Stress Caused by Temperature Gradient in Portland Cement Concrete Pavements

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Concern has been expressed in Florida that, because of a nonlinear temperature gradient in a portland cement concrete (PCC) pavement, internal stresses could be developed such that the life of the pavement would be seriously reduced. A research program was undertaken by the Florida Department of Transportation to determine the actual temperature gradient in a PCC pavement. For a period of 9 months, hourly temperatures were recorded from a 9-in.-thick test pavement in Gainesville, Florida. The temperature data were analyzed to determine what curve best fit the data and what were the actual maximum compressive and tensile stresses caused by the nonlinearity of the temperature gradient. These results were compared with those obtained from the AASHO Test Road and with Bergstrom's prediction method. The results indicated that the nonlinearity of the temperature gradient in a PCC pavement did not have a significant impact on its performance.

Fluctuations in air temperature and in the intensity of solar radiation cause stresses in a concrete pavement. Recently a new portland cement concrete (PCC) pavement in Florida experienced premature cracking. It was hypothesized that a stress that would significantly contribute to the failure of the pavement could be generated by the nonlinearity of the temperature gradient. To evaluate this hypothesis it was decided to examine historical temperature data (1983 and 1984) from a test road that was constructed in Gainesville, Florida. The test road had a pavement thickness of 9 in., which was the same as that of the distressed pavement.

Concrete is sensitive to volumetric change caused by thermal fluctuation. A model must be assumed in order to isolate the stress due to the nonlinearity of a temperature gradient. Bergstrom *(1)* presented this method in 1950. It is assumed that pavement temperature is increased by some amount above that which would correspond to zero stress (Figure 1*a*). The energy that increases the temperature of the pavement is applied only to the surface of the pavement through the air and solar radiation. This causes a temperature gradient in the pavement. If the displacements of the pavement (axial and curling) are completely prevented, an axial compressive stress across the whole cross section is generated. This total stress is found by integrating across the section and dividing by the depth of the pavement (Figure 1*b*). When this axial stress is subtracted from the total stress, the resulting stress will cause a curling bending moment in the pavement. This moment can be calculated by taking the stresses about any convenient point (i.e., the bottom of the pavement). This moment will result in a curling stress distribution as shown in Figure 1*c*. When both the axial and the curling stresses are subtracted from the total temperature stress, the resulting stress is that caused by the nonlinearity of the temperature gradient of the pavement (Figure 1*d*). A linear temperature gradient would result in zero stresses in Figure 1*d*. Even though this nonlinear temperature stress was determined assuming complete restraint of the pavement, it exists whether the pavement is restrained or not.

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TESTING PROCEDURES

The Gainesville, Florida, test road (Figure 2) consists of six slabs, each 12 ft wide and 20 ft long, made of PCC placed on undisturbed soil. The road does not support any vehicular traffic. The compressive strength of the concrete in the pavement averages about 5,000 psi. Five thermocouples were implanted in the center of Slab 4 to measure the temperature of the concrete (fresh and hardened). The thermocouples were spaced at 1, 2.5, 4.5, 6.5, and 8 in. below the surface of the pavement. No temperature measurements were made at the top and bottom of the pavement. The thermocouples were secured to a 1/4-in. wooden dowel imbedded in the fresh concrete and connected to a Fluke programmable data logger. The data logger was programmed to take temperature measurements from all five sensors at 1-hr intervals. In some cases, measurements were made at 30- and 15-min intervals. With some discontinuities, measurements were taken from November 1983 through August 1984 in conjunction with other ongoing research. Temperature measurements at only three levels have been continued to the present. The months of December 1983 and November 1984 were almost continuously monitored with at least hourly measurements.

METHOD OF ANALYSIS

The temperature data were analyzed in a three-step procedure. In the first step, the objective was to identify the time intervals that created the maximum tensile and compressive stresses caused by a nonlinear temperature gradient so that further analysis could be focused on only these incidents. The second step was to determine what form of equation best fit the experimental temperature data. The third and final step was to conduct stress analyses on the critical days with the best-fit equation to determine the nonlinear temperature stresses.

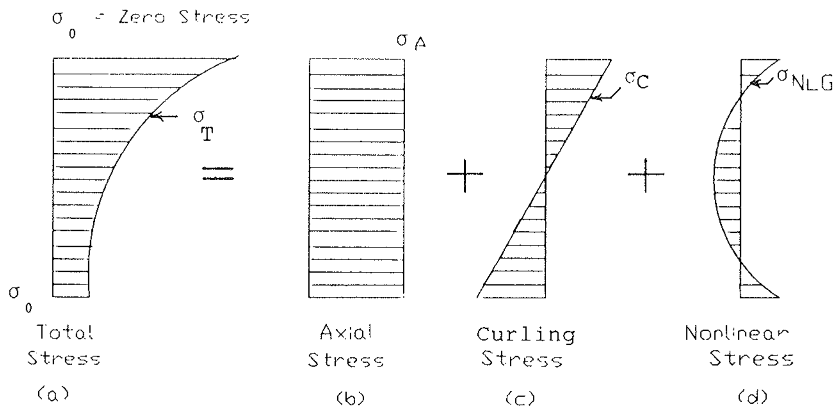

FIGURE 1 Typical temperature stresses in concrete pavements.

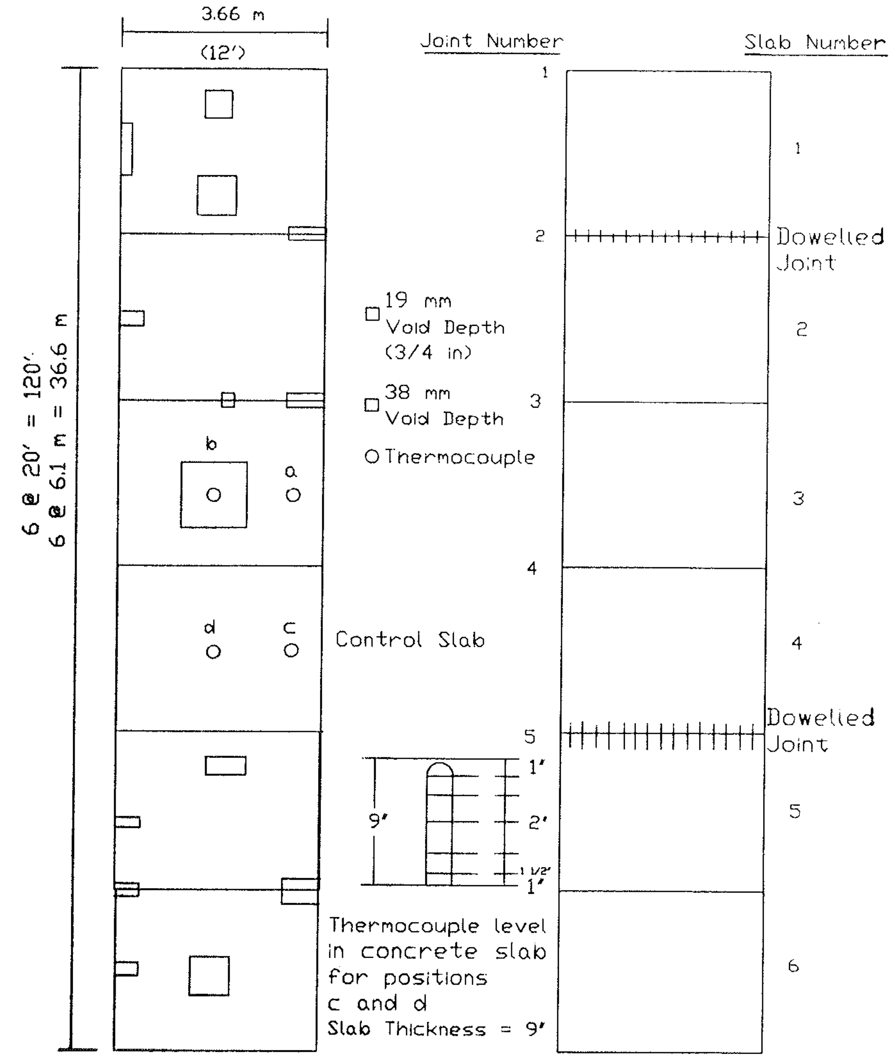

FIGURE 2 Details of test road.

FORTRAN ANALYSIS

Because five temperature thermocouples were used, the method that was used to first examine the data was to assume a linear temperature gradient between sensor locations. The temperature gradient for the top 1 in. of pavement was found by extending the line connecting the temperatures taken at the 1- and the 2.5-in. levels below the pavement surface. The bottom 1 in. of pavement was assumed to be at the same temperature as the sensor located 8 in. below the surface of the pavement. A FORTRAN program was written that first divided the pavement into 90 levels and then determined the area for each section and summed to give the total area. This number was multiplied by the coefficient of thermal expansion (assumed to be 6×10^{-6} degrees Fahrenheit) and Young's modulus of elasticity (assumed to be 3.5×10^{6} psi) to give the total force on the cross section. Dividing this total by the depth of the pavement (9 in.) and a strip of the pavement 1 in. wide gave the axial stress above some predetermined temperature of zero stress. This was assumed to be zero degree (°F) for convenience in calculations, but any temperature is acceptable because the magnitude of the axial and curling stress is not the subject of this study.

The next step was to determine the curling stress of the pavement. This was done by taking the moments of the areas of the 90 levels that remained after the axial stress was subtracted from the total stress at each level. This stress had to conform to the double triangular stress areas shown in Figure 1*c*. Subtracting the curling stress plus the axial stress from the total stress yielded the stresses that were caused by a nonlinear temperature gradient. The value of this method is that it does not require an assumed equation to examine the thousands of individual time intervals observed.

SAS ANALYSIS

When the day and times of maximum stresses (top, bottom, and midway in the pavement) had been determined, the corresponding temperature gradients were analyzed using linear regression to see what equation would give the best fit. The following models (equations) were tested: parabolic parallel to the thickness, parabolic parallel to the temperature, semilog, log-log, semilog with axes reversed, and the Gompertz growth equation. This analysis was accomplished using SAS Version 5 *(2)*. The parabolic model parallel to the temperature axis gave the best fit at all of the time intervals examined. The model was next fitted to 325 time intervals. The curve fit was extremely good. Using the correlation coefficient (R^2) as the measure of the goodness of fit, it was found that 255 time intervals had R^2 greater than 0.99 (1.0 is a perfect fit). Forty-nine time intervals had a fit between 0.95 and 0.99, and 18 time intervals had a fit between 0.90 and 0.95. The three remaining intervals had R^2 of 0.85, 0.84, and 0.75.

DISCUSSION OF RESULTS

The parabolic model parallel to the temperature axis is

$$t = A + By + Cy^2 \tag{1}$$

where

t = temperature (°F),
y = location above the bottom of the pavement (in.), and
A, B, C = factors fitted by linear regression.

Representative values of A, B, C, and R^2 for August 14, 1984, are given in the following table.

Hour	*A*	*B*	*C*	R^2
Midnight	96.09	0.1841	−0.11789	0.9993
4:00 a.m.	93.24	−0.2906	−0.0819	0.9990
8:00 a.m.	90.71	−0.5673	−0.0426	0.9990
Noon	91.98	−0.8172	0.3125	0.9984
4:00 p.m.	98.32	0.8178	0.2250	0.9999
8:00 p.m.	99.87	1.2641	−0.1593	0.9747

The temperature in Equation 1 is related to stress by assuming a temperature for zero stress, as was done previously, and then subtracting this temperature from the derived temperature and, finally, multiplying by the coefficient of thermal expansion and the modulus of elasticity:

$$\sigma_T = E\,\alpha\,t \tag{2}$$

where α is the coefficient of thermal expansion and E is the modulus of elasticity.

The axial stress at any level in a 9-in. pavement can be found to be

$$\sigma_A = E\,\alpha\,(A + 4.5B + 27C) \tag{3}$$

By finding the moment by double integration, the curling stress (if fully restrained) can be found to be

$$\sigma_C = E\,\alpha\,[(y - 4.5)\,B + 9\,(y - 4.5)C] \tag{4}$$

Subtracting σ_A plus σ_C from σ_T yields the stress due to the nonlinearity of the temperature gradient:

$$\sigma_{NL} = E\,\alpha\,C(y^2 - 9y + 13.5) \tag{5}$$

This result is not unexpected because the only nonlinear term in the parabolic equation is y^2 and C is only associated with this term.

Using the fitted parabolic equations, the maximum compressive stress (Figure 3) due to a nonlinear temperature gradient was found to be 113 psi on August 14, 1984, at 1:00 p.m. eastern daylight time (EDT) [12 noon eastern standard time (EST)]. An examination of all of the data revealed that the maximum nonlinear compressive stress occurred at about 12 noon EST throughout the year.

Levels of stress near the maximum occurred throughout the testing period. Representative stresses (psi) are given in the following table.

Date	*Stress (psi)*
December 23	60
January 1	100
February 1	107
March 13	104
April 2	91
July 25	109

The maximum tensile stress due to the nonlinearity of a temperature gradient (Figure 4) of 113 psi occurred on August 15 at 8:00 p.m. EDT. The maximum nonlinear tensile and compressive stresses occurred in both the top and the bottom of the pavement. Unlike the time of occurrence of the maximum nonlinear compressive stress, that of the maximum nonlinear tensile stress varied throughout the test period. In December 1983 it occurred about midnight and became progressively earlier in the evening until it reached 8:00 p.m. EDT on August 5, 1984.

The maximum tensile stress is much higher than that measured at other times. Representative values are given in the following table.

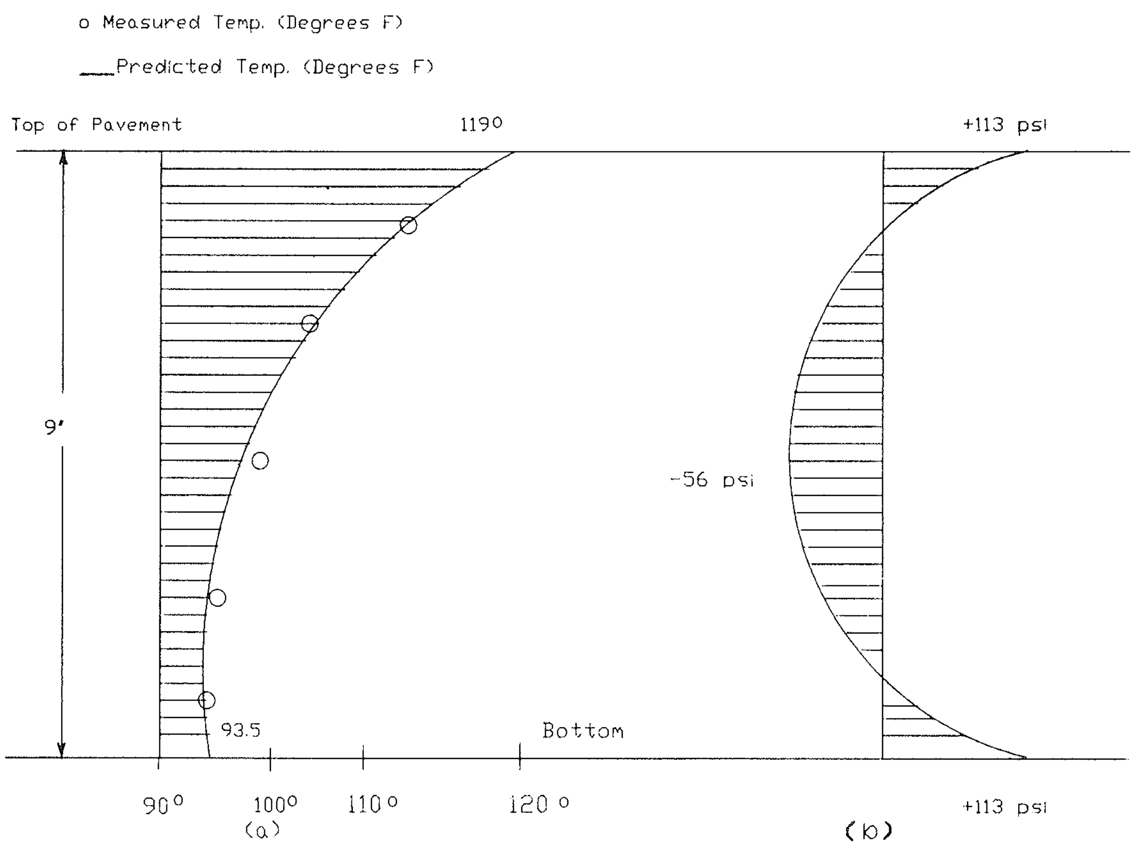

FIGURE 3 Temperature gradient and nonlinear temperature stresses on August 14, 1984, at 1:00 p.m. EDT.

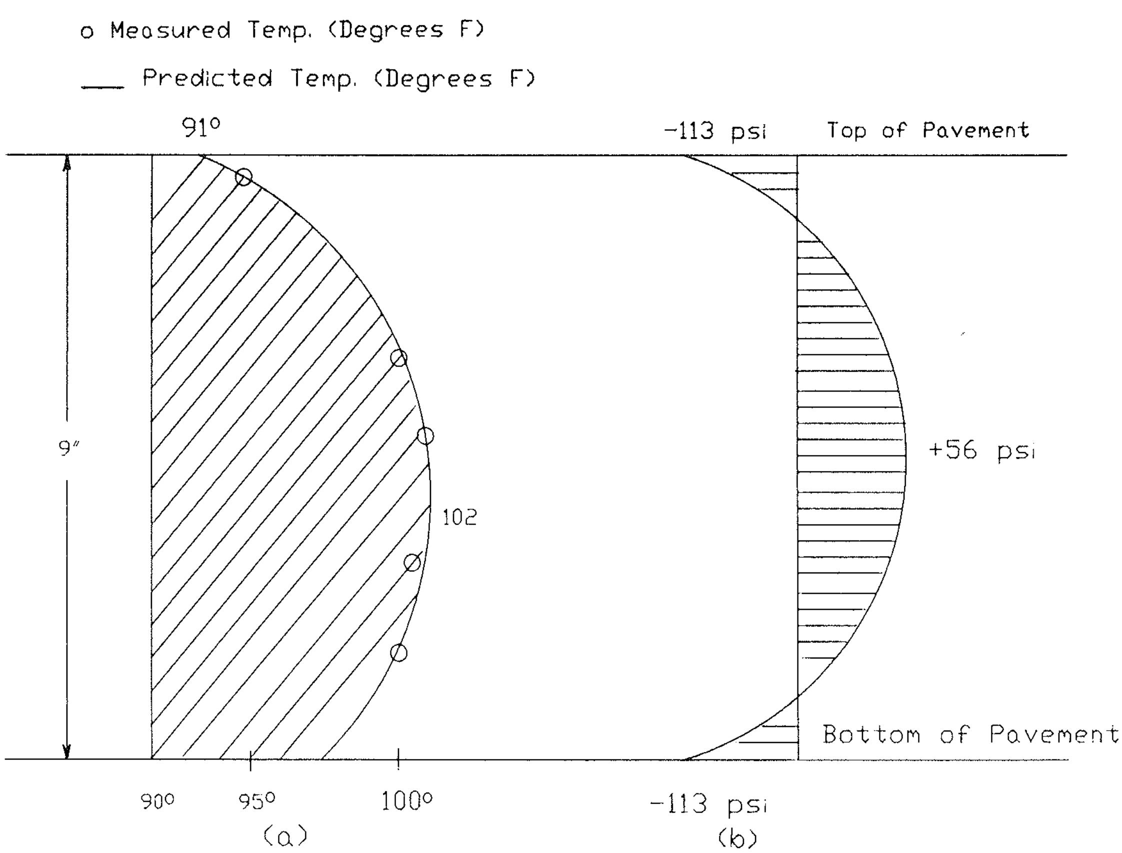

FIGURE 4 Temperature gradient and nonlinear temperature stresses on August 15, 1984, at 8:00 p.m. EDT.

Date	*Maximum Tensile Stress (psi)*
December 23	37
January 30	30
February 6	43
March 14	58
April 2	40
July 25	53

The highest tensile stress on a previous day (August 14) was 56 psi. The reason for the high tensile stress on August 15 is the rapid cooling of the surface of the pavement, which was probably caused by an evening thunderstorm, just before 6:00 p.m. EDT. The temperatures were recorded automatically so that no one was present at 6:00 p.m., but at 5:00 p.m. the sky was reported as being heavily overcast.

That the maximum nonlinear tensile and compressive stresses have the same value is purely coincidental. Bergstrom's *(1)* analysis using the same modulus of elasticity, coefficient of thermal expansion, and temperature difference between the top and bottom of the pavement produced a compressive strength of 63 psi. Bergstrom used an exponential (semilog) model that did not provide a good fit to the test road data.

During July 1986 an additional temperature sensor, insulated from incident solar radiation, was placed on the surface of the pavement. On July 9, 1986, at 12:00 noon EDT the temperature at the 1 in. below the surface level reached 116°F while the surface had a temperature of 122°F. This differential between the surface and 1 in. below the surface is what had been predicted by the model. This is additional confirmation of the validity of the parabolic model.

Figures 5 and 6 are plots of the air temperature, the temperature 1 in. from the top, 1 in. from the bottom, and in the middle of the pavement for August 14, 1984, and August 15, 1984, respectively. During the night, concrete temperatures varied closely with variations in air temperature, but during the daylight hours incident solar radiation on the surface of the pavement played a much larger part than did air temperature, as shown by the rapid rise in the temperature of the top of the pavement. This may be primarily a phenomenon of more southerly regions because Bergstrom *(1)* reported that in Sweden concrete temperatures varied with air temperatures. The area of maximum nonlinear tensile stress is clearly defined by the region in which the temperature at the middle of the pavement exceeds those at the top and the bottom in Figure 6. The area of maximum nonlinear compressive stress is not clearly defined and cannot be determined from Figure 5.

Figure 7 is a plot of the temperature gradients at 4-hr time intervals on August 14, 1984. The curves are quite similar to those found in the AASHO Road Test *(3)*.

The assumed value of 6×10^{-6} degrees Fahrenheit for the coefficient of thermal expansion is probably high for concrete made with porous Florida coarse aggregates. Initial findings from ongoing research have indicated a value of less than 4×10^{-6} degrees Fahrenheit. The assumed modulus of elasticity has been shown to be approximately correct for concrete of 5,000-psi compressive strength manufactured in Florida. If the lower value is used, the maximum nonlinear stresses would be +75 psi.

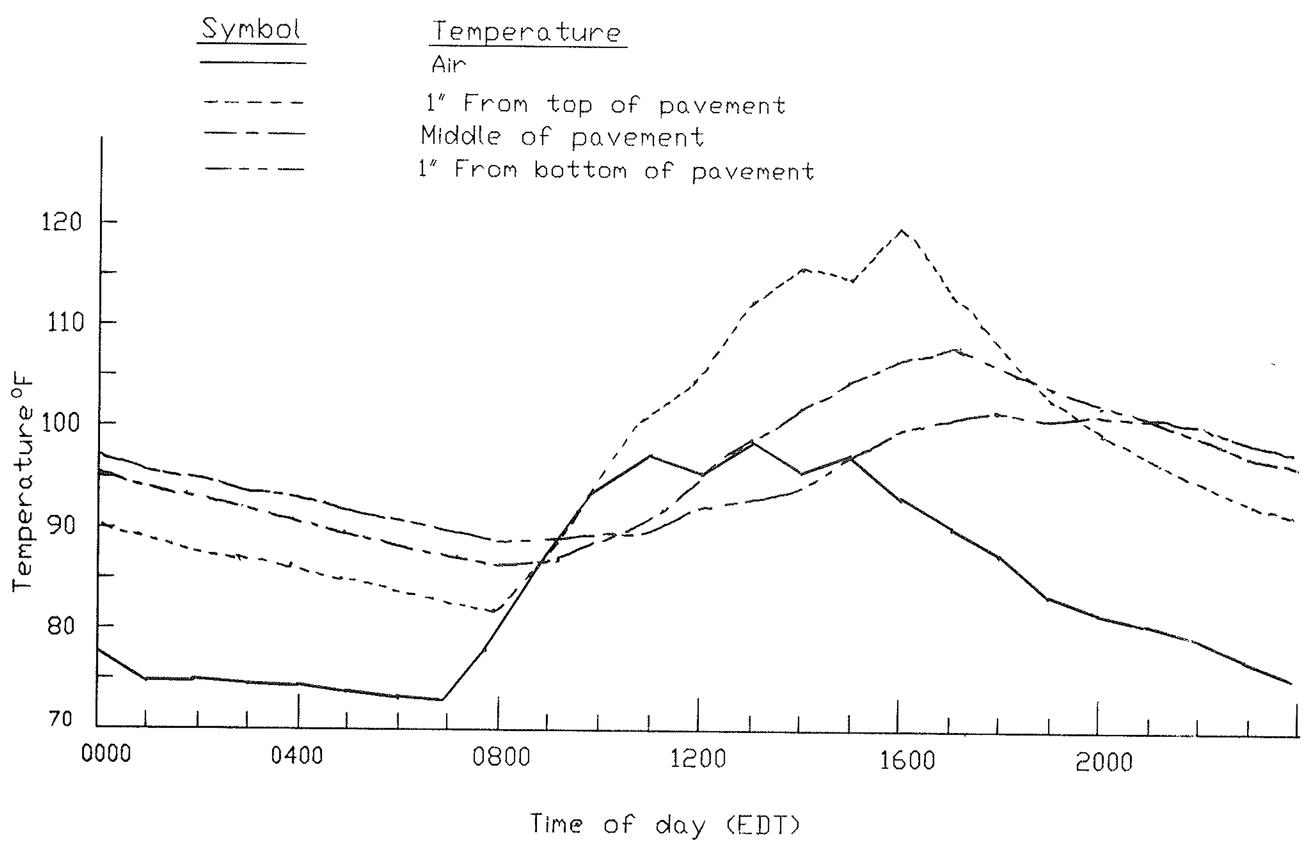

FIGURE 5 Temperature distribution for August 14, 1984.

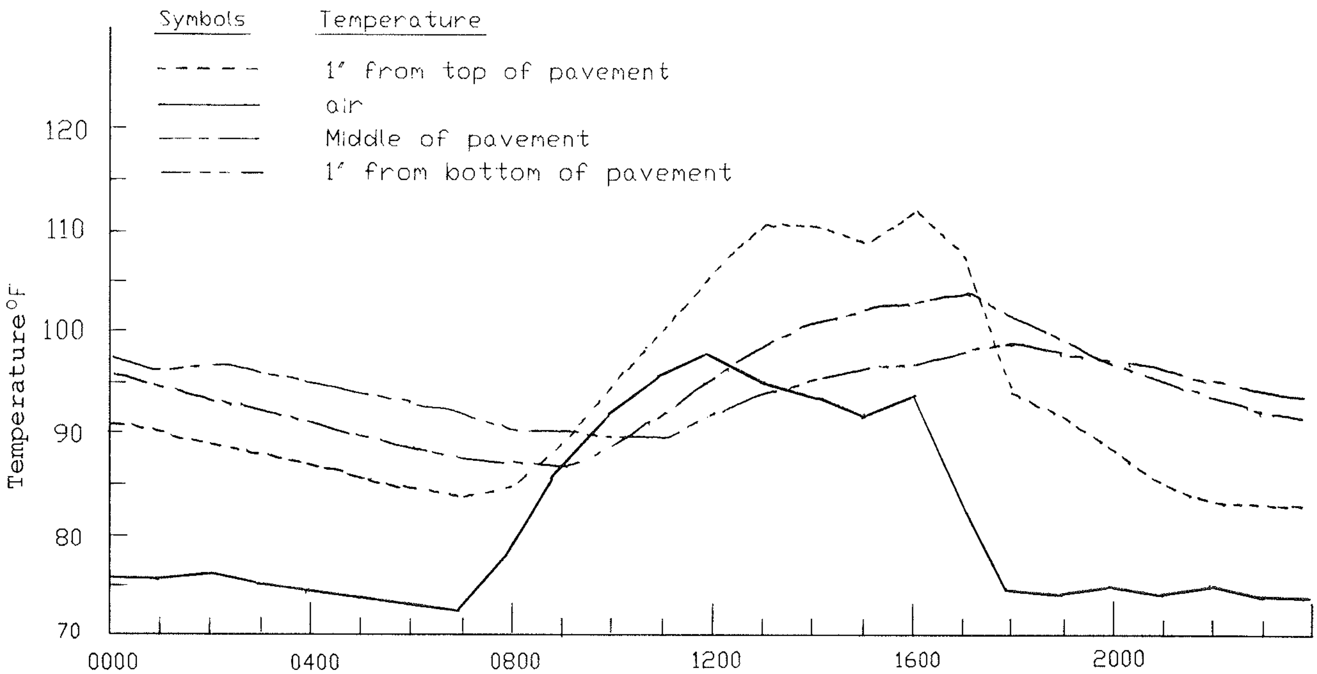

FIGURE 6 Temperature distribution for August 15, 1984.

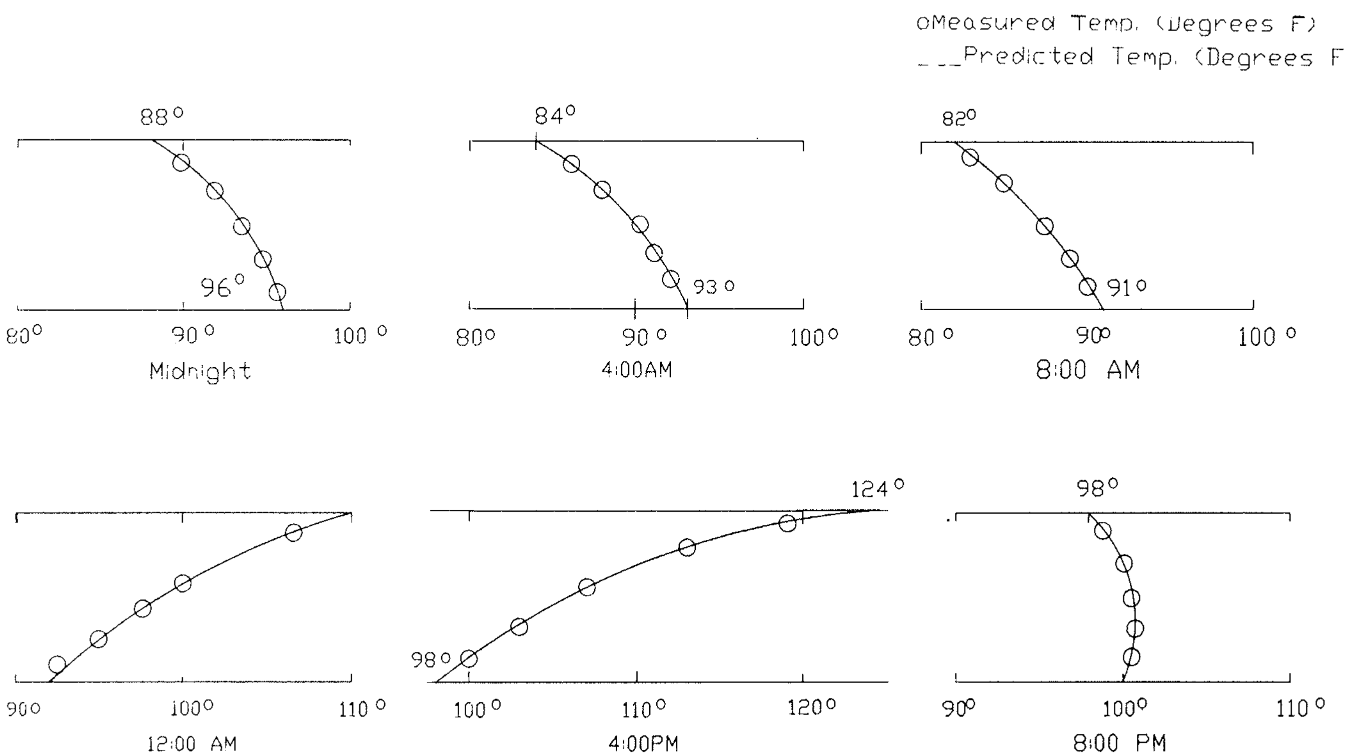

FIGURE 7 Temperature gradient at 4-hr intervals for August 14, 1984.

CONCLUSIONS

The following conclusions were drawn:

1. The maximum compressive stress due to the nonlinearity of the temperature gradient, and which is independent of the slab restraints, was found to be 113 psi and to occur at 1:00 p.m. EDT. This stress is not significant compared with the 5,000-psi compressive strength of the concrete. In addition, this stress occurs in the top and bottom of pavement and actually aids in the carrying of loads that cause flexural stresses in the pavement.

2. The maximum tensile stress due to the nonlinearity of the temperature gradient was found to be 113 psi and to occur at 6:00 p.m. EDT. The flexural strength (modulus of rupture = *R*) of a beam cut from the section of highway experiencing the premature failure was 671 psi with a corresponding core