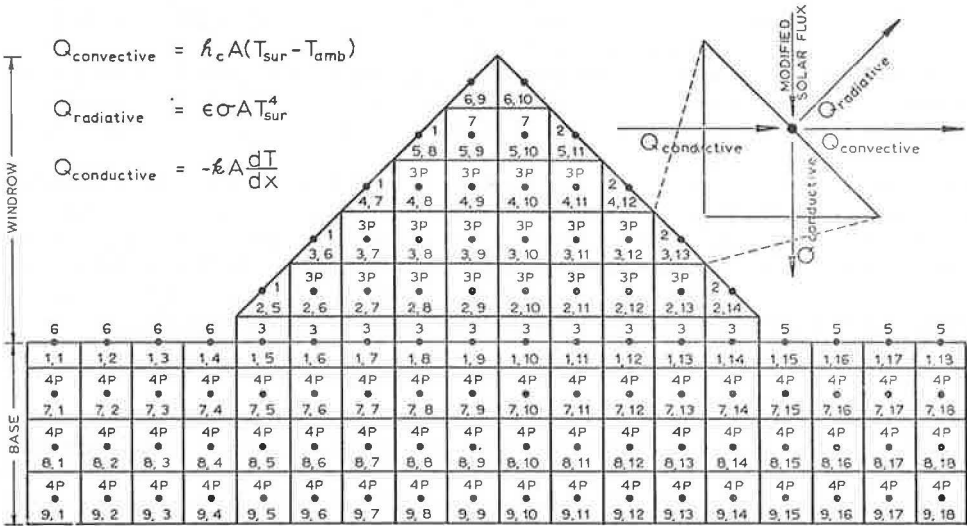


Table 1. Combinations of variables for each execution of computer program.

Run	Base Temperature (F)	Ambient Temperature (F)	Solar Flux (Btu/ft ² /hour)	Convective Heat Transfer Coefficient (Btu/ft ² /hour/deg F)	Width of Base of Windrow (ft)	Initial Mix Temperature (F)
1	10	10	80	1.5	6.0	300
2	10	10	80	1.5	6.0	275
3	10	10	80	1.5	6.0	250
4	50	50	175	1.5	6.0	300
5	50	50	175	1.5	6.0	275
6	50	50	175	1.5	6.0	250
7	100	90	265	1.5	6.0	300
8	100	90	265	1.5	6.0	275
9	100	90	265	1.5	6.0	250
10	10	10	80	1.5	4.8	300
11	10	10	80	1.5	4.8	275
12	10	10	80	1.5	4.8	250
13	50	50	175	1.5	4.8	300
14	50	50	175	1.5	4.8	275
15	50	50	175	1.5	4.8	250
16	100	90	265	1.5	4.8	300
17	100	90	265	1.5	4.8	275
18	100	90	265	1.5	4.8	250
19	10	10	80	1.5	2.8	300
20	10	10	80	1.5	2.8	275
21	10	10	80	1.5	2.8	250
22	50	50	175	1.5	2.8	300
23	50	50	175	1.5	2.8	275
24	50	50	175	1.5	2.8	250
25	100	90	265	1.5	2.8	300
26	100	90	265	1.5	2.8	275
27	100	90	265	1.5	2.8	250
28	10	10	80	1.5	2.0	300
29	10	10	80	1.5	2.0	275
30	10	10	80	1.5	2.0	250
31	50	50	175	1.5	2.0	300
32	50	50	175	1.5	2.0	275
33	50	50	175	1.5	2.0	250
34	100	90	265	1.5	2.0	300
35	100	90	265	1.5	2.0	275
36	100	90	265	1.5	2.0	250
37	10	10	80	4.9	6.0	300
38	10	10	80	2.8	6.0	300
39	10	10	80	5.1	4.8	300
40	10	10	80	5.7	2.8	300
41	10	10	80	2.3	2.0	300

Figure 2. Comparison of calculated temperatures for a 6- by 3-ft windrow under different environmental conditions at different initial temperatures.

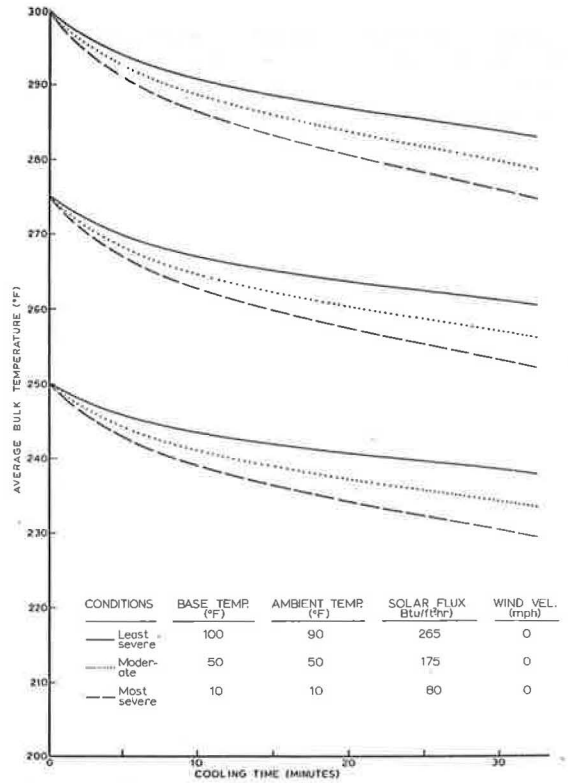


Figure 3. Comparison of calculated temperatures for a 4.8- by 2.4-ft windrow under different environmental conditions at different initial temperatures.

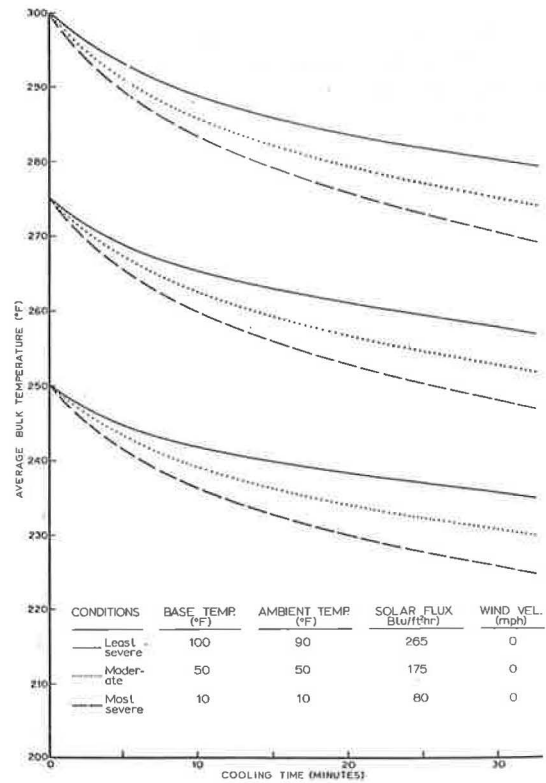


Figure 4. Comparison of calculated temperatures for a 2.8- by 1.4-ft windrow under different environmental conditions at different initial temperatures.

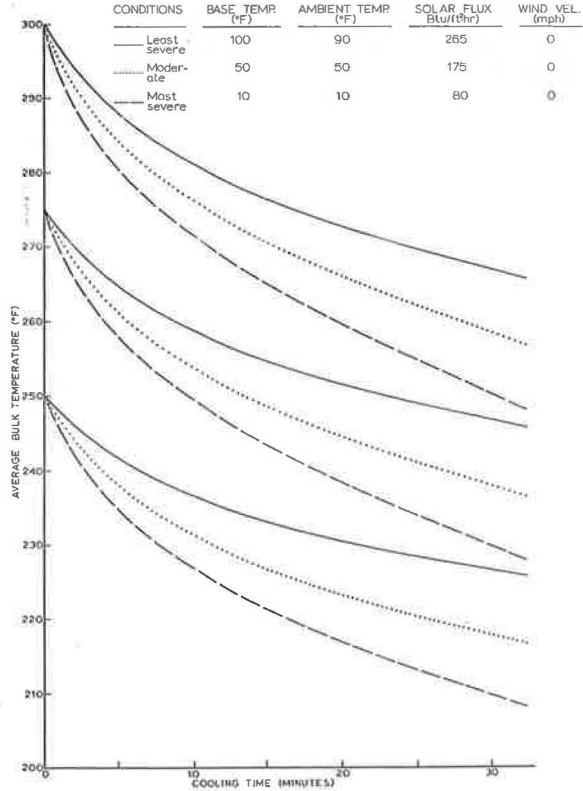
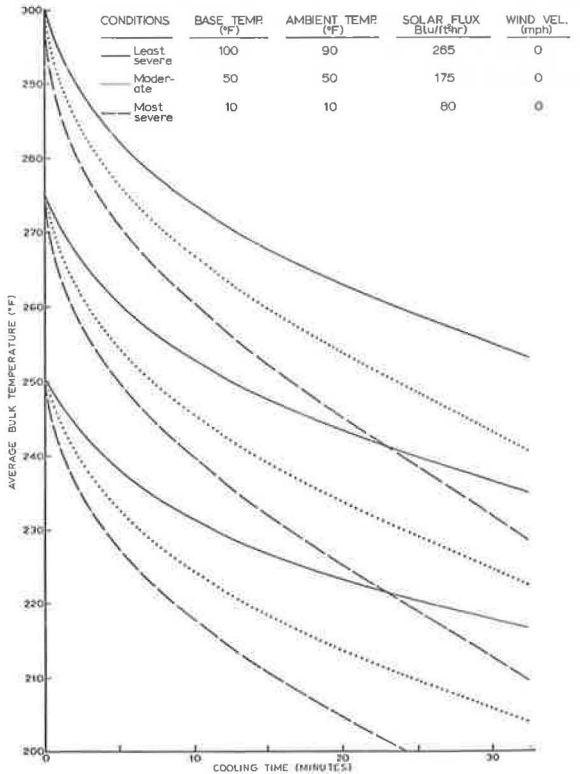


Figure 5. Comparison of calculated temperatures for a 2.0- by 1.0-ft windrow under different environmental conditions at different initial temperatures.



DISCUSSION OF RESULTS

The results of this study consist of the effect that each of the variable changes listed in Table 1 has on the cooling rate of the hot-mix asphalt concrete windrow.

Effect of Environmental Conditions

Because of the large number of possible combinations of the variables given in Table 1, executing the computer program for 3 values of each of 6 variables would require 6^3 or 216 computer runs. The average total elapsed time for each computer run was approximately 10 minutes. Therefore, the execution of all runs would have required 2,160 minutes or 36 hours of computer time. This prohibitive time requirement made it necessary to combine the effects of base temperature, ambient temperature, and solar flux into 3 groups representing most severe, moderate, and least severe environmental conditions. The most severe conditions were those that caused the fastest cooling of the asphalt windrow. The most severe conditions were used in runs 1, 2, 3, 10, 11, 12, 19, 20, 21, 28, 29, 30, and 37 through 41 in Table 1. The moderate conditions were used in runs 4, 5, 6, 13, 14, 15, 22, 23, 24, 31, 32, and 33. The least severe conditions were used in runs 7, 8, 9, 16, 17, 18, 25, 26, 27, 34, 35, and 36. The effects of these sets of environmental conditions can be seen in Figures 2, 3, 4, and 5. Figure 2 shows that for the largest windrow (6 by 3 ft) at the highest initial temperature (300 F) the difference in average bulk temperature for the least severe minus the most severe case after 30 minutes of cooling time is 8 F (284 F - 276 F). Figure 6 shows that for the smallest windrow (2 by 1 ft) at the same initial temperature (300 F) the difference in average bulk temperature after 30 minutes is much greater (22 F). This reflects the fact that a larger windrow has less surface-to-volume ratio than a smaller windrow, so that the surface effects are reduced on larger windrows. Each of the environmental effects is a surface effect; therefore, the same change in severity of environmental conditions does not affect the larger windrow as much as the smaller one.

Effect of Initial Asphalt Temperature

Three different initial temperatures of 300 F, 275 F, and 250 F were used in the study, as given in Table 1 and shown in Figures 2 through 5. In Figure 2 we see that for the largest windrow the total temperature drop under the most severe conditions at an initial temperature of 300 F was 24 F (300 F to 276 F) in 30 minutes. For the same windrow under the same severity of conditions after the same cooling time, the temperature drop was 20 F (250 F to 230 F) for an initial temperature of 250 F. These differences are even more pronounced for the smaller windrows, as can be seen from Figures 3 through 5. This is because conductive heat transfer increases as the temperature difference between the windrow and the base increases, because convective heat transfer increases as the temperature difference between the windrow and air increases, and because radiative heat transfer increases as the temperature of the windrow increases. Therefore, a hotter windrow will always cool faster than a cooler windrow under the same conditions. This fact was conclusively supported by Figures 2 through 5.

Effect of Size of Windrow

The most significant variable affecting cooling rates analyzed in this study was the size of the windrow. Windrow sizes were varied over a larger percentage range than the other variables, which accounted for some of the effect. For example, the initial temperature was varied from 300 F to 250 F or 83.3 percent of the highest value. The convective heat transfer coefficient was varied from 5.7 Btu/ft²/hour/deg F to 1.5 Btu/ft²/hour/deg F or 26.3 percent of the highest value. But the windrow size was varied from 6 by 3 ft or 9 ft³ per linear foot to 2 by 1 ft or 1 ft³ per linear foot, a reduction to 11.1 percent of the highest value. These relative ranges of the variables investigated do not minimize the pronounced effect of windrow size on cooling rate.

Comparison of Figure 2 and Figure 5 shows that for the same initial temperatures (300 F) under the same environmental conditions (the most severe case), the tempera-

ture drop after 30 minutes is 67 F for the 2- by 1-ft windrow whereas it is only 24 F for the 6- by 3-ft windrow.

All of these significant temperature drops due to windrow size are based on the surface-to-volume ratio effect in the windrow. The larger the windrow, the less surface it has per unit volume; thus the interior of the windrow is more effectively insulated from all boundary conditions that affect the cooling rates, and therefore the entire mass cools more slowly.

SUMMARY AND CONCLUSIONS

From the application of finite-difference techniques to a real-world problem impossible to solve by analytical methods, a significant amount of quantitative information has been presented about cooling rates of hot-mix asphalt concrete windrows under varied environmental conditions. This quantitative information can be put to valuable use by asphalt contractors. Just by knowing the approximate environmental conditions at a given time, they will be able, with the help of this study, to judge more accurately the allowable time to complete paving jobs.

The true value of the study, however, lies not only in the information presented here. The computer programs developed in this study may be used to calculate bulk temperatures for any of an almost limitless number of combinations of windrow sizes, initial temperatures, environmental conditions, and cooling times that might be of interest.

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