Temperature Response of Concrete Pavements

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Displacements of concrete pavement slabs are mainly associated with temperature. Slab curling and joint movements greatly influence the response of concrete pavements to traffic loads. Identifying the times and temperature conditions at which the pavement system offers the least resistance to traffic loads should be a prime concern to pavement engineers. Therefore research has been initiated to analyze pavement temperatures and evaluate the vertical and horizontal displacements in the pavement slabs. At the Bureau of Materials and Research of the Florida Department of Transportation, a specially designed test road was constructed to simulate actual design features of Florida highways. This test road was instrumented with linear variable differential transformers and thermocouples at various locations. A data acquisition and control unit was used to record and store simultaneously the pavement displacements and the temperatures at specified time intervals. Pavement temperatures collected over a period of 3 years were analyzed. Vertical displacements at slab corners, edges, and centers were evaluated. Horizontal slab movements at doweled and undoweled joints were also determined. This paper may provide some understanding of pavement response to temperature and further strengthen awareness of the effect of temperature on pavement system stiffness.

Temperature is an important factor influencing the functioning of concrete pavements. Variations in concrete temperature cause horizontal as well as vertical displacements in pavement slabs. Such displacements affect two sets of stiffness parameters, *(a)* the shear and moment resistance at joints, which determine the load transfer between adjoining slabs, and *(b)* the magnitude and direction of slab curling, which determine the degree of support offered by the subgrade. Consequently, the structural response of concrete pavements under traffic loads is highly dependent on temperature and its variation.

Temperature effects on concrete pavement behavior have been recognized since the mid-1920s. Westergaard *(1)* identified temperature curling as an important parameter affecting the structural behavior of concrete pavements. In 1940 Lang *(2)* studied the movement of concrete pavement slabs resulting from changes in temperature and moisture. He analyzed temperature data obtained from a 7-in. concrete slab over a period of 1 year. Friberg *(3)* presented a mathematical evaluation of horizontal slab movements, and the effect of the subgrade frictional resistance, on stress development in pavements. Harr and Leonards *(4)* conducted laboratory tests to measure temperature curling and compute subsequent stresses. They correlated the results from the laboratory tests with predicted response with an analytical model that they developed. Tayabji and Colley *(5)* reported that excessive slab movements caused by temperature variations may result in lockups of doweled joints. This could result in midslab cracking and spalling of the concrete surrounding the dowels.

It is the objective of this paper to more precisely describe the displacements of a concrete pavement slab associated with temperature variation and weather. Temperature data, accumulated between 1983 and June 1986 from a test road, are analyzed. This is followed by a description of pavement response to temperature, which is based on the analysis of displacement measurements that were obtained from test road slabs.

TEST ROAD

A concrete test road was constructed at the Bureau of Materials and Research of the Florida Department of Transportation. The layout of the test road, shown in Figure 1, incorporates six slabs with doweled and undoweled joints. Each slab is 20 ft long, 12 ft wide, and 9 in. thick. Since its construction in 1982, this test road has been used for a number of research activities designed to obtain basic understanding of concrete pavements.

Instrumentation

Air and pavement temperatures were measured using thermocouples. Figure 1 shows four locations in which arrays of thermocouples were imbedded in concrete at the time of construction. Arrays of two thermocouples were used in Slab 3, and in Slab 4 arrays of five thermocouples were installed. Figure 1 shows details of the arrangement of thermocouples in Slabs 3 and 4. Another thermocouple was used to monitor ambient temperature. This thermocouple was housed in a white-painted wooden box, with open bottom and numerous 1-in.-diameter holes on the sides. The box was installed on a 5-ft wood post and was 8 ft away from the nearest building.

Slab displacements were monitored using linear variable differential transformers (LVDTs). The LVDTs were installed in vertical and horizontal directions. The horizontal LVDTs were installed across doweled Joint 5 and undoweled Joint 4. A detailed diagram of a horizontal LVDT is shown in Figure 1. The brackets used to hold the LVDT were made out of a brown phenolic board that is highly weatherproof. The vertical LVDTs were installed at the center and edge of Slab 4. Two more vertical LVDTs were placed at both sides of Joint 4 at corners of Slabs 3 and 4. Figure 1 shows a schematic diagram of a vertical LVDT. As shown in this diagram, the LVDT is held at one end by a bracket fastened to the side of the slab. The

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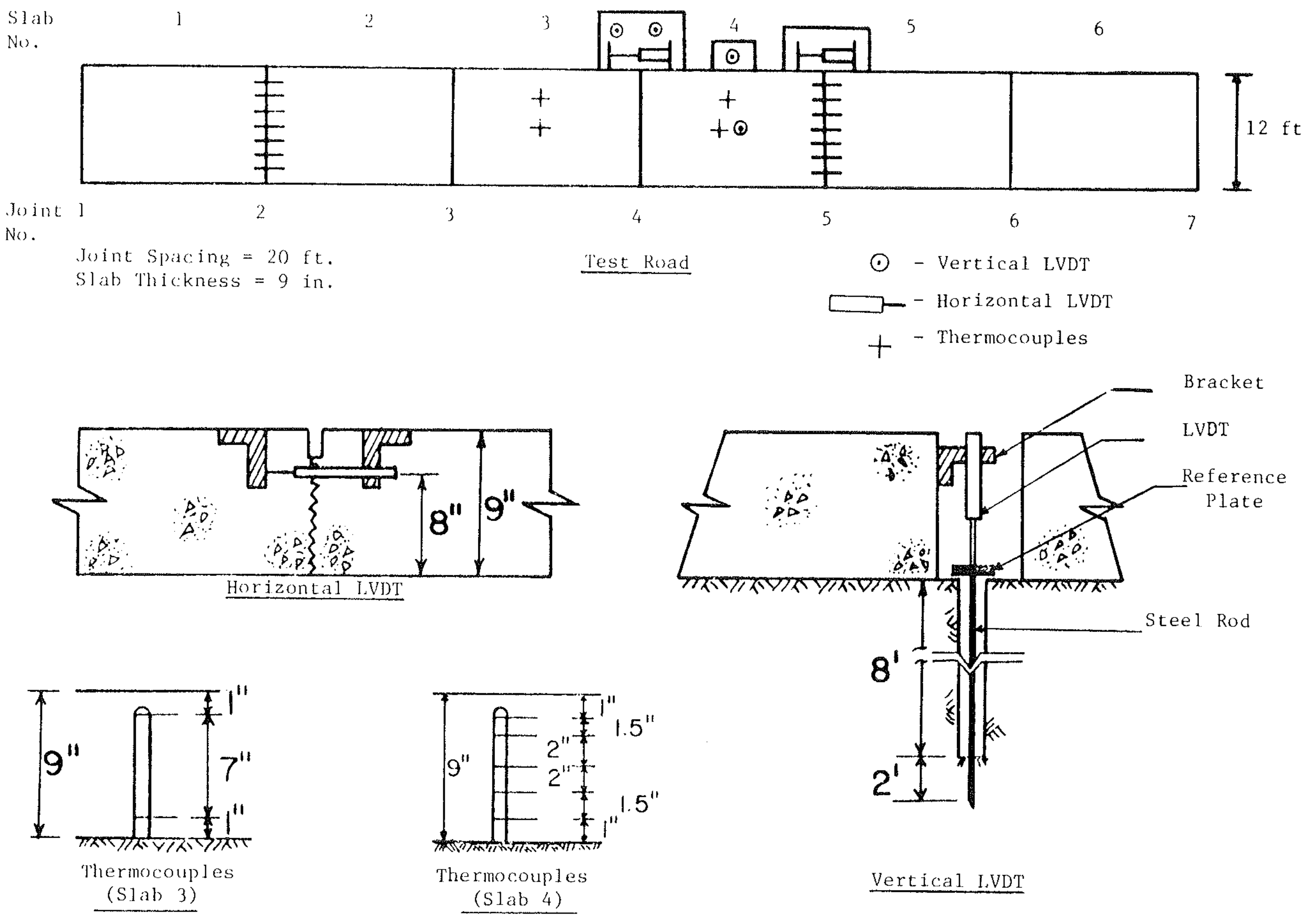

FIGURE 1 Layout of test road and details of instrumentation.

transformer core rests against a reference plate fastened to a 10-ft-long invar steel rod. This arrangement was necessary to isolate the reference plate from the surroundings and thus ensure precise measurement of slab displacements. The two corner LVDTs at Joint 4 were 4 in. apart, and the edge LVDT was installed midway between Joints 4 and 5.

Data Collection

Temperature measurements from the test road were recorded between 1983 and 1986. Pavement and air temperatures were normally recorded at 1-hr intervals. However in conjunction with other tests, temperatures were measured at 30- or even 15-min intervals. A programmable Fluke data logger was used to record simultaneously measurements from pavement and air thermocouples. Consecutive 24-hr cycles of temperature measurement were collected during the monitoring period. However, periods of interruption in data collection were experienced because of equipment maintenance.

The second part of the study, which involved the measurement of slab displacements, was conducted between January and June 1986. A data acquisition and control unit (HP 3497A) was programmed by an HP85B computer to record simultaneously the LVDT and thermocouple measurements at 30-min intervals. Horizontal slab displacements were monitored at the undoweled Joint 4 and the doweled Joint 5. Displacements in the vertical directions were also measured at the adjoining corners of Slabs 3 and 4 and at the center and edge of Slab 4. Data collection was continuous except during March, when the data recording system was unavailable. It should be mentioned that daily observations of weather conditions were documented to assist in the analysis of data.

ANALYSIS OF TEMPERATURE DATA

Information obtained from the temperature records included average pavement temperatures, temperature differentials, and characteristics of the different temperature gradients across the slab thickness. Average pavement temperatures were computed from temperature readings of the five thermocouples at the edge of Slab 4. Temperature differentials were computed by subtracting temperature readings at 8 in. below the slab surface from those at 1 in. below the surface. Negative temperature differential implied that surface temperature was lower than bottom temperature, and positive temperature differential indicated that the slab was warmer at the surface. Variation of temperature with time was determined for each of the five depths (1, 2.5, 4.5, 6.5, and 8 in.). Thorough examination of hourly temperatures at different slab depths revealed certain trends in temperature distribution across slab thickness.

Air and Pavement Temperatures

Figure 2 shows typical variation of air and pavement temperatures with respect to time during clear and sunny weather.

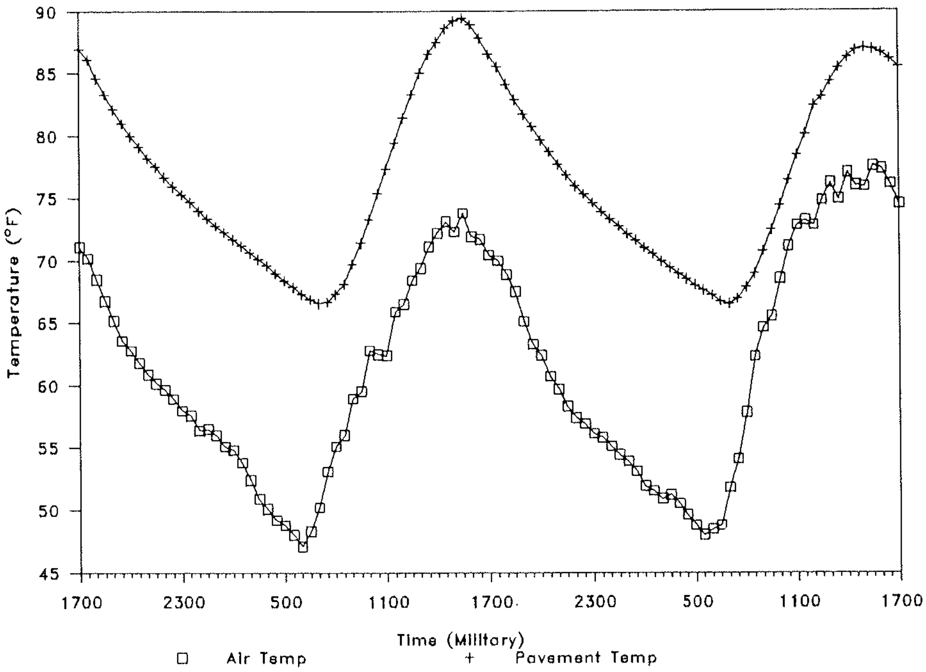

FIGURE 2 Temperature versus time.

Under such conditions, the temperature variation approximates a sine wave. However, it was observed that during cloudy and rainy weather temperature variation in the pavement did not follow any particular pattern. It is interesting to note that variation in pavement temperature follows a pattern that is similar to that of air temperature. The rate of variation in pavement temperature is higher during daytime than during nighttime. Solar radiation is likely responsible for the high rate of temperature variation during daytime hours.

Figure 2 also shows that pavement temperature is higher than air temperature. This observation was not limited to the data presented in Figure 2; a general trend was noted from the accumulated data. Under clear skies pavement temperatures were normally 15°F to 25°F higher than ambient temperatures. However, the difference in temperature drastically decreased during cloudy and rainy weather.

Maximum and minimum pavement temperatures occurred normally 1 to 2 hr after air temperatures reached their maxima and minima.

This trend is evident not only from the sample of data presented in Figure 2; it was observed in the majority of the samples that were randomly selected from the collected temperature data. Table 1 gives the results of the statistical analysis of temperature data obtained between 1983 and June 1986. A population of 230 sample days was randomly selected for the analysis. All months were represented in the analysis with equal numbers of samples. It is obvious from Table 1 that minimum temperatures occur most frequently between 5:00 a.m. and 7:00 a.m. for air and between 6:00 a.m. and 8:00 a.m. for pavement. On the other hand, maximum temperatures occur most frequently between 12:00 noon and 2:00 p.m. for air and between 1:00 p.m. and 3:00 p.m. for pavement.

Temperature Distribution

Figure 3 shows typical 24-hr variation in temperature at different slab depths. The temperature data were obtained on a clear day. As may be expected, the surface of the slab experiences the highest rate of temperature change. The rate of temperature change decreases with depth, reaching minimum at the bottom of the slab. It is evident from Figure 3 that slab temperatures during the night are coolest at the surface and warmest at the bottom. Soon after daybreak, the temperature at the slab surface starts to increase rapidly. After a short transition period, slab temperatures become warmest at the surface and coolest at the bottom.

Table 1 gives the most frequent times at which minimum and maximum temperatures occurred at the surface, center, and bottom regions of the slab. It can be observed that the different slab depths reach maximum and minimum temperatures at different times. Obviously, the temperature at the slab surface reaches maximum or minimum first, and the bottom temperature reaches similar levels last. The delay, as indicated by the data in Table 1, is between 2 and 4 hr.

The temperature differential between the surface and the bottom of the slab is responsible for the magnitude and direction of slab curling. Figure 4 shows typical variation of temperature differential with respect to time of day. It is evident that temperature differential is negative during night hours and positive during daytime hours. Figure 4 shows that maximum negative and positive temperature differentials occurred at 6:00 a.m. and 1:00 p.m., respectively. Table 1 gives similar times for a population of 230 days of temperature records.

The transition between negative and positive temperature differentials occurred twice during the 24-hr thermal cycle. It can be seen from Figure 4 that zero temperature differential occurred at approximately 9:00 a.m. and 7:00 p.m.

TABLE 1 MOST FREQUENT TIMES OF OCCURRENCE OF MAXIMUM AND MINIMUM TEMPERATURES

Description	Minimum		Maximum	
	Time (Military)	Percent Frequency	Time (Military)	Percent Frequency
Air Temperature	500 - 700	64	1200 - 1400	36
Average Pavement Temp.	600 - 800	81	1300 - 1500	68
Pavement Surface Temp.	600 - 800	72	1300 - 1500	71
Pavement Center Temp.	700 - 900	74	1500 - 1700	68
Pavement Bottom Temp.	800 - 1000	71	1700 - 1900	61
Negative Temp. Differential	---	---	500 - 700	54
Positive Temp. Differential	---	---	1200 - 1500	67

No. of Samples = 230 --- Not Applicable

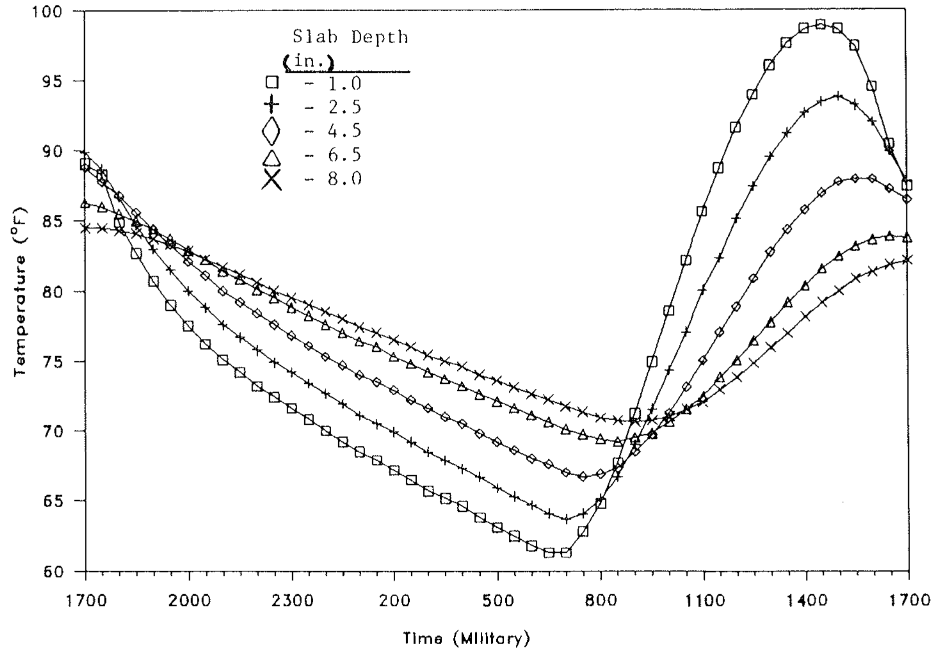

FIGURE 3 Temperature variation at different slab depths.

Figure 5 shows typical temperature gradients across the 9-in.-thick slab. The temperature gradients can be described as nonlinear. Results from another study (see paper by Richardson and Armaghani in this Record) showed that the temperature distributions are best modeled by parabolic equations. However, in many analyses of thermal stresses, temperature gradients have been assumed to be linear. This assumption has simplified the modeling of pavements without significantly affecting the accuracy of the computations. Therefore, for all practical purposes the temperature gradient can be approximated by a linear curve.

Effect of Weather Conditions on Pavement Temperature

Relating temperature data to weather conditions provided interesting information on the sensitivity of pavement temperature to changes in the weather. As might be expected, pavement temperatures fluctuated from season to season in a manner similar to fluctuations of ambient temperatures. However, temperature differential of the slab was not as much influenced by the magnitude of ambient temperature as it was by weather conditions. For example, the maximum temperature differentials were generally higher on clear days than on hazy or cloudy

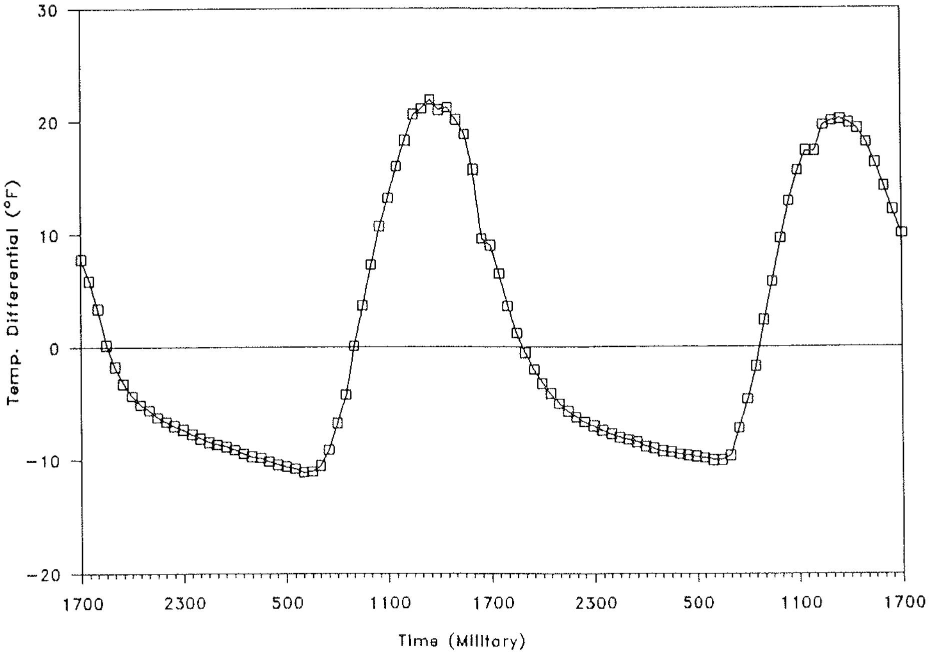

FIGURE 4 Temperature differential versus time.

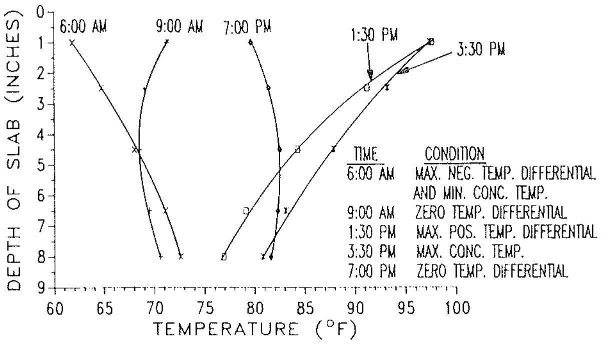

FIGURE 5 Typical temperature gradients for 9-in. slab.

days. Obviously, greater variations in air temperature are responsible for higher maximum temperature differentials.

An experiment was performed on the test road to study the effect of shade (normally associated with cloudy weather) on pavement temperature. Temperatures were measured from thermocouple arrays at the edge and the center of Slab 4 on 2 consecutive sunny days. During the first 24 hr, the thermocouple array in the center was covered with a white wooden box. At the end of this period the box was removed to provide equal exposure at both locations for the next 24 hr. Figure 6 shows the effect of shade on surface temperature at the center of the slab. It can be observed that during daytime the temperature of the shaded center is much lower than that of the edge. Such differences became insignificant during the night. However, when the shade was removed, temperatures at both locations were quite close; temperatures at the center were slightly higher during daytime.

A second test was conducted on the test road to determine the effect on pavement temperature of sudden exposure to moisture. The test was intended to model the temperature "shock" that results from an afternoon rain (a common weather situation in Florida during summer) on a hot pavement surface.

Figure 7 shows the air and pavement temperatures with respect to time. The linear temperature gradient, designated as A, represents the dry hot pavement at 3:00 p.m. Water at 76°F was applied to the surface of Slab 4 shortly after 3:00 p.m. An hour later, with surface flooding in progress, substantial changes in pavement temperature were observed, as illustrated by Condition B. Surface temperature dropped 8.5°F while the bottom of the slab had not yet felt the effect of surface quenching. As a consequence, the shape of the temperature gradient across the slab thickness shifted from linear to nonlinear. It has been demonstrated that the nonlinearity associated with rapid cooling of a pavement surface produces high tensile stresses, which could be critical if combined with stresses induced by traffic and slab curling (see paper by Richardson and Armaghani in this Record).

CONCRETE PAVEMENT RESPONSE TO TEMPERATURE

Under ideal conditions, a pavement slab responds to the temperature differential across its thickness in the manner shown in Figures 8*a*, 8*b*, and 8*c*. The ideal slab assumes a no-curl (flat) condition at zero temperature differential. At negative temperature differential the slab curls upward at the edges, with the corners exhibiting the largest curling while the center is in contact with the subgrade. In contrast, positive temperature differential causes upward curling at center and downward curling along the edges.

In reality, however, pavement slabs do not necessarily assume a no-curl position at zero temperature differential. In a separate study *(6)*, surface elevations along the undoweled Joint 4 of the test road were measured at various temperature differentials, as shown in Figure 9. It can be observed that the slab assumed the no-curl condition at +9°F temperature differential. The logical explanation for such inconsistency between the ideal and the observed pavement responses is the

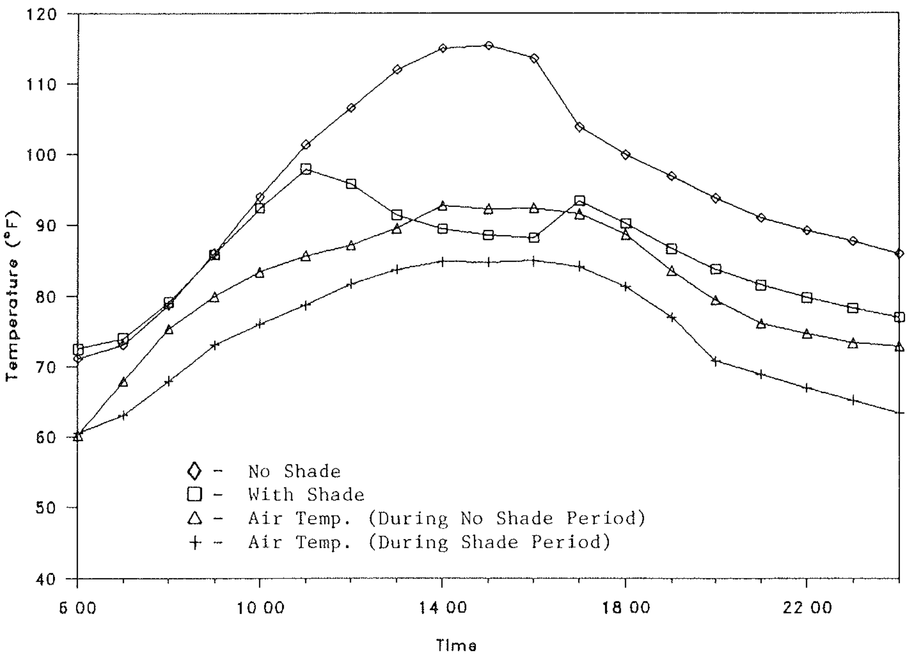

FIGURE 6 Effect of shade on concrete temperature.

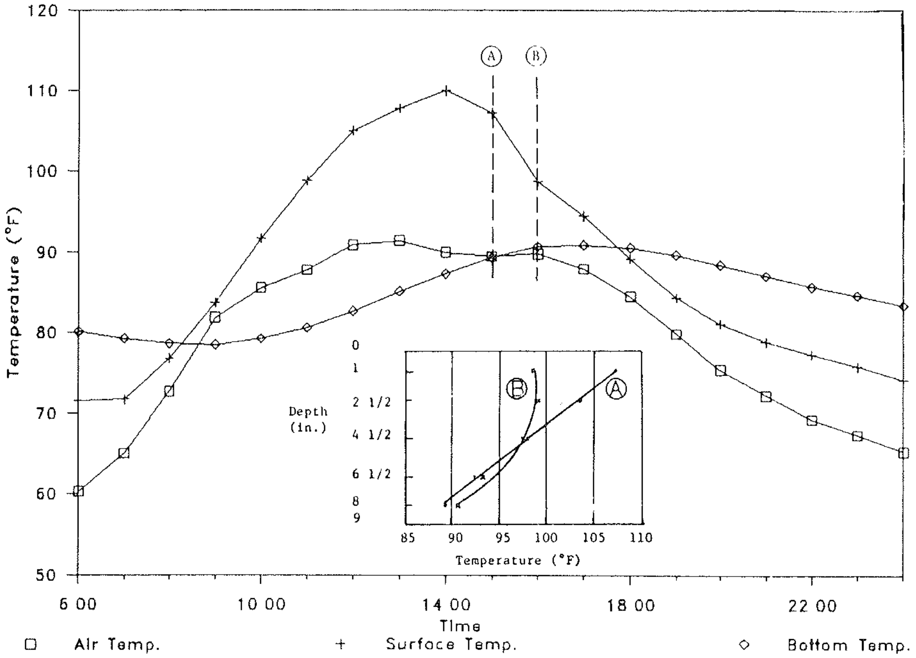

FIGURE 7 Effect of sudden exposure to moisture on concrete temperature.

possible influence on displacements of moisture or shrinkage differentials, or both, within the slab. Warping of slabs associated with moisture and shrinkage had also been observed by Harr and Leonards *(4)* and by Childs *(7)*. Figures 8*d* and 8*e* show upward warping due to moisture and shrinkage warping, respectively. It is therefore logical to assume that a +9°F temperature differential is required to offset the upward warping of the test road slabs associated with moisture or shrinkage, or both.

Analysis of Vertical Slab Displacements

Simultaneous recording of vertical displacements at the corner, edge, and center of a slab provided an excellent opportunity to compare the responses of different slab positions to variations in temperature. Figure 10 shows vertical slab displacements with respect to time. The four curves presented in this figure reflect surface elevations at the edge, center, and corner of Slab 4 and also at the corner of Slab 3 adjoining Slab 4. Slab displacements shown in Figure 10 correspond to temperature differentials shown in Figure 4.

It can be seen from close examination of Figures 10 and 4 that vertical slab displacements are highly sensitive to changes in temperature differential of the slab. Evidence of such sensitivity is the close association between rates of slab displacements, particularly at the corners, and the rate of change in temperature differential. Furthermore the maximum displacements

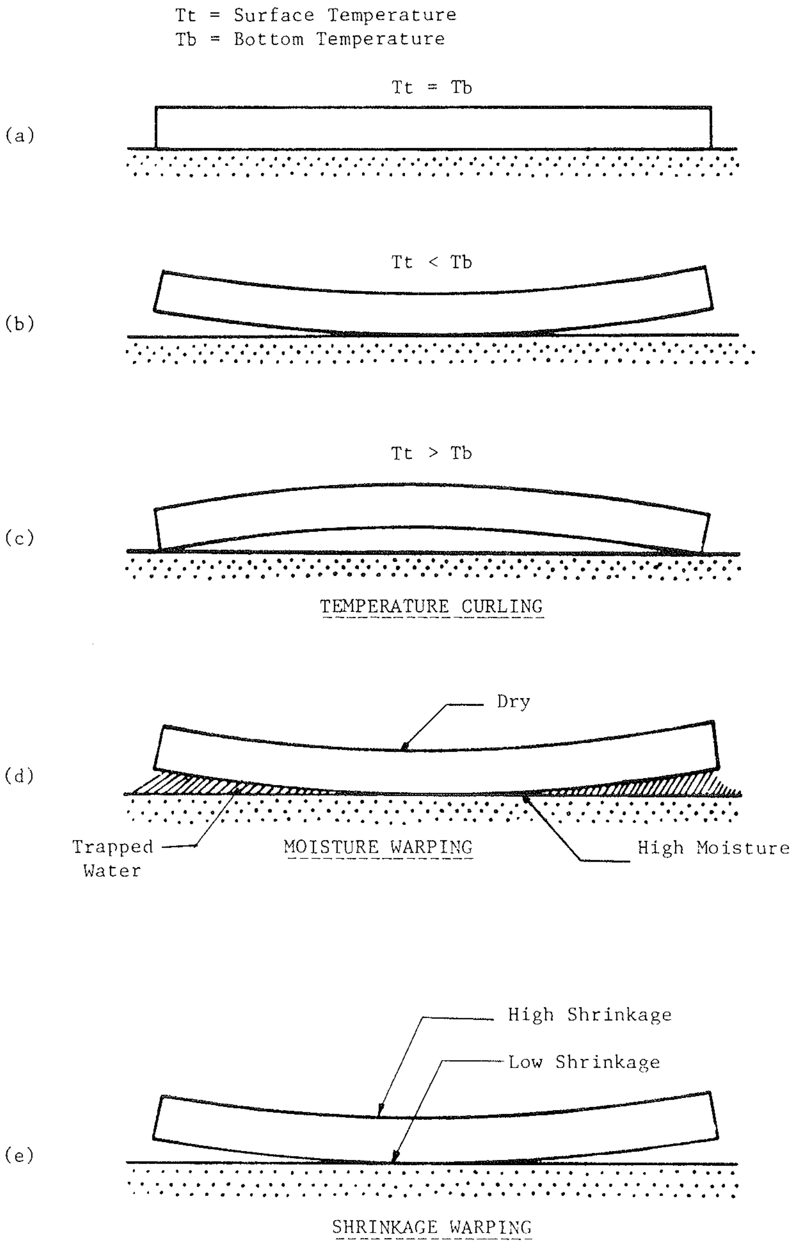

FIGURE 8 Curling and warping of pavement slabs.

at the different slab positions are almost concurrent with the maximum negative and positive temperature differentials.

The slab edge and corner displaced in a direction opposite to the displacement at the center. However, maximum displacements at the three positions were reached at about the same time. In reference to Figures 4 and 10, as the temperature differential changes from positive to increasingly negative, the edge and corner of the slab curl upward (indicated by an increase in negative displacement) while the center curls downward (indicated by an increase in positive displacement). The three slab positions reach maximum curling at approximately 6:00 a.m., which is about the time when temperature differential reaches maximum negative. Conversely, as the temperature differential gradually changes from negative to positive, the edge and corner of the slab curl downward while the center curls upward. The maximum displacements coincide at approximately 2:00 p.m., the time at which maximum positive temperature differential is also reached. It is interesting to note that the rate of vertical displacement is higher during the daytime. This can be attributed to a rapid increase in surface temperature of the pavement, which is associated mainly with intensifying solar radiation.

In addition to reaffirming that maximum slab curling occurs at the corner, Figure 10 shows another important characteristic of corner displacements at undoweled joints. Despite equal slab lengths, the adjoining corners of Slabs 3 and 4 exhibited variable displacements or uneven curling. Therefore it is logical to assume that the variability would be even higher if one of the adjoining slabs were shorter than the other, as in the case of randomly spaced pavement slabs. Such variability in displacements can result in possible restraint of joint movements, which in turn may induce stresses in the pavement.

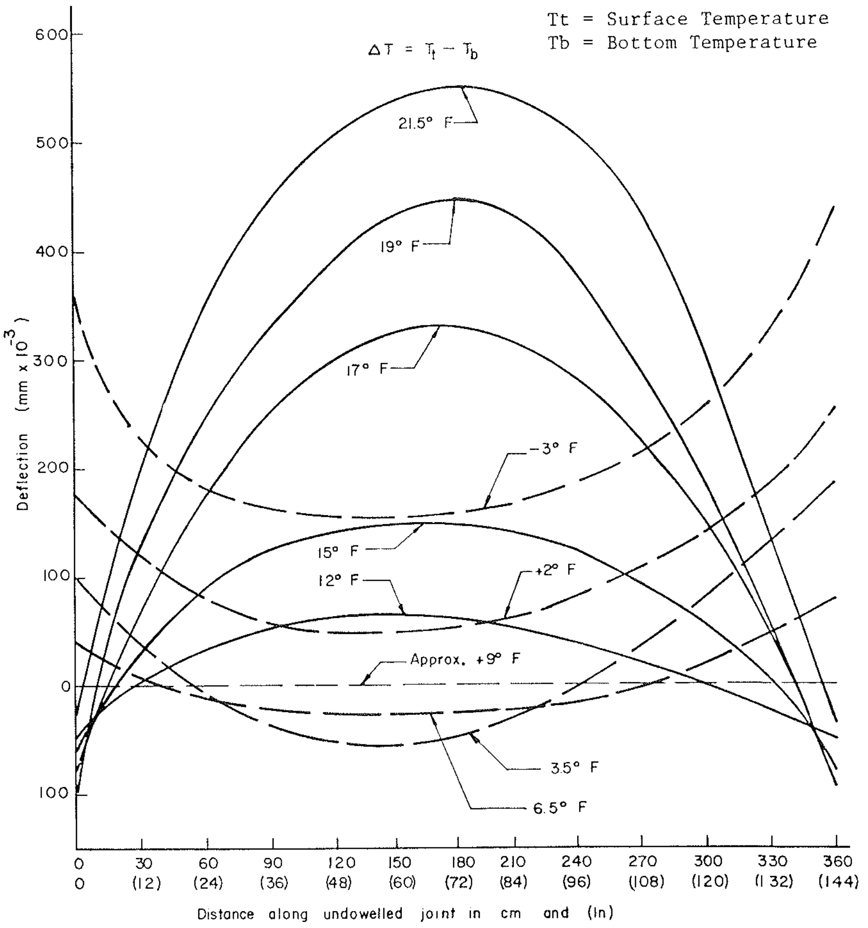

FIGURE 9 Deflection profiles along a joint due to change in the temperature differential.

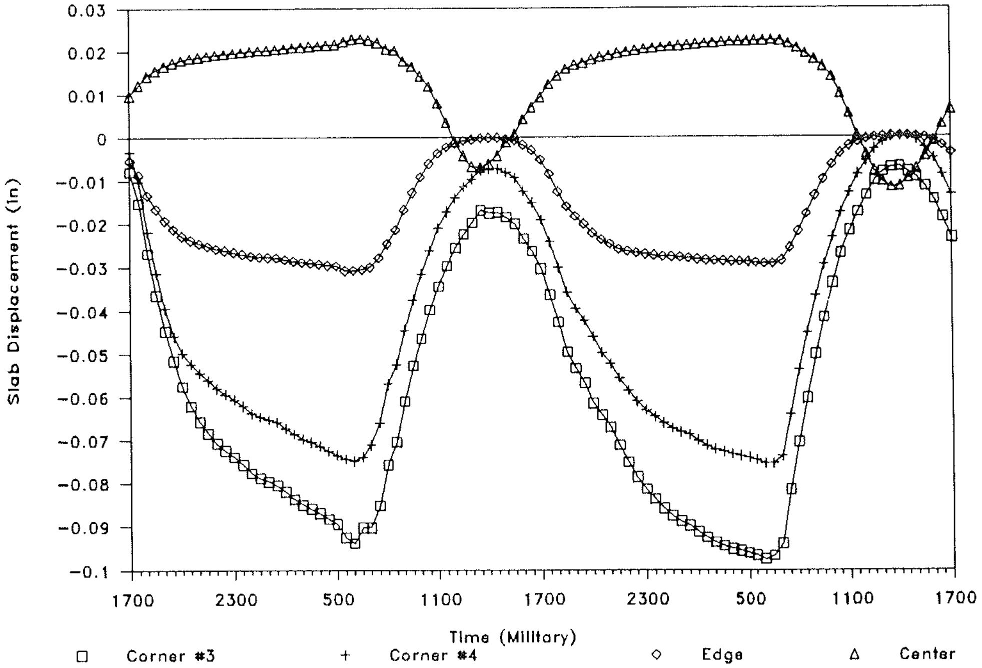

FIGURE 10 Vertical displacements of slab at center, edge, and corner (joint).

TABLE 2 MAXIMUM VERTICAL DISPLACEMENTS OF TEST ROAD SLABS

MONTH	TIME (MILITARY)		TEMPERATURE DIFFERENTIAL (°F)		AVERAGE CONCRETE TEMP. (°F)		MAXIMUM VERTICAL DISPLACEMENTS (inch)			
							CORNER		EDGE	CENTER
	FROM	TO	FROM	TO	FROM	TO	SLAB 3	SLAB 4	SLAB 4	SLAB 4
JAN.	700	1400	-7	+17	52	69	0.046	0.046	0.019	0.021
	1400	700	+19	-7	66	51	0.051	0.050	0.020	0.023
FEB.	600	1400	-9	+17	54	71	0.059	0.059	0.023	0.022
	1400	600	+17	-5	71	62	0.044	0.042	0.017	0.020
APRIL	600	1400	-11	+20	68	86	0.098	0.085	0.030	0.037
	1400	600	+21	-10.5	88	66	0.092	0.077	0.029	0.037
MAY	500	1300	-8	+25	77	99	0.089	0.068	0.028	0.045
	1400	500	+25	-7	103	86	0.084	0.066	0.026	0.040
JUNE	500	1400	-6.5	+23	89	107	0.081	0.065	0.026	0.036
	1400	500	+23	-6	107	89	0.080	0.066	0.027	0.035
					AVERAGE		0.072	.063	.025	.032

Table 2 gives the results of analysis of temperature and displacement data obtained from the test road between January and June 1986, excluding March. Listed in Table 2 are two maximum displacements observed for each of the 5 months. The first represents total displacement that occurred between early morning and afternoon. Directions of these slab displacements are downward at the edge and corner and upward at the center. The second maximum displacement represents the total displacement that occurred between afternoon and early morning of the following day. Directions of these slab displacements are upward at the edge and corner and downward at the center. The range of temperature differentials and average concrete temperature within which the maximum displacements occurred are also listed in Table 2.

The data in Table 2 indicate that higher displacements are associated with greater variations in daily temperature differentials. Almost all maximum monthly displacements occurred during dry, sunny days, characterized by wide variation of temperatures between day and night. Obviously, such weather conditions induced the necessary range of temperature differentials in the pavement slab to cause maximum vertical displacements.

The largest displacements occurred in April and May (Table 2). Such displacements were concurrent with the largest variations in temperature differential. The largest displacements at the corner, edge, and center were 0.098, 0.030, and 0.045 in., respectively. The average values of maximum displacements at the adjoining corners of Slabs 3 and 4 were 0.072 and 0.063 in., respectively. These values reflect the nonuniformity of displacements at the two adjoining corners. The differences were evident at larger displacements.

The influence of slab curling on pavement stiffness is clearly shown in Figure 11 *(6)*. At a high negative temperature differential the corner deflections are significantly high. This reflects a reduced stiffness in the pavement system, brought about by loss of subgrade support, which is associated with upward curling. As the temperature differential becomes less negative and gradually more positive, the slab corner will displace downward, increasing the area of subgrade support. Figure 11 shows that the corner deflections decrease as the temperature differential becomes gradually more positive. This

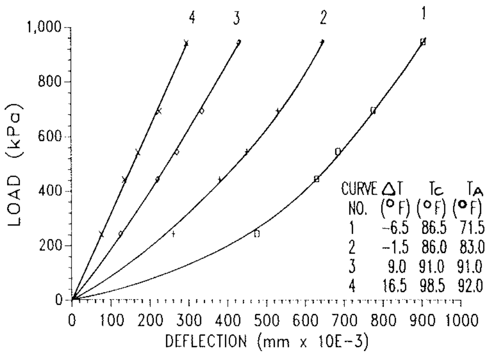

FIGURE 11 Typical load deflection relations at slab corner (ΔT = temperature differential, Tc = concrete temperature, and TA = air temperature).

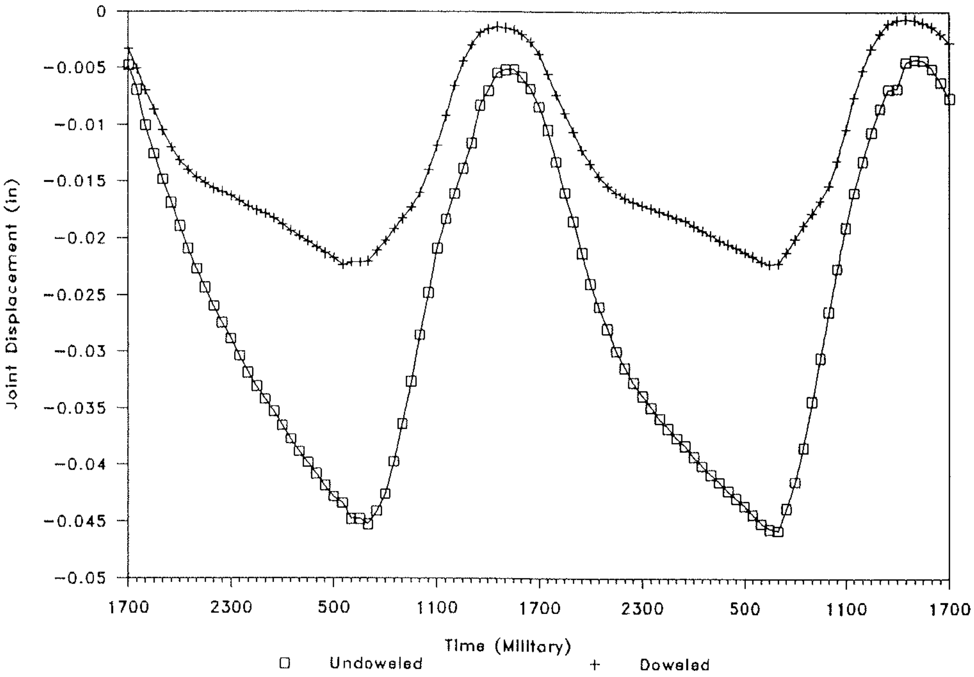

FIGURE 12 Horizontal joint displacement.

TABLE 3 MAXIMUM HORIZONTAL DISPLACEMENTS AT TEST ROAD JOINTS

MONTH	TIME (MILITARY)		TEMPERATURE DIFFERENTIAL (°F)		AVERAGE CONCRETE TEMP. (°F)		MAXIMUM HORIZONTAL DISPLACEMENTS (inch)	
	FROM	TO	FROM	TO	FROM	TO	UNDOWELED JOINT	DOWELED JOINT
JAN.	800	1400	-11	+12	39	55	.034	.010
	1400	800	+7	-11	59	39	.033	.009
FEB.	800	1400	-9	+12	49	62	.034	.018
	1500	800	+11	-7	73	58	.030	.012
APRIL	700	1500	-11	+21	67	88	.043	.023
	1500	700	+21	-10.5	88	65	.043	.021
MAY	600	1500	-7	+26	72	96	.041	.016
	1500	600	+26	-6	96	75	.037	.018
JUNE	600	1300	-6	+20	84	102	.035	.016
	1300	600	+22	-6	105	88	.033	.014
					AVERAGE		.036	.016

implies that, as a result of improved stiffness, a pavement system offers greater resistance to applied traffic loads.

Analysis of Horizontal Slab Displacements

Figure 12 shows typical slab displacements at undoweled and doweled joints. Pavement temperatures recorded during the same period were shown in Figure 2. It is obvious that displacements at both joints are sensitive to fluctuations in pavement temperatures. Pavement slabs expand and contract in response to increase and decrease of pavement temperatures, as clearly demonstrated by Figures 12 and 2. During the night, as pavement temperature decreases, the joint opening will increase correspondingly. Maximum opening occurs at approximately 7:00 a.m., which is concurrent with minimum pavement temperature. Shortly after daybreak, the joint opening will begin to close as the pavement temperature starts to increase and the opening will reach minimum width at approximately 2:00 p.m. This timing coincides with maximum pavement temperature.

It should be noted that slab curling can also contribute to joint opening and closing. The rotation associated with curling of adjoining slabs can cause further opening and closing of joints depending on the direction of rotation. However, because of the difficulty in assessing the contribution of slab curling, joint movements are normally attributed to expansion-contraction by changes in pavement temperature.

An important observation can be made from Figure 12. The doweled joint allowed only about 50 percent of the slab displacements allowed by the undoweled joint. This observation is true not only for the sample data presented in Figure 12. Table 3 gives the results of analysis of data recorded throughout the 6-month study. The largest joint displacements were recorded in April. The displacement at the doweled joint was 0.023 in. compared with 0.043 in. at the undoweled joint, a difference of about 46 percent. Looking at the averages of monthly maximum displacements, the difference is even greater, about 55 percent. This is a strong indication of the resistance offered to slab displacements by doweled joints. Such movement restraints can contribute to stress development in the pavement. These stresses may be critical if they occur in conjunction with stresses that are induced by traffic loads and temperature.

CONCLUSIONS

Temperature records obtained from a concrete test road in Florida were analyzed. Slab displacements associated with temperature variation were also measured and analyzed. On the basis of findings from this study, the following conclusions are drawn:

1. Pavement slabs reach their minimum daily temperatures between 6:00 a.m. and 8:00 a.m., and their maximum temperatures occur between 12:00 noon and 2:00 p.m.
2. Maximum and minimum pavement temperatures generally occur about 1 hr after ambient temperature reaches similar levels.
3. The maximum negative and positive temperature differentials in pavement slabs occur, on average, at 6:00 a.m. and 2:00 p.m., respectively. Such timing almost coincides with minimum and maximum pavement temperatures.
4. The largest vertical displacements recorded at the corner, edge, and center of the slab were 0.098, 0.030, and 0.045 in., respectively. Maximum daily displacements were concurrent with maximum temperature differentials in the slab.
5. Vertical displacements exhibited by the two sides of an undoweled joint were nonuniform. On average, one side of the joint displaced about 13 percent more than the other side.
6. The largest horizontal displacements recorded at undoweled and doweled joints were 0.043 and 0.023 in., respectively. Maximum joint opening and closing were reached at approximately 7:00 a.m. and 3:00 p.m., respectively.
7. The average horizontal displacement at the doweled joint was only 45 percent of the displacement at the undoweled joint. This suggests that doweled joints offer resistance to slab movements, a condition that can induce stresses in the pavement.
8. Weather conditions significantly influenced temperature response of pavements. Clear, sunny weather characterized by wide variations of ambient temperature produced larger displacements in pavement slabs.
9. The temperature distribution in the pavement slab changed drastically in response to sudden exposure to moisture and shade at the pavement surface.

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