Bituminous Pavement Temperature Related to Climate

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Advances in bituminous pavement technology have pointed out the sensitivity of the viscoelastic properties of mixes to varying temperatures. This paper reports on the documentation of pavement temperatures in a northern climate and on a method of pavement temperature prediction using digital simulation.

A 6-in. and a 12-in. thick test pavement of dense-graded high-type bituminous mix was fully instrumented with thermocouples to measure for a full year at 5-min intervals the temperature patterns resulting from exposure to an actual climate. The pavement temperatures recorded were summarized to indicate the distribution of temperatures with depth and with time. The temperatures were also related to important climate parameters, including changes in air temperature and in the solar energy received by the pavement.

Analysis of gradients and temperature extremes clearly indicates the need for temperature measurements on the very surface of the pavement for correlation with solar energy received, the importance of which has not been emphasized in other investigations.

A digital simulation model of heat flow into the pavement was developed for computer solution. This makes possible the prediction of pavement temperatures given specific climate parameters. Such an investigative tool can be used to extend pavement temperature knowledge in lieu of long and tedious temperature observations of actual pavements.

•AS pavement technology advances, more attention is being directed toward the ability of pavements to withstand more repetitions of heavier wheel loads. For flexible pavements, this involves a better understanding of viscoelastic properties related to the stresses and strains, stiffness, and deflections experienced under repeated heavy loads. Since viscoelastic properties are greatly affected by temperature, these properties cannot be completely understood without a more complete knowledge of the temperatures to which bituminous pavements are subjected when exposed to actual climates.

Bituminous pavements are characteristically dark-surfaced and can be composed of either asphalts or tars. Although asphalts and tars differ in their origin and methods of production, their viscoelastic properties are generally similar. For this reason, asphalt was chosen for this study as being representative of bituminous paving mixtures in general.

DOCUMENTATION OF PAVEMENT TEMPERATURE

Recent literature reveals the interest of researchers in more knowledge of pavement temperatures. According to Whiffin and Lister (20), "Bituminous roads deteriorate markedly with the rise of temperature due to the reduction of the viscosity of the bitu-

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mens and tars which causes a reduction of the dynamic elastic moduli of the layers forming the road. These experiments emphasize the necessity of recording temperature when measuring dynamic stresses of deflections of roads under traffic."

B. F. Kallas (8) stated, "The use of thicker asphalt paving courses in many heavy-duty highways has resulted in the need for more information on temperature variations in pavement structures. Temperature data are necessary in studies on pavement deflections, stresses, and strains under moving wheel loads. Pavement temperature data are of interest in any studies or testing involving the temperature-dependent mechanical properties of paving mixtures or paving asphalts."

Cold temperatures increase the stiffness of the asphalt concrete. This allows the pavement to offer considerably greater resistance to loads. Although this is a favorable characteristic, cold temperatures may also result in unfavorable effects in the pavement. A pavement will not deflect as much when cold, and heavy loading may cause cracking in the asphalt concrete. Dorman (5) points this out and suggests that in the design stage of a pavement conservatively high values of stiffness (psi) be used.

High pavement temperatures decrease the stiffness of asphalt concrete, and also increase the possibility of densification and possible rutting of the pavement under heavy loads. Monismith and Secor (11) and Monismith (9) indicate that a change of temperature from 40 F to 140 F may cause the viscous component of asphalt concrete to decrease by a factor of 100. Pell (14) points out how tensile strain is caused by high pavement temperatures.

Thicker asphalt-treated sections will be less affected by temperature than thinner sections, according to Dorman (5) and Whiffin and Lister (20). Jimenez and Gallaway (6) state that the flexibility of thin asphaltic concrete slabs is greater than that of thicker ones, but thinner slabs have less resistance to repeated loads.

The load-carrying capacity of a pavement is much lower in the spring, when the temperature in the pavement is 75 to 90 F, according to a study in Canada (3). Sudden changes in pavement temperature may cause serious effects on the pavement. Monismith et al (12) state that a sudden warming of the pavement surface may cause a considerable reduction in the fracture strength of the asphalt concrete, thus permitting cracks to develop.

In addition to the foregoing references, a number of other papers have shown important relationships between temperature and the properties of pavement mixtures. Among these are Secor and Monismith (19), Monismith (10), and Pagen (13).

Need for Temperature Data

An understanding of the viscoelastic behavior of asphalt paving mixtures derived from theory and laboratory work cannot be put to full use without a more thorough knowledge of the temperatures to which actual pavements will be subjected when they are exposed to actual climates. There appears to be a lack of data on temperatures observed in detail within heavy-duty asphalt pavements exposed to actual climates. Studies in College Park, Maryland (8), and in Louisiana (1) have partly filled the gap, but each was limited to observations of a test site exposed to only one type of climate. Detailed observations similar to these are needed to document temperatures within thick, dense-graded asphalt pavements exposed to other climates representative of large areas where asphalt pavements are used.

Adequate documentation of pavement temperatures would at least give guidance for selecting most appropriate testing temperatures for laboratory procedures and investigations. It is also conceivable that adequate documentation of temperature variation with depth, and for various climates, would provide valuable data for more valid analyses of performance, as well as for the development of more sophisticated design procedures. Since there have been no recent studies on asphalt concrete pavement temperatures in a northern climate, this is proper justification for this project.

The purpose of this project, therefore, was to document the variations of asphalt concrete pavement temperatures occurring in the northern New York State climate. Also sought was a numerical simulation model of this pavement that could predict pavement temperatures, given any particular climate conditions. This paper is based on work completed at Clarkson College of Technology (15).

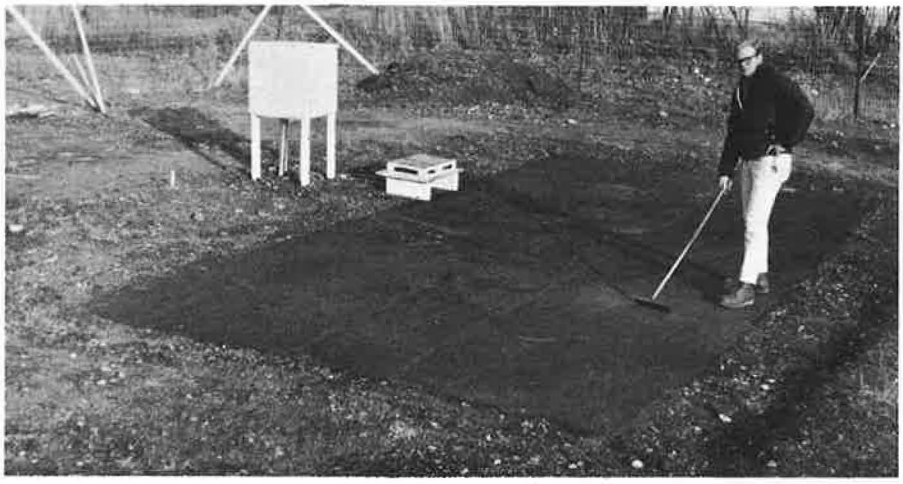

Figure 1. General view of pavement test site.

TEST SITE DEVELOPMENT AND DATA ACQUISITION

The test pavement was located at Potsdam, N.Y., on the campus of Clarkson College. The test section was built on the south side, 175 ft behind a three-story building. This location was chosen because it was not shielded from the sun and wind.

The asphalt concrete test pavement shown in Figure 1 was 12 ft wide and 24 ft long. A 10-ft long section was constructed with a 6-in. thick pavement, and a 12-ft long section was constructed with a 12-in. thick pavement. A 2-ft long transition section was placed between these two sections similar to the test pavement design reported by Kallas (8).

On one edge of the asphalt concrete test section was placed a vertical section of 1-in. thick expanded polystyrene insulation. This insulation extended the width of one edge of the test section (12 ft) and was placed to a depth of 2 ft. The reason for the placement of this insulation will be explained later.

To obtain the data required for the project, temperature probes were located at successive 2-in. depths in the pavement. Temperature probes were located at depths of 2, 4, and 6 in. in the 6-in. thick pavement. Probes were also located at depths of ¼ in., 18 in., and 4 ft 4 in. in the gravel base beneath the pavement. The location of the probes is shown in Figure 2.

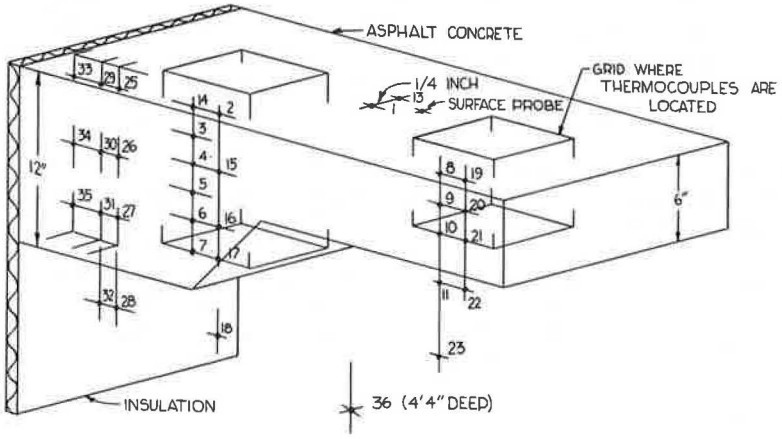

Figure 2. Temperature probe locations.

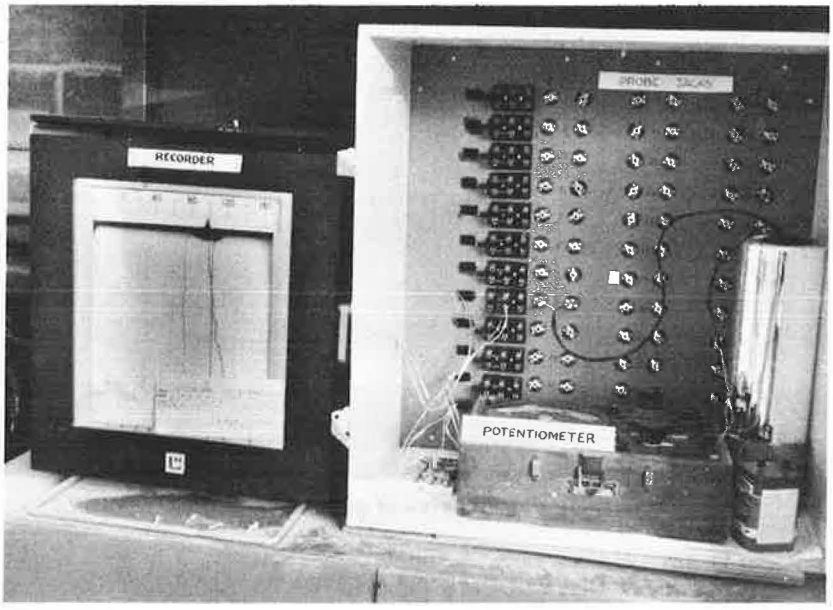

Figure 3. Multipoint recorder and manually operated potentiometer.

The asphalt concrete, which by New York State specifications (16) was Type 1-A, was placed in 2-in. lifts. The asphalt concrete used was a dense-graded hot mix at a temperature of about 260 F. It was compacted in place with a 6-ton roller. After each 2-in. lift was completed, the thermocouples for that level were placed at predetermined locations. The elevation of the tip of each temperature probe was then determined with the aid of a surveying level and rod. To protect the insulation on the thermocouple duplex wire from the heat of the asphalt concrete during construction, asbestos tape was wrapped around each wire as it was placed before the next 2-in. lift covered it.

The temperature probes installed in the test pavement were iron-constantan thermocouple probes, constructed according to Johnston (7).

A Leeds and Northrup Speedomax G, Model S, multipoint temperature recorder was used for the study. This recorder was capable of reading 12 iron-constantan thermocouples, one every 24 sec, or the same thermocouple once every 4 min 48 sec. The range of this instrument was -30 F to 170 F, with an accuracy of ±1 F. The recorder was checked for accuracy during the testing period by using an ice bath. One of the probes placed on the automatic recorder was an air temperature probe. This probe was located in a standard weather station 40 ft west of the test pavement. A Taylor stripchart recorder was located in the weather station as a check of the thermocouple air temperature probe. The accuracy of this instrument was ±2 F over its recording range of -10 F to 90 F, and it could be read to within the nearest 15 min. The other eleven monitored probes were usually those probes located within the asphalt concrete pavement.

The thermocouple temperature probes that were not wired to the multipoint recorder could be read by the use of a manually operated portable potentiometer. Both of these readouts of temperatures were located in a building south of the test section. Figure 3 shows both the multipoint recorder and portable potentiometer.

A solar radiation instrument to measure daily values of total solar radiation was built according to instructions in Whillier and Tout (22) and Whillier (21). The instrument, consisting of silicon solar cells and a Ferranti Type FKt DC ampere-hour meter, was located near the test pavement. This instrument is shown in Figure 4.

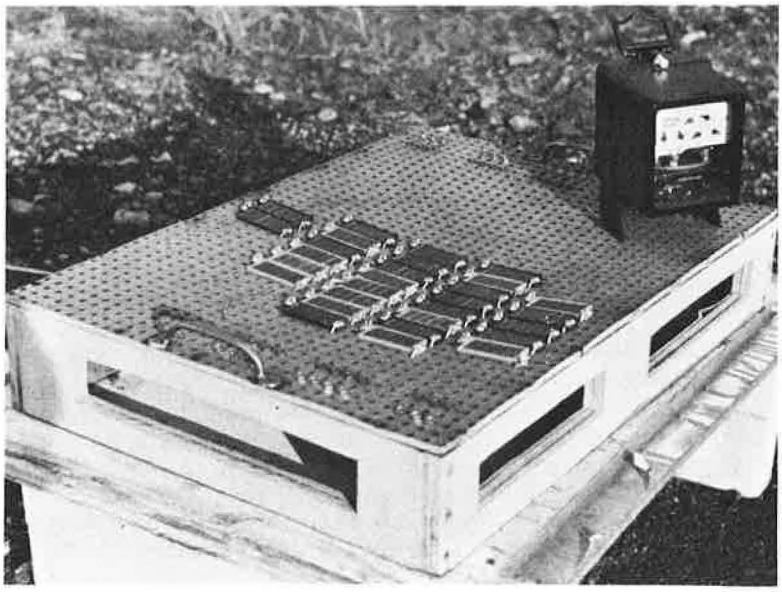

Figure 4. Solar cells and DC ampere-hour meter.

Data Collection

This project involved the collection not only of asphalt concrete pavement temperatures, but also of such data as soil temperatures beneath the pavement, air temperature data, percentage of cloud cover, and amount of solar radiation received each day. The multipoint recorder collected continuous detailed data from August 1, 1966, to July 31, 1967. From these data, hourly temperatures for each probe were taken from the recorder graph and placed on data sheets for data analysis.

The manually-operated potentiometer was used only as a check against the automatic recorder and as a back-up system in case of breakdown in the automatic recorder.

All readings of cloud cover were recorded by human observations. It is realized that information obtained was quite crude, since it was difficult to describe the type, color, amount, and thickness of any clouds that made their appearance over the site. A very general approach was used in collecting these data. The amount of cloud cover was placed into one of five categories: 0 percent cloud cover, 0-20 percent, 30-70 percent, 80-100 percent, or 100 percent. Along with these percentage of cloud cover records, a time record was kept to describe how long the sky remained in any one cloud condition. Records were also kept of any rain or snow that fell on the test section.

Snow was removed as quickly as possible from the pavement so that the snow cover would not influence the pavement temperatures, except when snow-cover-effect studies were in progress.

RESULTS

Climate During Test Period

The pavement temperatures during the year 1966-67 were obviously produced by the climate conditions occurring during this period. It is thus of interest to know how this particular year compares with that of an average year in northern New York. This comparison is shown in Figure 5. The average monthly air temperature during the data collection period is compared with the average monthly air temperature for the long-term average for this area. The monthly solar radiation received is also plotted; however, since there is no long-term average monthly solar radiation available, no comparison could be made.

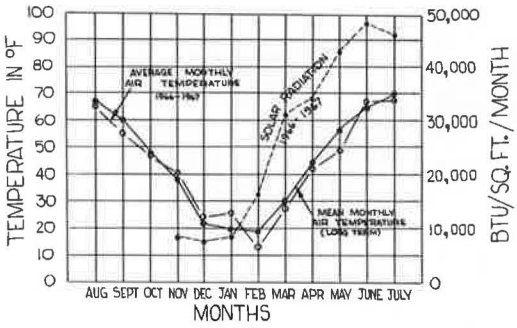

Figure 5. Mean monthly air temperature and solar radiation.

Maximum and Minimum Pavement Temperatures

The maximum pavement temperatures during the one-year recording period occurred on June 28, 1967. The temperatures at the surface and at depths of ¼, 2, 4, 6, 8, 10, and 12 in. were 144, 131, 122, 111, 103, 98, 94, and 90 F respectively. These occurred between 2 and 5 o'clock in the afternoon when the air temperature was 83 F. The highest air temperature during the testing period occurred at 2 p.m. on August 9, 1966, when the air temperature was 91 F.

The minimum pavement temperatures during the recording period occurred on February 8, 1967. The temperatures at the depths of ¼, 2, 4, 6, 8, 10, and 12 in. were 5, 7, 10, 14, 15, 19, and 21 F respectively. These occurred at 6 and 7 a.m. when the air temperatures were -7 and -5 F respectively. The lowest air temperature of the testing period occurred at 7, 8, and 9 a.m. on February 13, 1967, when the air temperature was -18 F.

Temperature Cycles for a 24-Hour Period

Asphalt concrete pavement temperatures follow a cycle pattern typical of that produced in a conducting medium by approximately sinusoidal boundary conditions. This cycle can be generalized for a short time period (24 hours) or for a long time period (1 year).

For a period of 24 hours during a completely sunny day in the summer, the temperature cycle generally follows the pattern shown in Figure 6. It can be seen that at each depth a maximum temperature and a minimum temperature is reached during the cycle. The maximum temperature occurs first at the surface. As the depth of the pavement increases, the time at which the maximum temperature is reached occurs later and later than the time the maximum temperature was reached at the surface. This lag time is also observed for the minimum pavement temperatures at each depth.

The surface pavement temperature reaches the highest value during the afternoon and then during the night becomes the lowest for the entire pavement. The surface probe has the greatest temperature extremes of any location in the pavement. The deeper the probe is in the pavement, the flatter the curve. Below 12 in., the damping of the diurnal temperature wave is almost complete.

Figure 7 shows data taken from the test section on August 7, 1966. This plot shows the temperature cycles for the air temperature probe and the ¼ and 12-in. probes.

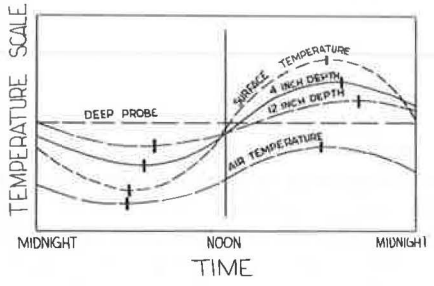

Figure 6. Generalized temperature cycles for a sunny day.

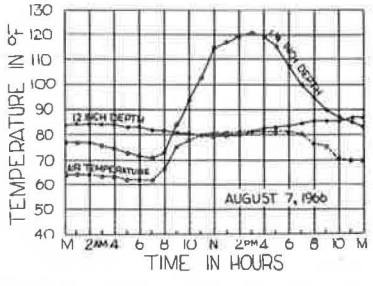

Figure 7. Temperature cycles on a sunny summer day.

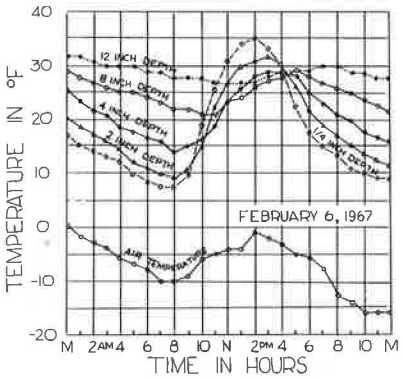

Figure 8. Temperature cycles on a sunny winter day.

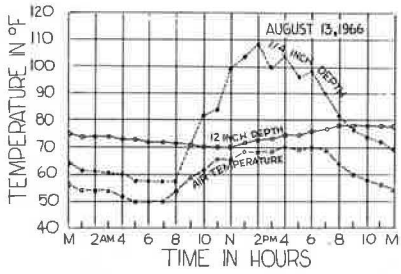

Figure 9. Temperature cycles on a partly cloudy summer day.

This was a completely sunny day. The ¼-in. probe is a smooth curve with only one peak, which occurred in the middle of the afternoon. Figure 8 shows the same type of curve for a completely sunny day during the winter.

Cloud cover will, however, affect the surface temperature greatly. This is shown by Figure 9, a plot of August 13, 1966, when the sky was a deep blue except for some fluffy white clouds that occupied less than 20 percent of the sky. The ¼-in. depth temperature cycle is no longer smooth as in Figures 7 and 8, but is rough, having many peaks. Figure 10 shows August 15, 1966, as an example of a summer day when there was 80-100 percent cloud cover in the sky. On cloudy days such as this, all the temperatures in the asphalt concrete pavement are nearly equal. During the heavy rain that occurred in the afternoon of August 15, all the probes in the various depths of the pavement recorded the same temperature. Then, as the rain stopped in the early evening, the pavement temperatures at the various depths again began to spread apart. Figure 11 shows the data for August 9, 1966. On this day the sky was very clear until 2:30 p.m., when the skies became partly cloudy. The effect on the ¼-in. temperature probe is clearly evident. Then, at 6:30 p.m., a moderate rain started to fall on the test pavement. The air temperature fell 8 F in less than 5 min. The ¼-in. probe also started to decrease at a constant rate. However, there was no effect on the temperature at the 12-in. depth. In fact, the 12-in. probe was not affected by any of the weather changes that occurred during the day.

Monthly Temperature Distribution in Pavement

Figures 12 through 23 show the temperature distribution of the air temperature and ¼, 2, 4, 6, 8, 10, and 12-in. depths of each month during the testing period. A common characteristic of these distributions is that for every month the ¼-in. depth

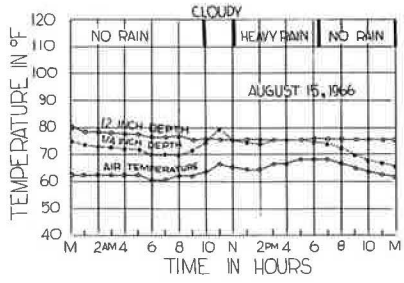

Figure 10. Temperature cycles on a rainy summer day.

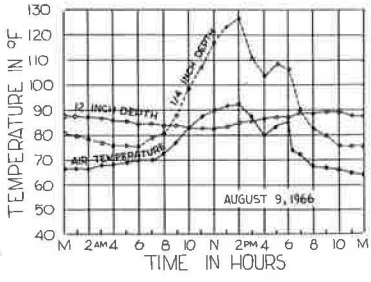

Figure 11. Temperature cycles on a fair, then partly cloudy, then rainy day.

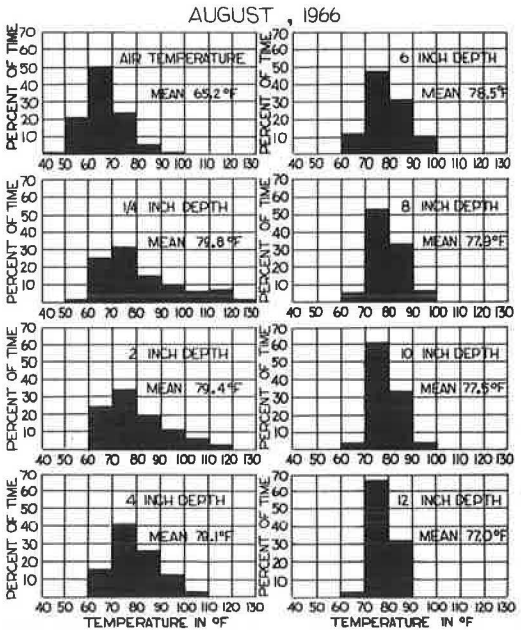

Figure 12. Temperature distribution in asphalt concrete pavement, August 1966.

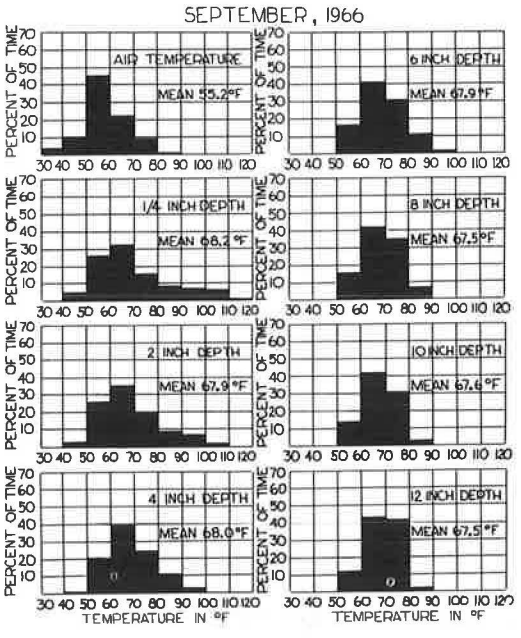

Figure 13. Temperature distribution in asphalt concrete pavement, Sept. 1966.

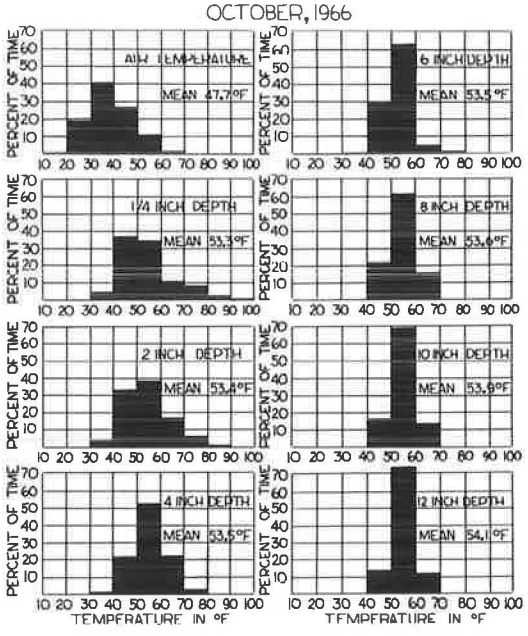

Figure 14. Temperature distribution in asphalt concrete pavement, Oct. 1966.

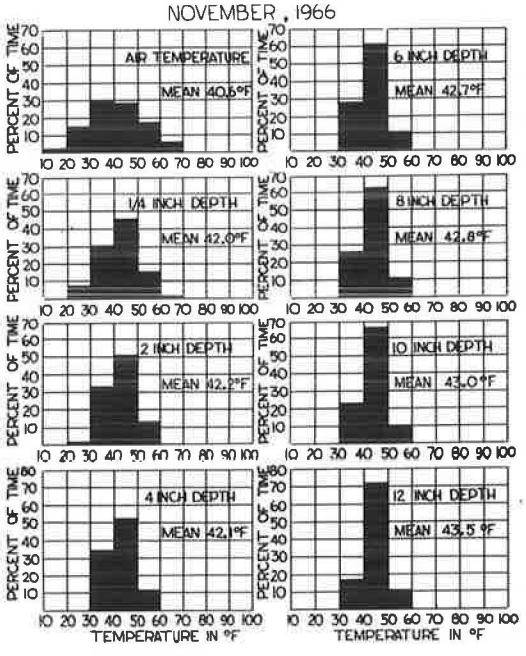

Figure 15. Temperature distribution in asphalt concrete pavement, Nov. 1966.

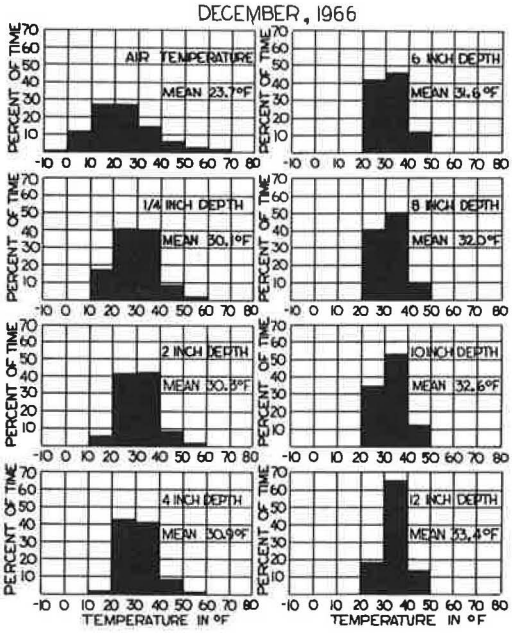

Figure 16. Temperature distribution in asphalt concrete pavement, Dec. 1966.

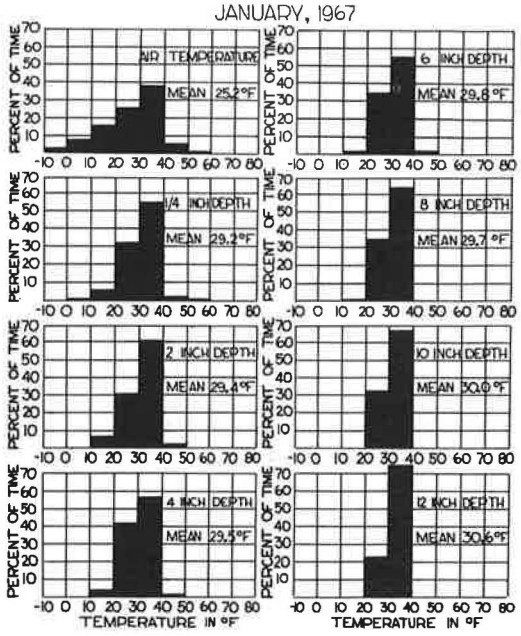

Figure 17. Temperature distribution in asphalt concrete pavement, Jan. 1967.

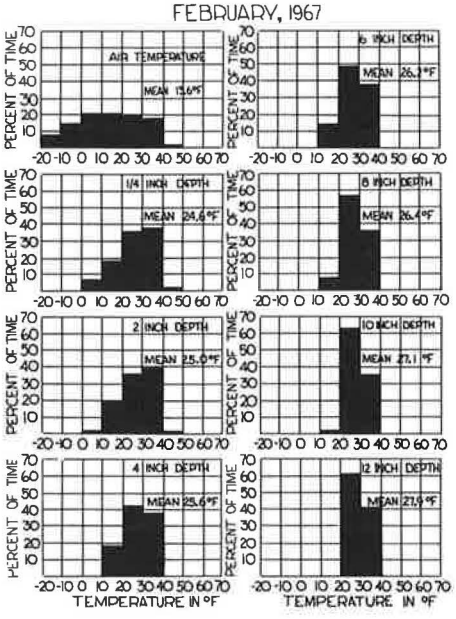

Figure 18. Temperature distribution in asphalt concrete pavement, Feb. 1967.

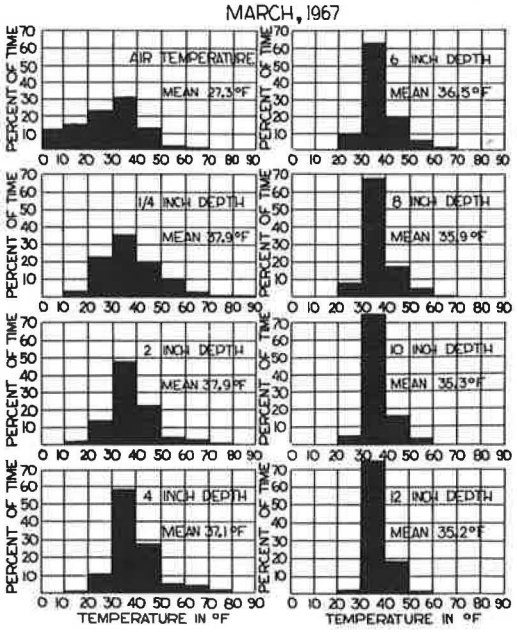

Figure 19. Temperature distribution in asphalt concrete pavement, Mar. 1967.

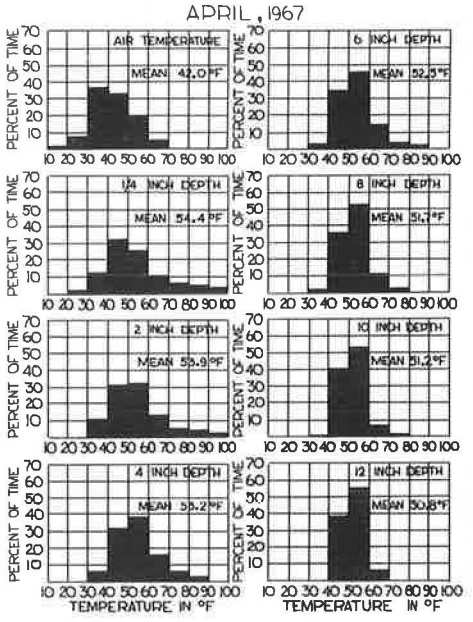

Figure 20. Temperature distribution in asphalt concrete pavement, April 1967.

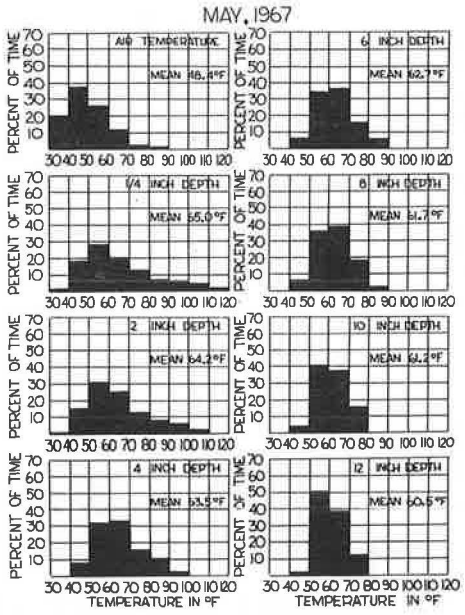

Figure 21. Temperature distribution in asphalt concrete pavement, May 1967.

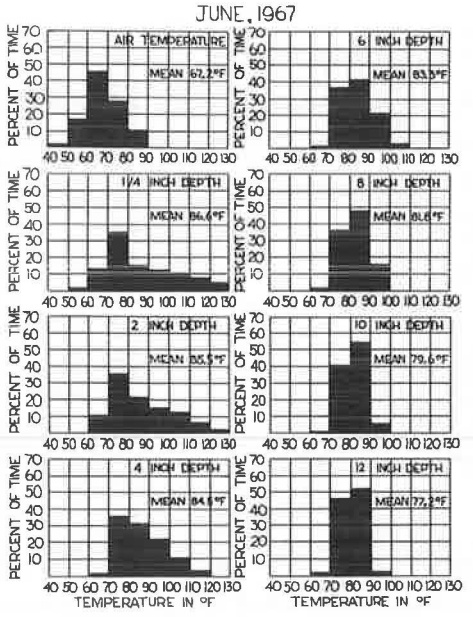

Figure 22. Temperature distribution in asphalt concrete pavement, June 1967.

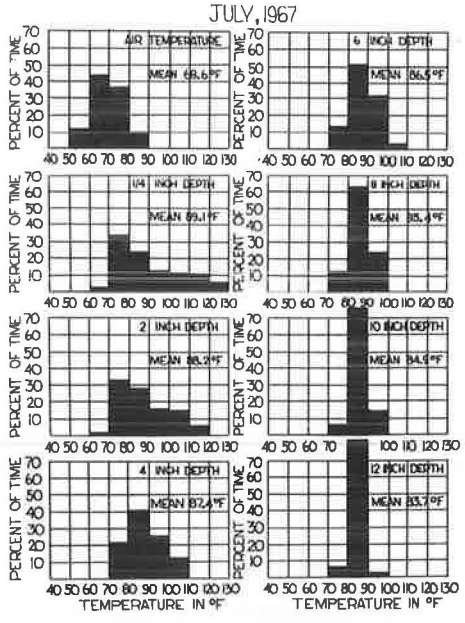

Figure 23. Temperature distribution in asphalt concrete pavement, July 1967.

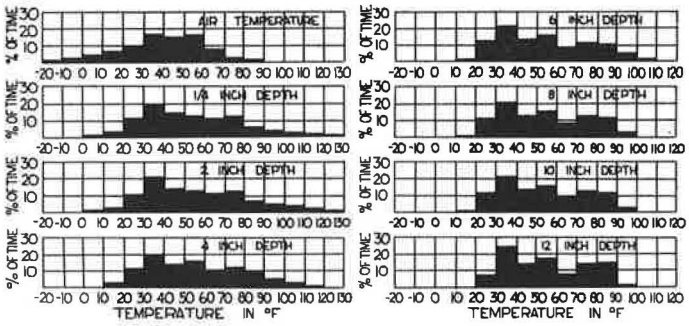

Figure 24. Temperature distribution in asphalt concrete pavement, yearly summary.

distribution curve always has the greatest range of temperatures and as depth increases a smaller range of temperatures is experienced. This is one indication that as the depth of the pavement increases, the temperature stabilizes.

During the summer months, the distributions of the upper depths tend to have a greater spread of temperatures on the high side of the mean. This can be seen in Figure 12 for August 1966. The distribution for the ¼-in. depth "stretches out" from 90 F to 130 F. This same shape occurs during September (Fig. 13) and October 1966 (Fig. 14). In Figure 15, November 1966, this "stretching out" of the curve becomes less obvious for the ¼-in. depth than for the previous months.

During January 1967 (Fig. 17), however, this "stretching out" occurs on the opposite side (on the decreasing temperature side) of the distribution. This occurs again for February (Fig. 18). Then the "stretching out" reverses again for the month of March (Fig. 19) and appears on the increasing temperature side of the distribution. This continues for all the warm months of the year.

From these observations, it can be concluded that the small percentages of extreme temperatures that occur near the surface of the pavement during the summer are on the higher temperature side of the mean. During the winter this reverses, and the extreme temperatures on the surface are on the lower temperature side of the mean.

Yearly Temperature Distribution

Figure 24 shows the yearly distribution of temperatures for air temperature and the ¼, 2, 4, 6, 8, 10, and 12-in. depth in asphalt concrete. Again, as the depth in pavement increases, less variation in temperature occurs.

Effect of Thickness on Pavement Temperature

Some roads in this country have a relatively thin layer of asphalt concrete pavement on them, while others are much thicker. In the study of pavement temperatures, the question might be raised as to whether or not the thickness of the pavement changes the temperature at various depths. For this reason, the test section in this project was constructed in such a way that some of the temperature probes were placed in a 6-in. thick section (probes at the 2, 4, and 6-in. depth in the asphalt concrete pavement and 12-in. depth in the soil) and others in a 12-in. thick section (2, 4, 6, 8, 10, and 12-in. beneath the surface). Daily observations of these probes were conducted. It was noted that both sections behaved in the same manner, and that the temperatures at the same depth in each of the two sections were usually very similar. Most of the time individual probes at the same depth on both sections were within 1 or 2 deg of each other. Small plus and minus differences between corresponding probes at the same depth seldom differed by more than 0.2 F.

After observing the temperature differences between the two test sections of asphalt concrete pavement, it can be concluded that there is no important difference between the temperatures at a depth of 2, 4, 6, and 12 in. for the 6-in. thick pavement and those

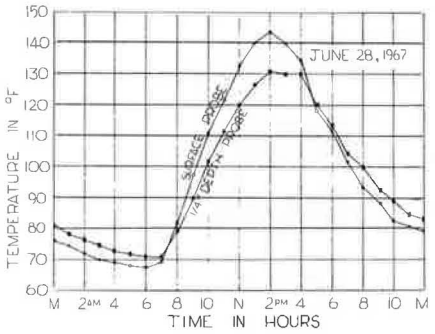

Figure 25. Difference in temperature between surface probe and ¼-in. probe.

at a depth of 2, 4, 6, and 12 in. in the 12-in. thick pavement, probably because the thermal properties of the asphalt concrete and the subgrade material are numerically similar.

Surface Probe Accuracy

Difficulties—When the "surface" probe was first installed in the pavement it was placed on the surface and covered with a thin layer of asphalt concrete. After the pavement was compacted, the probe was located at a depth of ¼-in. from the surface. It was assumed that this probe would give representative temperatures for the surface of the pavement. During the winter months this assumption was brought into question. Figure 8 shows why. It is a plot of the surface temperature for February 6, 1967, when the air temperature was very cold. At 6 a.m. the air temperature was -12 F. The ¼-in. probe, however, only reached 6 F. There seemed to be an unreasonable gap between the air temperature and surface temperature. It was suspected that the ¼-in. of asphalt concrete on top of the surface probe was hindering that probe from recording the actual surface temperature.

New Surface Probe—As the weather became milder during late winter, a new surface probe was added to the pavement. This probe was placed flush with the surface of the pavement, so that one side of the probe was exposed to the air. The other three sides of the probe were surrounded by asphalt concrete. A comparison of the temperatures of the new surface probe and the ¼-in. probe were made. Figure 25 shows this comparison for June 28, 1967. It is seen that during the day the new surface probe recorded surface temperatures to be 13 F higher than those recorded by the ¼-in. probe. It was felt that this new probe gave a better representation of the surface temperature of the pavement than did the ¼-in. probe.

Correct Installation of Surface Probe—From this information, it was concluded that the uppermost fraction of an inch of asphalt concrete sometimes experiences a large temperature gradient. To record the surface temperature, it is necessary to take great care in the location of the probe. Figure 26 shows how the surface probe should be installed. It is recommended that one part of the thermocouple tip be exposed to the air. Care must be taken that the probe be flush with the pavement surface and that the color of the exposed tip is the same color as the asphalt concrete.

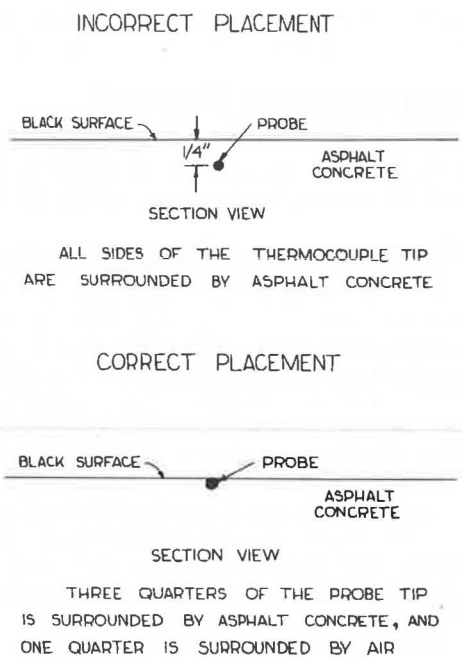

Figure 26. Installation of surface probe.

Temperature Gradients in Pavement

When observing temperatures in pavements, it is important to realize that temperature varies with both time and depth. When describing pavement temperatures, can one temperature adequately

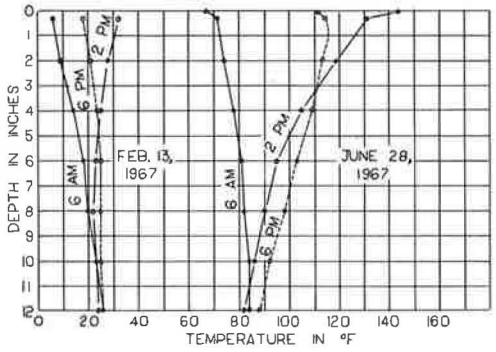

Figure 27. Temperature gradient in pavement on a sunny summer day and a sunny winter day.

represent the entire pavement temperature? Figure 27 answers this question. On June 28, 1967, at 2 p.m., the surface temperature was 144 F and the 12-in. depth temperature was 82 F. There was a 62 F difference in pavement temperature within a 12-in. difference in pavement depth. Pavement temperature also varies with time. On June 28, 1967, at 6 a.m. the surface temperature was 67 F. At 2 p.m., the surface temperature was 144 F. Within an 8-hour period, the surface temperature increased 77 F. It can be concluded that no one temperature is representative of the pavement, but that pavement temperatures vary greatly both with time and depth.

Importance of Solar Radiation

Potsdam, New York, is located at 44° latitude and 76° longitude, at an elevation of 440 ft above sea level. There is no industry in the area that might cause any smog conditions. It is known that both air temperature and solar radiation can add heat to the pavement to raise the temperature. However, just what effect would be produced by both these factors acting together on the test pavement was unknown. It would be interesting to discover whether the air temperature or solar radiation has a greater effect on increasing the pavement temperature. By comparing various days that were monitored for temperatures it was hoped to determine some comparison between the two methods of producing heat flow to or from the pavement.

Figure 28 shows a plot of two days that received the same amount of solar radiation, but with air temperatures that were different. The two days were April 12 and April 13, 1967. Both days were completely sunny with no cloud cover. The only difference in the two days was the air temperature. April 12 was cool, with a high air temperature of 40 F and a low air temperature of 20 F. April 13 was warmer, with a high of 64 F and a low of 26 F. The difference in air temperature in the middle of the two afternoons was 24 F. However, the peak temperature difference of the ¼-in. probe for the two days was only 12 F (84 F on April 12 and 96 F on April 13). This suggests that a 24 F increase in air temperature produced a 12 F increase at the ¼-in. pavement depth.

Figure 29 shows two days that had similar air temperatures, but had different values of solar radiation. The days were November 22, 1966, and April 12, 1967. Both days were completely sunny with no cloud cover. On November 22, the high air temperature for the day was 52 F and the low was 26 F. On April 12, the high air temperature was 40 F and the low was 20 F. The air temperature patterns for these two days were similar, with the air temperature of November 22 being a few degrees warmer than that of April 12. The biggest difference between the two

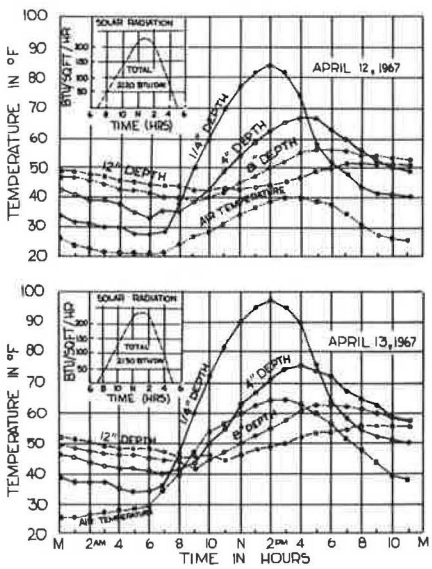

Figure 28. Change in pavement temperatures at different air temperatures with similar solar radiation.

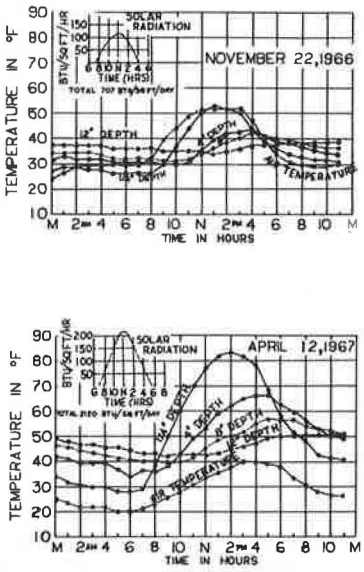

Figure 29. Change in pavement temperatures at different solar radiation values with similar air temperatures.

days was that on November 22 707 Btu/sq ft/day of radiation was received by the solar cells while on April 12 the figure was 2125 Btu/sq ft/day. The peak temperature difference of the ¼-in. probe for the two days was 31 F (84 F for April 12 and 53 F for November 22). Even though the air temperature of November 22 was higher than the air temperature of April 12, the larger amount of solar radiation received on April 12 caused the pavement temperatures on that day to be much higher than on November 22, 1966.

From these graphs it can be concluded that solar radiation changes have a greater effect on pavement temperatures than is caused by varying air temperature.

Nature of Solar Radiation—Figure 30 shows a plot of daily solar radiation actually received at the test site (including the interference of cloud cover) from October 28, 1966, to July 31, 1967. The lowest amount of radiation occurred on December 7, 1966. On this particular day 0.0 Btu/sq ft/day was recorded as the amount of solar radiation received by the solar radiation instrumentation. Although some radiation must have been received during that day, the signal produced by the solar cells was so weak that it was unable to generate the necessary 0.05 ampere (corresponding to approximately 25 Btu/sq ft/hour) needed to start the DC ampere-hour meter. The highest amount was received on June 27, 1967, when 2405 Btu/sq ft/day was recorded. If cloud cover did not interfere, the maximum possible solar radiation would be received on June 21, while the minimum amount would be received on December 21. This is because the sun is highest in the sky on June 21 (travels the longest path in the sky), and lowest in the sky on December 21 (travels the shortest path in the sky). In general, Figure 30 verifies the expected pattern; i.e., in spite of marked fluctuations caused by varying cloud cover, the lowest daily amounts of solar radiation occurred in December. Starting in January 1967, the daily amounts of solar radiation increased until June 1967.

Figure 31 shows a typical record of solar radiation throughout the day in northern New York at various times of the year. All of these days were completely clear and free of clouds. On December 21, 1966, 644 Btu/sq ft/day were received by the solar cells. On March 16, 1967, this increased to 1630 Btu/sq ft/day, and by June 27, 1967, the daily amount was 2405 Btu/sq ft/day. The maximum amount of hourly radiation increased during this period. The peak reading on December 21, 1966, was 120 Btu/sq ft/hour, on March 16, 1967, it was 240 Btu/sq ft/hour, and by June 27, 1967, it was 310 Btu/sq ft/hour.

If there were no cloud cover or haze in the sky the maximum possible solar radiation would be received on

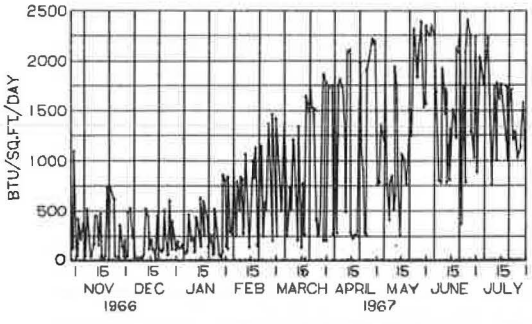

Figure 30. Daily solar radiation received by solar cells.

any given day of the year. Since the sun's path changes every day of the year, this maximum amount of daily solar radiation also changes. Figure 32 illustrates how the changing path of the sun affects the maximum possible daily solar radiation in northern New York. The daily solar radiation values of all zero percent cloud cover days were plotted. Then the points were connected to produce a curve that represents the maximum daily solar radiation that could be expected in northern New York. It can be seen that the low point of this curve is near December 21 and the maximum is near June 21.

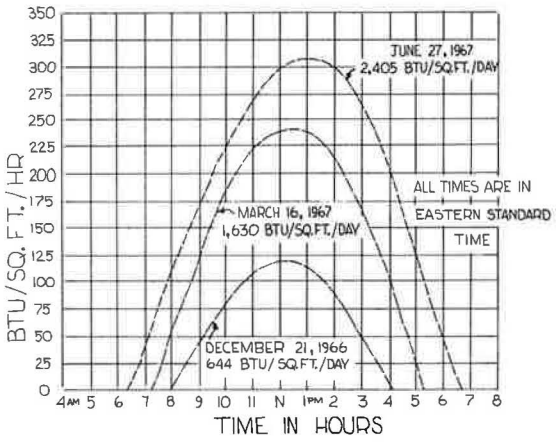

Figure 31. Seasonal effect on solar radiation received.

Solar Radiation Absorbed by Pavement—Not all the solar radiation received at the pavement surface will be accepted by the asphalt concrete pavement. Color is a major factor in determining how much solar radiation is absorbed by the pavement. A black pavement will absorb more solar energy than a white pavement. During the data collection period, the test pavement was kept black and as clean as possible so that the surface did not turn grey. Black-top driveway sealer was applied soon after initial construction and this helped to maintain a uniformly black color on the pavement surface. This ensured that the maximum amount of solar radiation was accepted by the pavement, and helped to ensure that the pavement temperatures were being observed under reasonably uniform conditions.

Edge Effects

When this test section was first constructed, the size of the pavement was chosen to be 24 by 12 ft. In order to obtain accurate values of temperatures for the various depths within the pavement, the question was brought up of how close to the edge of the pavement a thermocouple could be placed and still give a true temperature reading of a depth without any effect from the soil that surrounded the test section. Since there was no time to investigate this problem before the site was actually constructed, it was decided to assume that there were edge effects and that precautions had to be taken against them.

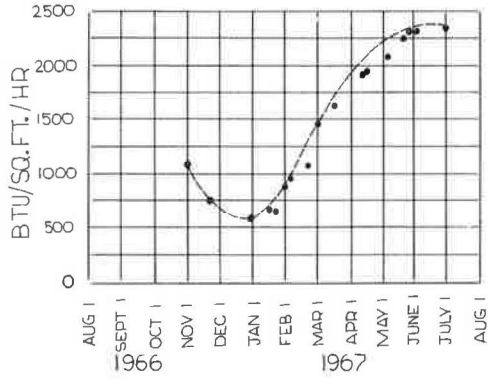

Figure 32. Maximum solar radiation received by solar cells.

All of the test probes in the asphalt concrete test section were placed in a 4 by 4-ft square in the center of each side of the test section. It was assumed that the probes would be far enough from the edge of the pavement that there would be no edge effects, if such effects existed. The two areas in which the probes were located on each section can be seen in Figure 2.

It should be pointed out that although the test section was 24 by 12 ft (288 square feet), only two 4 by 4-ft sections (32 square feet) were used for actual testing. The rest of the area was unused for actual data collection. The question that could next be asked is whether or not it would

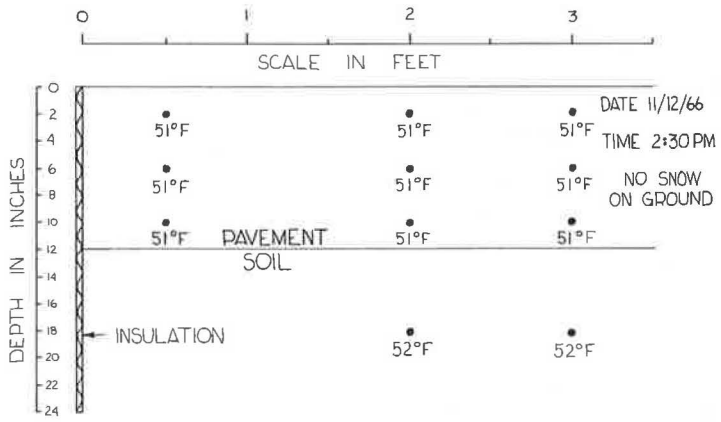

Figure 33. Check on edge effect when pavement experienced a negligible vertical temperature gradient.

have been possible to construct a smaller test section and still avoid any edge effects.

It was decided to place on one edge of the asphalt concrete test section a vertical section of 1-in. thick extruded expanded polystyrene plastic foam insulation. This insulation extended the width of one edge of the test section (12 ft) and was placed to a depth of 2 ft. To determine whether or not this insulation prevented any edge effects, a series of probes were placed ½, 2, and 3 ft from the insulation. At various times during the fall and winter, the manually operated potentiometer was used to obtain readings from the edge-effect probes located near the vertical insulation.

Figure 33 shows one set of data taken November 12, 1966. There appears to be no serious edge effects. No snow was on the edge of the test pavement when the data were taken. Figure 34 shows a set of data taken on January 18, 1967, when 3 ft of snow was piled on the edge of the test pavement. The data suggests that there is no edge effect problem in this case either. This would indicate that if an edge effect existed, the 1-in. thick vertical insulation eliminated it and helped maintain horizontal isotherms under the test pavement. It can be concluded that two 2 by 2-ft test sections could have been constructed and have served as well as the 12 by 24-ft section, as long as the sides of the section were protected by 1-in. thick vertical insulation. The possibilities for more economic test site design and construction for future studies are obvious.

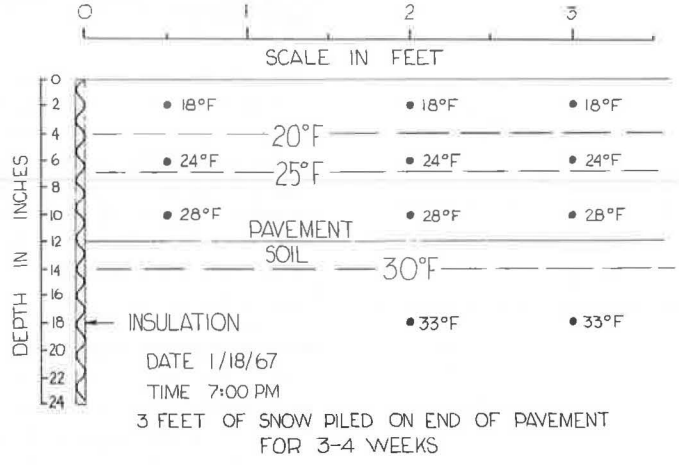

Figure 34. Check on edge effect when pavement experienced a definite vertical temperature gradient.

Insulating Effect of Snow

One of the auxiliary studies conducted involved the insulating effect of snow. When snow covered the test pavement and the air temperature was near 30 F, it was noted at several times during the winter that the pavement temperature would be 32 F throughout the entire thickness. If this snow remained on the test section (undisturbed) and the air temperature turned suddenly cold, would the snow act as an insulator and keep the pavement temperature from being radically influenced?

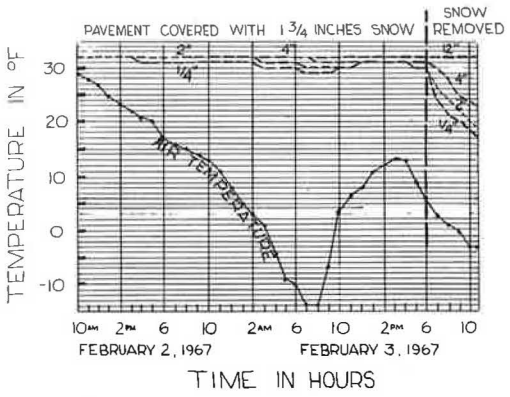

Figure 35. Insulation effect of snow.

To answer this question, a certain sequence of weather conditions was necessary. First, there had to be a snowfall with the air temperature near 32 F. Then, shortly after the snowfall, the air temperature had to decrease markedly. With the snow left on the pavement, it could be observed if the snow acted as an insulator. On February 2 and 3, 1967, this set of conditions occurred.

The result of this experiment may be seen in Figure 35. On February 2, $1\frac{3}{4}$ in. had accumulated when the snowfall ceased at 10 a.m. The snow was light and powdery. The air temperature then fell quickly, and at 7 a.m. on February 3 the air temperature was -14 F. During this period of time, the snow was not removed from the pavement. The pavement temperature remained very close to 32 F. At 6 p.m. on February 3, the snow was removed from the pavement. The pavement temperature immediately fell sharply. The insulation effect of $1\frac{3}{4}$ in. of snow is shown clearly by this plot.

DIGITAL SIMULATION OF PAVEMENT TEMPERATURES

Techniques and Advantages of Digital Simulation

Assembling data in the form described in the foregoing is both expensive and time-consuming. Furthermore, while it may give a reasonable picture of annual pavement temperature variations in northern New York State for the years 1966-67, not too much can be inferred about maximum temperatures for other years and even less about pavement temperatures at other locations. Thus the most useful application of data of the sort just described is its use in the development of a general scientific method that will be applicable to pavements of any composition anywhere in the world.

The ready availability of digital computers has made such a development possible, if one is able to discretize both the conducting medium and the time domain into small nodal increments and into small time steps. Such a digital program has already been completely described and used with hypothetical surface boundary conditions (18) that are varied simply in a sinusoidal manner over several years. The resulting subsurface temperature variations predicted for the simulated years are typical of those often measured at various underground sites. Based on this program, actual underground temperatures that were monitored during the 1964-65 winter were simulated on a computer. The predicted temperatures compared well with those actually found in the ground, and the depths of frost penetration through the winter were closely predicted (4).

In the case of asphalt concrete pavement, of most interest are maximum and minimum temperatures, and they are seen to occur for short periods during given extreme day or night conditions. Thus the simulations already noted must be modified for purely diurnal use. This is done by making the subsurface conducting increments and the time steps much smaller in size, thereby giving a more detailed picture of the underground temperature patterns than is required when a complete year of time is involved.

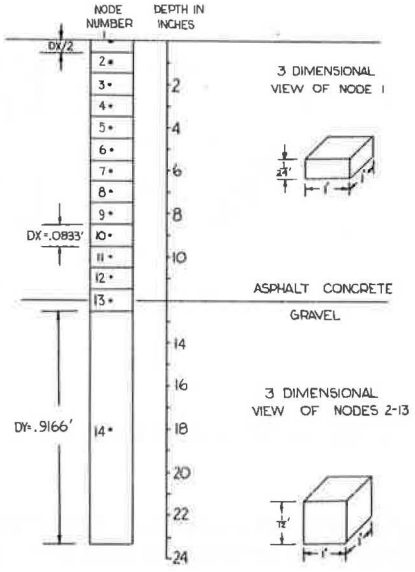

Figure 36. Nodes used in simulation model.

Other than this change in mesh and time-step size, the programs already used are unchanged. These are forward-difference, one-dimensional transient heat-flow programs that are terminated at the depth below which the diurnal temperature wave does not reach. The initial temperature conditions are inserted in the computer and it "steps through time" computing new sets of temperatures in response to air temperature and solar input conditions that are continually applied to the surface nodal increment. These conditions are, in this case, the actual measured values obtained at the test site. If the program were to be used to predict maximum asphalt concrete temperature at a different location, these boundary conditions could be obtained from weather records at the location of interest.

Errors in Discretized Models

The engineer unfamiliar with finite-difference methods is often concerned with loss in accuracy due to the incremental modeling of a continuum. In fact, the surprising thing about finite-difference methods is not their inaccuracy, but the remarkable predictions possible with models having only a very few increments and huge time steps. In the case of diurnal variations of temperature in asphalt concrete pavement, a small enough time step must be chosen so that both air temperature variations and solar energy input changes can be varied on the upper boundary with reasonable accuracy. As suggested in Figure 39, a time step of one hour is probably fine enough, although a quarter-hour time step was actually used because of mathematical stability requirements. Based on previous studies (18), this fine a time step with a 24-hour temperature cycle will produce finite-difference errors that are far less than 1 percent of the maximum temperature swing.

Previous work also suggests that conduction systems having seven to ten nodes will yield results with vanishingly small finite-difference errors, particularly when the surface temperature condition is not changing sharply (18). In this study, a 13-node model was used (Fig. 36), amply fine for any practical purposes. Thus it is reasonable to infer that any difference between the simulation and actual temperatures is due entirely to conceptual and instrument defects in the model and real systems—i.e., poor estimates of convection coefficient, asphalt thermal or radiation properties, crude modeling of reradiation terms, and failure of instruments to record temperatures exactly at the depth anticipated. The point, then, is that these and many other experimental and property uncertainties far outweigh the tiny effects of a discretized model. Indeed, one of the powerful applications of computer simulations to future systems of this sort will be to estimate, using trials, various parameter values that are difficult to measure directly on the site.

DEVELOPMENT OF MODEL

Two basic types of prediction were desired from the digital simulation. The first output required was the prediction of the temperature-wave movement at various depths in the pavement. These daily pavement temperature cycles have been described earlier. The second desired output was to predict extreme pavement temperatures at various depths. Both of these outputs should be responsive to input climatic conditions.

Much work has been done to develop methods of predicting pavement temperatures. Not all methods have been able to obtain the output data mentioned. Barber (2) obtained

pavement temperatures by using a solution of the diffusion equation. Basically, this approach was only good for an average prediction over many days of average weather. What was desired here, however, was a means of predicting extreme values of pavement temperatures, that is, the few cases of hottest or coldest pavement temperatures in a 5- or 10-year weather cycle. The digital simulation method is best for such predictions, because of its ability to cope with many climatic parameters and its computational speed.

Basic Structure of the Simulation Model

When setting up a simulation model, it must be remembered that there are three basic mechanisims for heat flow that occur at any surface location on the pavement. They are conduction, convection, and radiation. Each has different heat transfer rate equations (17). In order to apply these equations, a representative section of the pavement must first be divided into small sections called nodes. In general, the basic heat transfer equations, or a combination of these equations, relate a given node to surrounding nodes, and are used to compute a temperature after each small time interval at the given node. The temperature computed for any node is the average temperature of the entire volume, and usually represents the temperature at the center of the node. Since the temperature of a particular computer node is assumed to occur at the center of that node, it was desirable to have the centers of the nodes in the simulation model be at the location of the temperature probes in the field pavement study. This allowed the simulation pavement temperatures to be directly compared with the actual field pavement temperatures. The equations of the nodes in the simulation model were thus derived in such a way as to place their centers at the depth of the thermocouple probes (2, 4, 6, 8, 10, 12, and 18 in.).

Figure 36 illustrates the various nodes used in the simulation model. Basically, the numerical model consisted of a column of nodes that had a cross-sectional area of 1 sq ft. Node 1 is shown to be only half as high as the next twelve nodes. This was done to place the temperature of Node 1 directly on the surface of the pavement. Actually, Node 1 is a standard node sliced in half so that its center point is exposed. Node 1, on the very surface of the test pavement, is the node at which solar radiation is introduced into the test pavement. Nodes 2 through 12 are all asphalt concrete nodes, and thus all have the same heat transfer equations. Nodes 2 through 12 are all $\frac{1}{12}$ ft in height and have a convenient cross-sectional area of 1 sq ft. The centers of these nodes are located at 1-in. increments starting at 1 in. from the surface. Node 13 is called a "mixed node." It is the same size as Nodes 2 through 12, but it contains half gravel and half asphalt concrete. The actual test section has a pavement thickness of 12 in.; below this is more than 24 in. of gravel. This design was carried over into the simulation model. Node 14 is called a "termination node." It is a gravel node and has the heat transfer properties of gravel. Its purpose is to mathematically terminate the column of nodes. Since it is larger than the other nodes, its predicted temperatures will be less accurate than those of the other nodes. Note that the model assumes no diurnal temperature effect below 24 in.

Input Information for Simulation Program—Certain heat transfer or thermal properties had to be found for both gravel and asphalt concrete for use in nodal equations (18). The values used in this simulation model are given in Table 1, which lists the various input information required for the computer program. Besides the thermal properties for the various nodes, initial temperature values had to be entered into the program. These were obtained from the actual test section. If a simulation program was to be tried for a certain day starting at 6 a.m., then the initial pavement temperatures for the nodes were obtained from the actual test pavement at 6 a.m.

Certain weather data needed in the surface node equations must be placed into the program. Air temperature in degrees Fahrenheit and solar radiation in Btu per square foot per hour had to be known as a function of time for the simulation model.

Use of the Simulation Model

Before actually using the simulated model the type of day had to be selected. It could have been a completely sunny day, a cloudy day, a rainy day, or even a day with snow.

TABLE 1

INPUT FOR SIMULATION PROGRAM

TEST SITE

A. Asphalt concrete properties [from Barber (2)]
   1. Density, ρ, 140 lb/cu ft
   2. Conductivity, K, 0.7 Btu/sq ft/hr, F per ft
   3. Specific heat, C_p, 0.22 Btu/lb F
   4. Convection coefficient, H, 2.7 Btu/h F sq ft

B. Gravel properties (last node) [from Carrol, Schenck, and Williams (4)]
   1. Density, 110 lb/cu ft
   2. Conductivity, 0.75 Btu/sq ft/hr, F per ft
   3. Specific heat, 0.20 Btu/lb F

C. Initial conditions

   Initial temperature at each node, F

D. Properties related to radiation
   1. Absorptivity, F, 1.00 (assumed black body)
   2. Emissivity, ϵ, 0.90

WEATHER INPUT

A. Air temperature, F
B. Solar radiation, Btu/sq ft/hr

As the first step in the simulation model, it was decided to try only completely sunny days. Bright sunny days facilitate simulation since the high-level solar input overrides minor predictive errors in radiation to surroundings, wind effects, evaporative losses, etc. Also, such days are always associated with maximum pavement temperatures.

On April 29 and April 30, 1967, the weather at the test section was fair and clear. There were no clouds in the sky. The simulation computation was started at 6 a.m. on April 29. This was chosen as the starting time because it was still dark, and thus the initial pavement temperatures would not show any effects of the sun. The simulation ended at 6 a.m. on April 30, 1967. By starting before sunrise on one day and ending before sunrise on the next day, the simulation model was checked both during the daylight and the nighttime hours.

Initial Nodal Temperatures—Since the program was started at 6 a.m. on April 29, it was necessary to find input pavement temperatures for the 14 simulation nodes. This required a knowledge of the pavement temperatures for every inch of pavement from the surface level down to the 12-in. level. Also, a temperature had to be known for the 18-in. depth (gravel node). Since the thermocouple temperature probes were not located every inch in the test pavement, it was impossible to find the required initial pavement temperatures directly. The initial conditions were known for the surface, 2, 4, 6, 8, 10, 12, and 18-in. depths from the test section instrumentation. A graph of this information (pavement temperature vs depth) is shown in Figure 37. From this curve it was possible to interpolate the temperature of the pavement at any depth. The initial pavement temperatures used for the simulation for April 29 are listed in Figure 37.

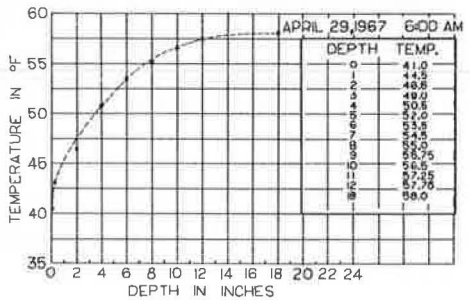

Figure 37. Initial pavement temperatures for April 29, 1967.

Solar Radiation Input—Next, the input information for solar radiation had to be found. This information was collected at 15-min intervals during the day of April 29. The data collected are shown in Figure 38. The solar radiation data collected for that day were obtained by the DC ampere-hour meter and solar cells. Any absorbing surface in the sun will not, however, retain the total amount of the incoming radiation. Some of the solar radiation absorbed by the pavement will be reradiated back to the surroundings. The amount of back-radiation in Btu per square

foot per hour is assumed here to be simply a function of the difference between the fourth power of the temperature of surface and the fourth power of the surrounding air temperature (17). This back-radiation term is actually far more complex. However, this crude approach did produce good results. Omitting this correction resulted in a poorer simulation. During the night, there is also a difference between the pavement surface temperature and the air temperature. This suggests that there is probably surface back-radiation at night also. Back-radiation appears in the heat balances as a negative term (-Btu/sq ft/hour). During the day, this back-radiation value is subtracted from the radiation value, usually resulting in a net positive (incoming) heat-flow term. This corrected radiation, which is the net amount absorbed by the pavement, is shown in Figure 38 as the "corrected value" curve.

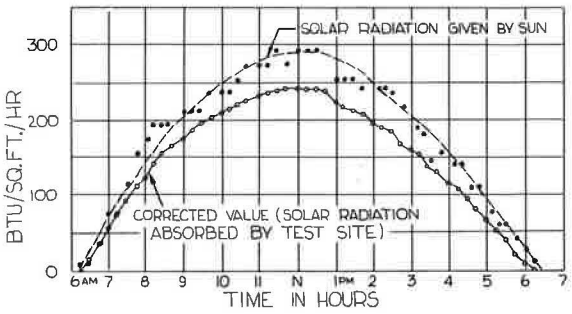

Figure 38. Solar radiation for April 29, 1967.

Results of Simulation—The pavement temperatures for the simulation model are shown in Figure 39. The simulation temperatures are compared with the actual pavement temperatures for the surface, 2, 4, 6, and 12-in. depths. It is evident that the simulated temperatures and the observed temperatures follow the same pattern, and thus the simulation model can predict interior and surface temperatures on a sunny day.

Figure 40 shows the results of this simulation for the surface node expressed in heat-flow terms. In the all-important surface node there are various types of heat flow, as follows:

1. Net radiation—A positive value of net radiation means that radiation is entering the node, while a minus value means that it is leaving the node and going to the surroundings.
2. Convection heat flow—A positive value means that convection is occurring from the air to the surface node. A minus value means that the pavement is losing heat, with convection occurring from the surface node to the air.

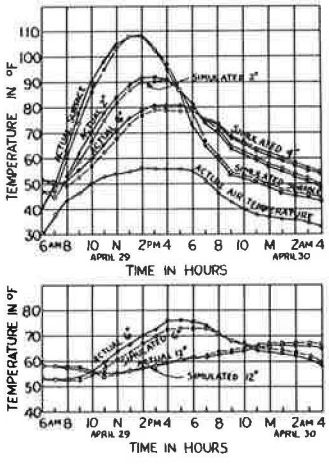

Figure 39. Comparison of simulated pavement temperatures with observed pavement temperatures for April 29 and 30, 1967.

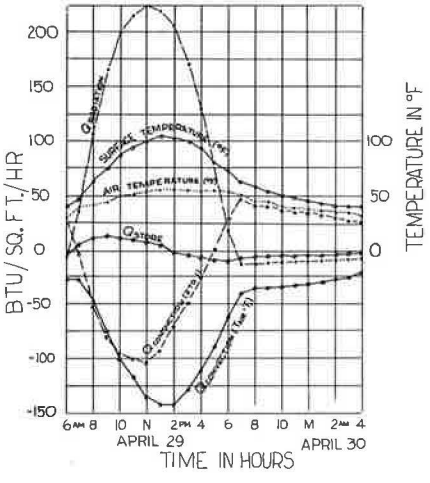

Figure 40. Analysis of heat transfer at surface node for April 29 and 30, 1967.

3. Conduction heat flow—A positive value means that the first node is gaining heat from below. This heat travels from Node 2 to Node 1. A minus value of conduction heat flow shows that heat is traveling from Node 1 to Node 2, or that the flow of heat is in a downward direction.

4. Heat that is being stored or lost in Node 1—A positive value shows that there is a gain of heat in Node 1, while a negative value means that a greater amount of heat is leaving Node 1 than is entering.

The detailed breakdown of the output of the simulation program for all types of heat flow affecting the surface node is plotted in Figure 40. It can be seen that the computer is providing a detailed picture of what is occurring in the pavement as the day progresses. As expected, radiation input increases until about noon and then starts decreasing. At 7 p.m. it becomes a negative value. This means that back-radiation to the surroundings is occurring. This back-radiation continues during the nighttime hours. From sunrise to 2 p.m., the stored energy is positive. It then changes to a negative value, meaning more heat is now leaving the node than is entering it. From the plotted information it can be observed that as long as the area under the stored heat curve is positive, the surface pavement temperature increases as would be expected. The area under the stored heat curve has a direct relationship to the slope of the surface temperature curve. A large change in area under the stored heat curve will obviously correlate with a large rate of change in surface temperature.

Convection heat flow remained minus during the entire simulation period; that is, the convective heat was always traveling away from Node 1 to the air. Conduction remained minus during most of the daylight hours of April 29, indicating that the heat flow was downward into the pavement. During the late afternoon, however, this value became positive. At 7 p.m. the value of conduction heat flow became a positive maximum. Although this upward flow is continuous during the night, it is not as great as at 7 p.m.

It can be seen by this analysis that the actual pavement temperatures can be both predicted and understood in relation to the basic heat transfer mechanisms operating.

Limitations and Advantages of Simulation

When using this simulation, initial pavement temperatures had to be provided as input information. However, the main purpose of this simulation was to develop a computational method by which pavement temperatures could be predicted for any part of the country. The U.S. Weather Bureau has both solar radiation and air temperature records for many areas that can be used as boundary conditions in a simulation model. No similar information, however, could be found for initial pavement temperatures. If the simulation is started before sunrise, a close assumption might be made for these temperatures. This would be purely an "educated guess." If the area is nearby, a thermometer could be placed in the soil before sunrise, and an estimation of sorts could be made in that manner. Before sunrise, the surface temperature of soil and asphalt concrete are fairly similar. It is therefore possible to obtain a "ballpark" figure for initial pavement temperatures. The real question is: How much in error do these initial conditions have to be before a serious error in simulation predictions is produced?

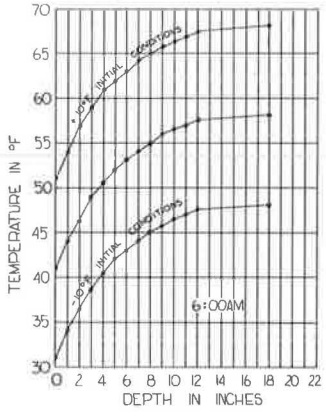

Figure 41. Variation of initial pavement temperature conditions assumed for April 29, 1967.

To answer this question, two simulation studies were run on the computer. Both were similar to the simulation model of April 29 and 30, 1967. The only difference was that one model had all initial

conditions 10 F lower than the correct ones, while the other had the initial conditions 10 F higher than the correct ones (Fig. 41). The purpose of this numerical experiment was to see how sensitive the simulation predictions were to errors in initial conditions.

Figure 42 shows the results of this test by showing the temperature curves of the surface and the 6-in. depth of pavement. It is seen that the peak temperature of the day for pavement surface does not change greatly due to a 10 F error in the initial nodal temperature conditions. The surface temperature curve as a whole is also not greatly affected by the error. As the depth in the pavement increases, the 10 F error affects the temperature curve more. This is seen for the plot of the 6-in. depth. The greater the depth of pavement, however, the more constant is the temperature during the day and also over a long period of time, and thus, the easier it might be to obtain these initial conditions. The conclusion from this test is that a 10 F error in initial nodal conditions does not affect the upper few inches of the pavement greatly, but as the depth increases, so does the resulting error of the temperature curve.

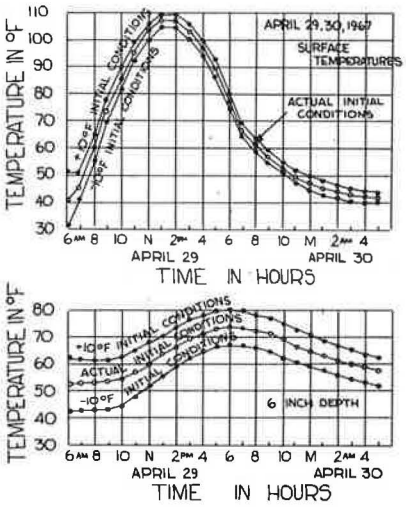

Figure 42. Results of comparison using assumed initial pavement temperatures for April 29 and 30, 1967.

Importance of Simulation—With further advancements in this type of digital simulation, it should be possible to predict maximum temperatures entirely from weather data. This simulation method can also be used as an investigative tool to determine what types and amounts of heat flows occur in highway pavements. Such a study will enable the highway researcher to understand better what is actually happening in highway pavements.

Trials similar to those summarized were attempted for winter (no sun) days but were not as successful, probably because small heat flows are difficult to predict and minor errors have large temperature effects. The simulation as described in this paper is a good tool for predicting maximum temperatures occurring within bituminous pavements, but more work is needed to predict minimums. However, it should be noted that minimum temperatures of the surface seldom drop below the lowest air temperature, barring an unusually clear night producing a so-called radiation frost. Thus local weather records are immediately usable for predicting "worst minimums." "Worst maximums" require a simulation study as described here.

CONCLUSIONS

1. Documentation of pavement temperatures has been made for one year at a northern New York State location. Resulting pavement temperatures are shown to be directly related to major climate factors of air temperature and solar radiation, and to vary greatly with depth.
2. Solar radiation (radiation) has a greater influence on heat flow in the pavement than does air temperature (convection) for the increasing or decreasing of bituminous pavement temperatures. Researchers making pavement temperature studies should recognize this fact and provide for measurement of radiation as well as air temperature.
3. The problem of accurately measuring temperatures that occur at the very surface of the pavement is important. It is necessary that great care be taken when placing a surface probe.
4. A successful numerical simulation model has been developed that is able to predict maximum temperatures that will occur on the surface and within bituminous

pavements. To obtain these simulated pavement temperatures, air temperature, solar radiation values, and initial pavement temperatures must be placed into the simulation model as input information. With this information, it is possible to predict actual pavement temperatures for any climate by the aid of a computer, without the necessity of constantly recording pavement temperatures.

5. The simulation model developed works well for sunny days, and thus for predicting maximum temperatures of the pavement. However, cold temperatures, which usually occur on winter, overcast, and snowy days, are much more difficult to simulate since the heat flows are much smaller and minor input or constant errors become crucial. More work is needed to predict minimum temperatures within pavements from weather data.

6. Additional studies are needed in various other climates to relate climate factors and pavement temperatures using actual test site data coordinated with the development of simulation models.

7. Since mechanical properties of bituminous paving mixtures are very temperature-dependent, paving technologists should seek meaningful ways to account for the steep temperature gradients and the temperature fluctuations that occur within actual pavements. For example, in surface courses, large temperature reversals can occur within minutes and the surface can experience substantial extremes in temperature within hours. Base courses, on the other hand, are subject to much less temperature fluctuations. Design, the analysis of performance, and laboratory testing all should develop procedures that account for temperature behavior of actual pavements.

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