THERMAL EFFECTS DURING THE CURING OF CONCRETE PAVEMENTS AND BRIDGE DECKS

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Final Report

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Final Report to UTRC
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CONTENTS

Abstract

This project will use fundamental heat and mass transfer principles to predict the temperature. water content. and unreacted cement profiles that exist during the first 72 hours of curing in concrete pavements and bridge decks. The goal of the project is to determine under what conditions concrete can be successfully placed. All pertinent heat and mass transfer mechanisms will be considered. A two-dimensional model of a bridge deck will be developed and model results will be compared with actual experimental data. Traditional concrete and concrete containing flyash and microsilica additives will be considered. Where possible, the information from this program will be used to calculate the thermal stresses in the concrete.

I. Introduction and Background

It has long been known that the life expectancy of concrete pavements. roadways. and bridge decks depends upon how the concrete composing these structures is cured. If concrete is allowed to freeze during the early curing stage, liquid water will not be available to fuel the hydration reactions and strength development in the concrete will cease. When the water thaws, strength development may continue. but if much of the frozen water sublimates or if multiple freeze-thaw cycles occur. the concrete may never develop its full strength. Moreover. as the water expands during freezing, it may introduce irreparable stress fractures. If the concrete is allowed to reach excessive temperatures in its interior during the cure, the hydration and condensation reactions are uncontrolled, thermal stresses may get too high, and the material may never develop its rated strength. To insure the viability of concrete structures. state and federal specifications regulate how the concrete is to be formed from its constituent components, how the concrete is to be mixed, how long it can remain in the mixer before being placed, and under what environmental conditions it can be placed [1.2]. Nearly all these specifications are based on an enormous body of construction experience. To a lesser extent, well-controlled experiments have also played their part. These experiments cannot cover every possible set of conditions. It would be advantageous to have models or correlations that could be used to estimate the state of concrete at any time during the curing cycle as a function of the environmental conditions that exist during the cure.

Although there has been much theoretical and experimental work regarding the chemistry of cement and the material properties of various mixtures of concrete [3-13],there has been little work done regarding the effect of curing conditions on concrete pavements. A number of well-controlled experiments have been performed considering the effects of curing temperature, humidity, and composition of the concrete [3,4,5,6,8,9,12]. These experiments do provide useful background information but many are not directed toward a fundamental understanding of the chemical and physical changes occurring and so the data they provide is of limited usefulness. Actual construction projects cure concrete under uncontrolled conditions. and the concrete is subject to many environmental changes on its way to becoming a solid substance. Assessing the state of the concrete during the cure is still more of an art than science.

The importance of curing conditions and the state of the concrete during the cure has led to a wide body of literature documenting construction experience. In the past one developed a "feel" for concrete by reading through the collected experiences of others and working on actual construction projects. It is only recently that researchers have begun to apply transport phenomena principles to predict the temperature and the water fraction in concrete over time (the state of the concrete). Most of this work concerns fully cured concrete systems [14-19]. The goal was to predict the temperature of concrete pavements and bridge decks exposed to different environmental conditions. The researchers considered diurnal and seasonal variations in absorbed solar radiation, changes in convective heat transfer as a function of variable wind speeds. and changes in conductive heat transfer as a function of roadway construction (slab thickness, bed condition and composition. etc.). There have been some more sophisticated models such as the Climatic-Materials-Structural (CMS) Pavement Analysis Program from the University of Illinois [14] which also included mass transfer effects and attempted to simulate how much water the concrete would absorb and whether that water would freeze and crack the material. A lesser amount of work has been devoted to predicting mass and heat transfer during the curing stage. Though the CMS model claimed to be able to predict these effects, it has never been implemented for such a task.

Recently. a report from the Strategic Highway Research Board (SHFP-C/FR-92-101) was issued that considers the thermal effects in concrete pavements during curing and specifies standard conditions under which concrete may be successfully placed [20]. This work represented a significant modeling effort. but suffered from a number of problems. The first problem was that the model formulation was nearly impossible to follow due to its non-standard construction. The governing balance equations and boundary conditions were ambiguously specified. Secondly, the model results were presented in a tabular format consisting of a set of acronyms stating either "yes, the cement can be placed' or "no. the cement cannot be placed." These results were generated for a certain set of conditions. but did not cover all relevant conditions. The program is not available to fill in the published tables. The third problem was that the model did not consider the effects of mass transfer. Heat removal by the evaporation of water was not included. The large heat of vaporization of water makes evaporation a significant heat transfer mechanism. Finally, the model only considered a concrete pavement slab. It did not address different roadbed materials nor was it applicable for the bridge deck problem.

It is clear that to be a useful tool, the transport model for thermal and mass transfer effects must be reformulated in a way suitable for field engineers and in a way that includes all pertinent heat transfer mechanisms. Since most new concrete pavement construction includes bridge decks, this model must be extended to account for the different geometry and processing conditions associated with bridge deck construction.

II. Experimental Results

The experiments to be conducted this year included measurements on a bridge deck placement over the Mourningkill in Saratoga County. Temperature profiles, wind speeds. net radiation fluxes, relative humidities. and ambinet temperatures were measured both above and below the bridge deck. Figures 1-8 present these results. All measurements were made by the SUNY Albany Atmospheric Sciences Department. Due to a thunderstorm, there was a measurement blackout from 33 to 48 hrs in all the data.

The most interesting aspect of the data is the difference in temperature profiles between the two positions. Above the support beam temperatures are noticably cooler reflecting the fact that the supports act as heat transfer fins removing more heat from the sections directly above them. The relatively low thermal conductivity of the concrete prevents the cooling process to extend much beyond the area immediately above the support beams.

III. Modeling Results

Following the success of the 1-D model (Appendix I) we developed to predict profiles in concrete pavements. we turned to developing a 2-D model for the bridge deck system. The simplified deck structure used in the model is shown below in Figure 1. This figure also shows the important heat and mass transfer mechanisms incorporated in the model. We use a finite element formulation so that the geometry can be easily changed if we find that our simplified description is not accurate enough. The details of the 2-D model were based on the 1-D formulation and the 2-D model used the same basic set of equations describing the temperature profile. the water content. and the reaction of cement.

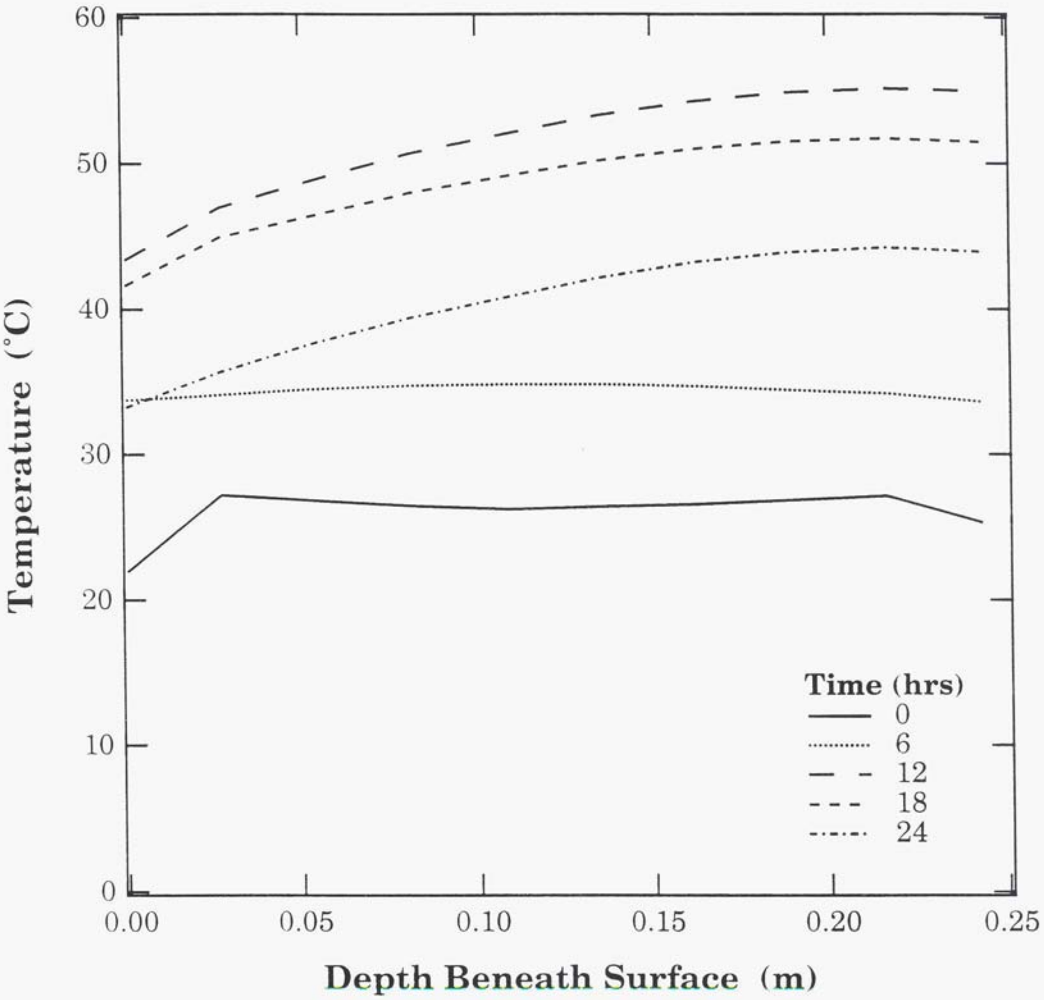

Figure 1 Temperature profile between support beams for the first 24 hrs.

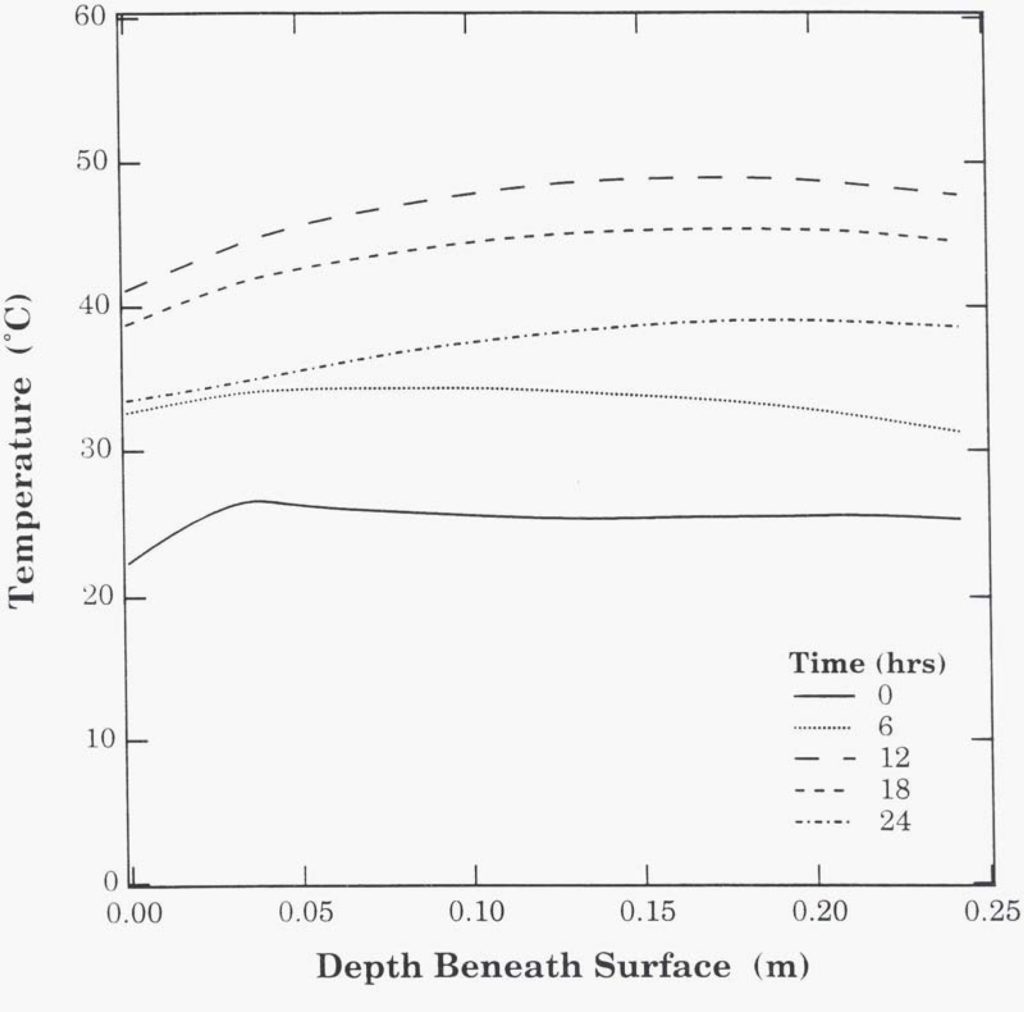

Figure 2 Temperature profile above support beam for the first 24 hrs.

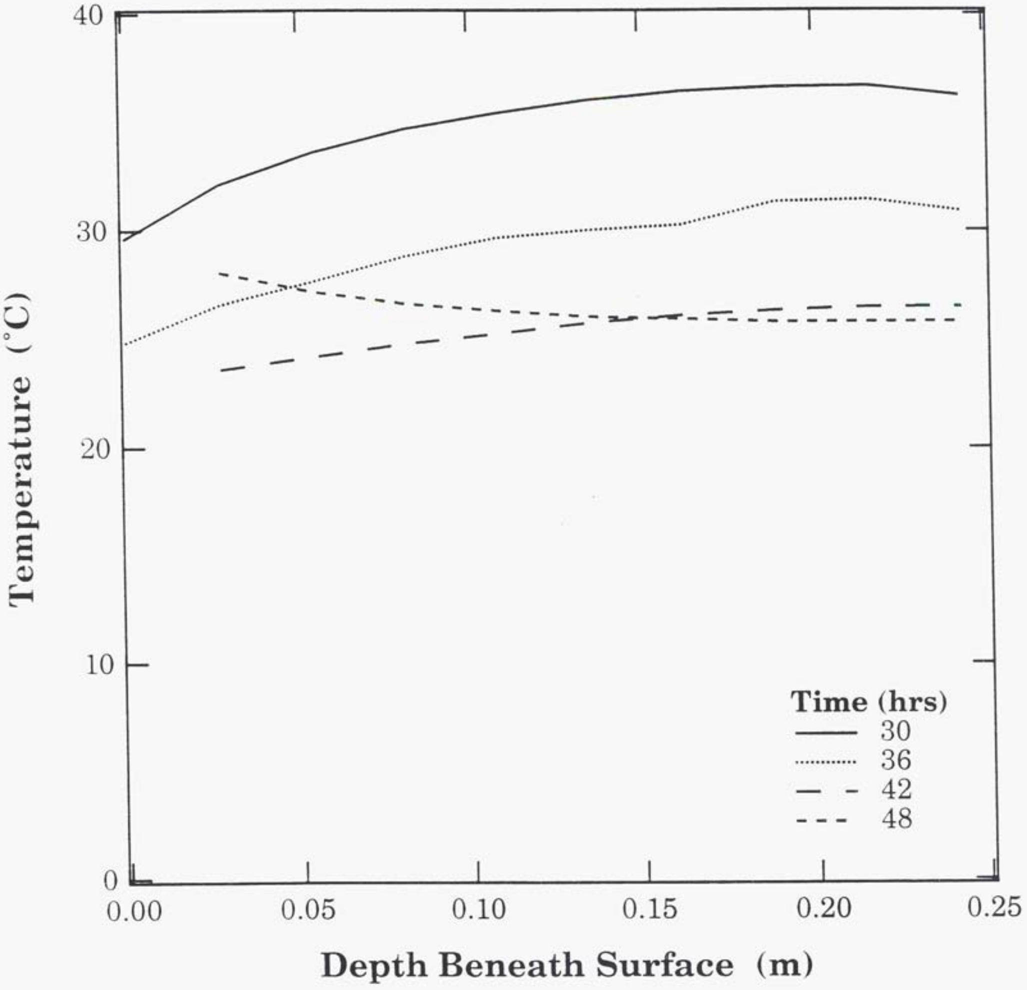

Figure 3 Temperature profile between support beams for the second 24 hrs.

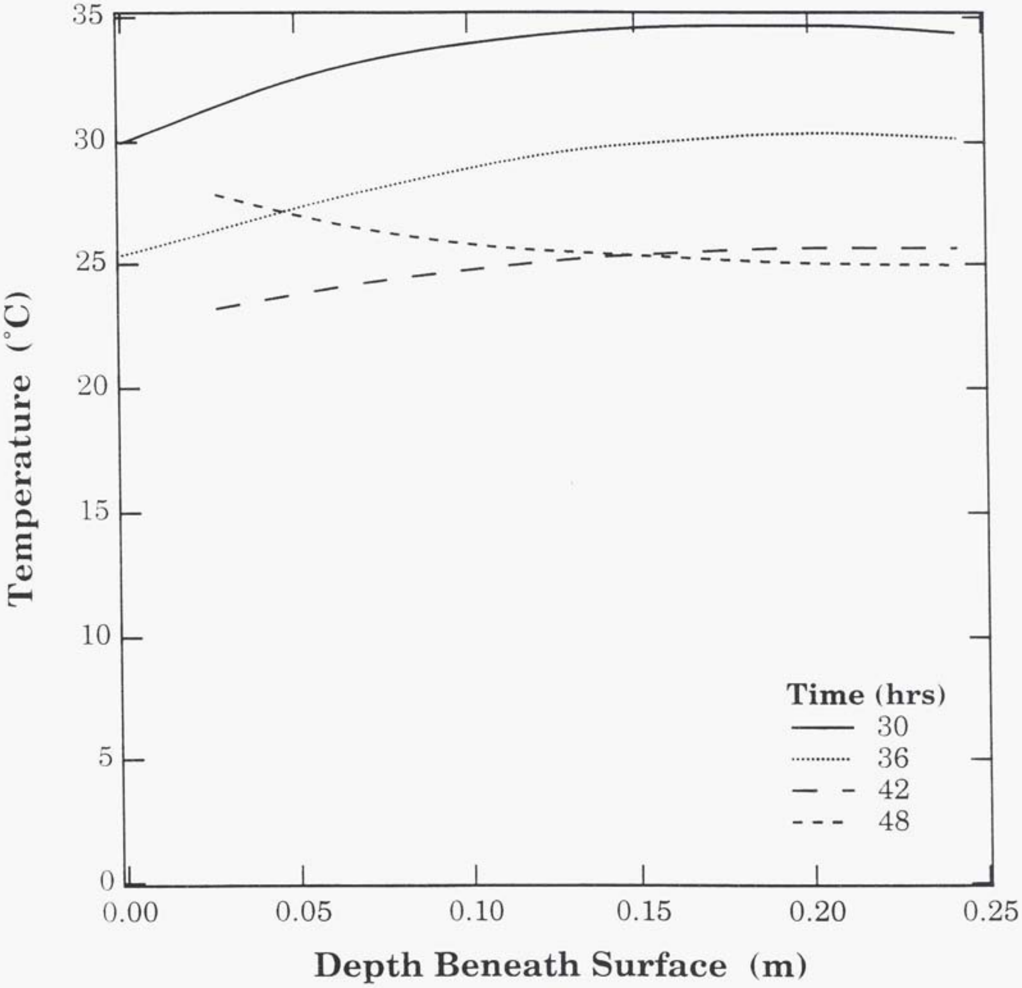

Figure 4 Temperature profile above support beam for the second 24 hrs.

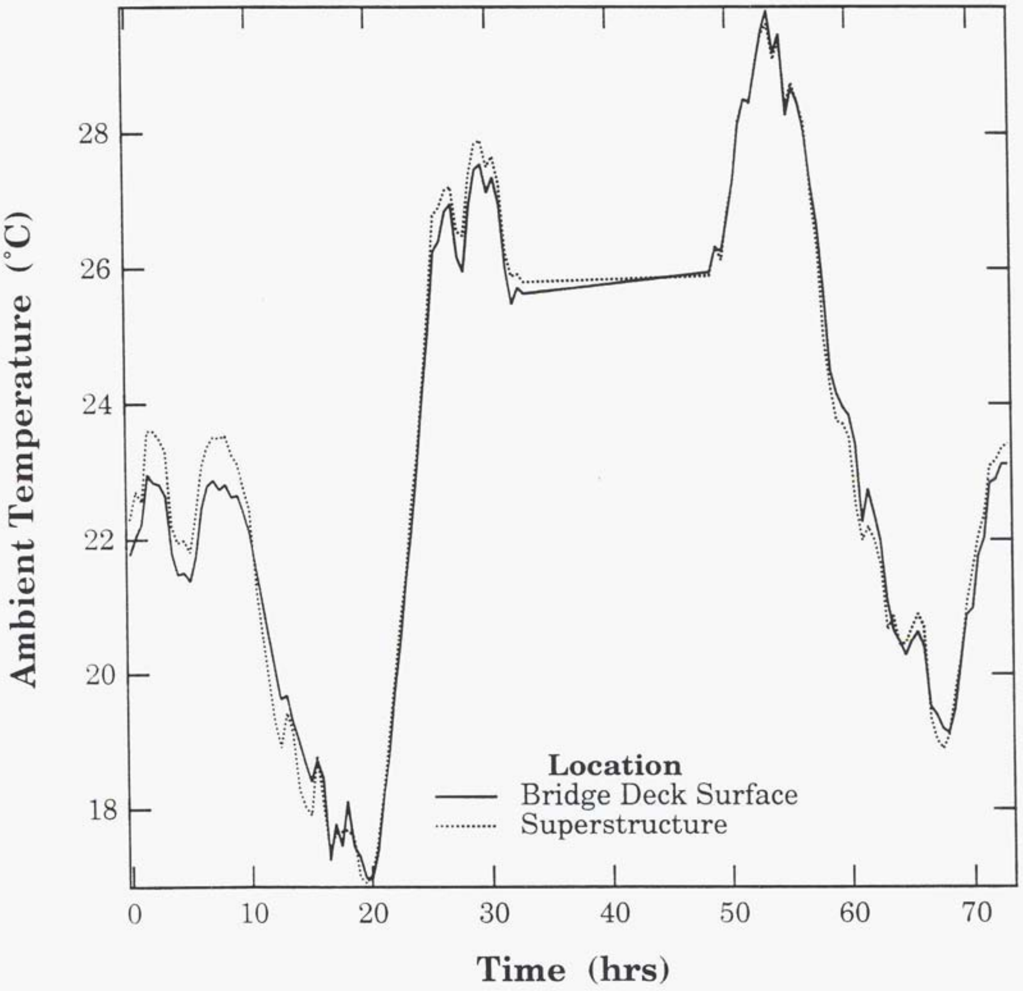

Figure 5 Ambient temperatures above and below the bridge deck.

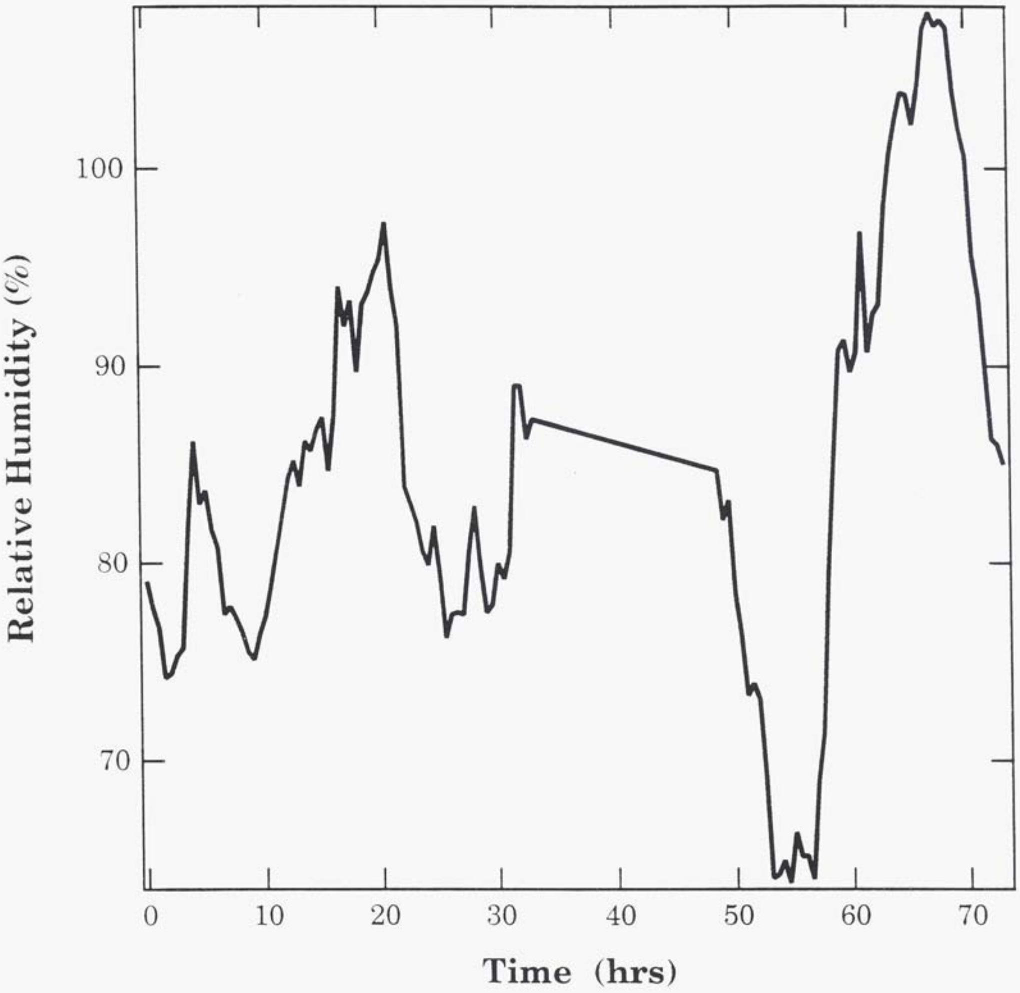

Figure 6 Relative humidity at the surface of the bridge deck.

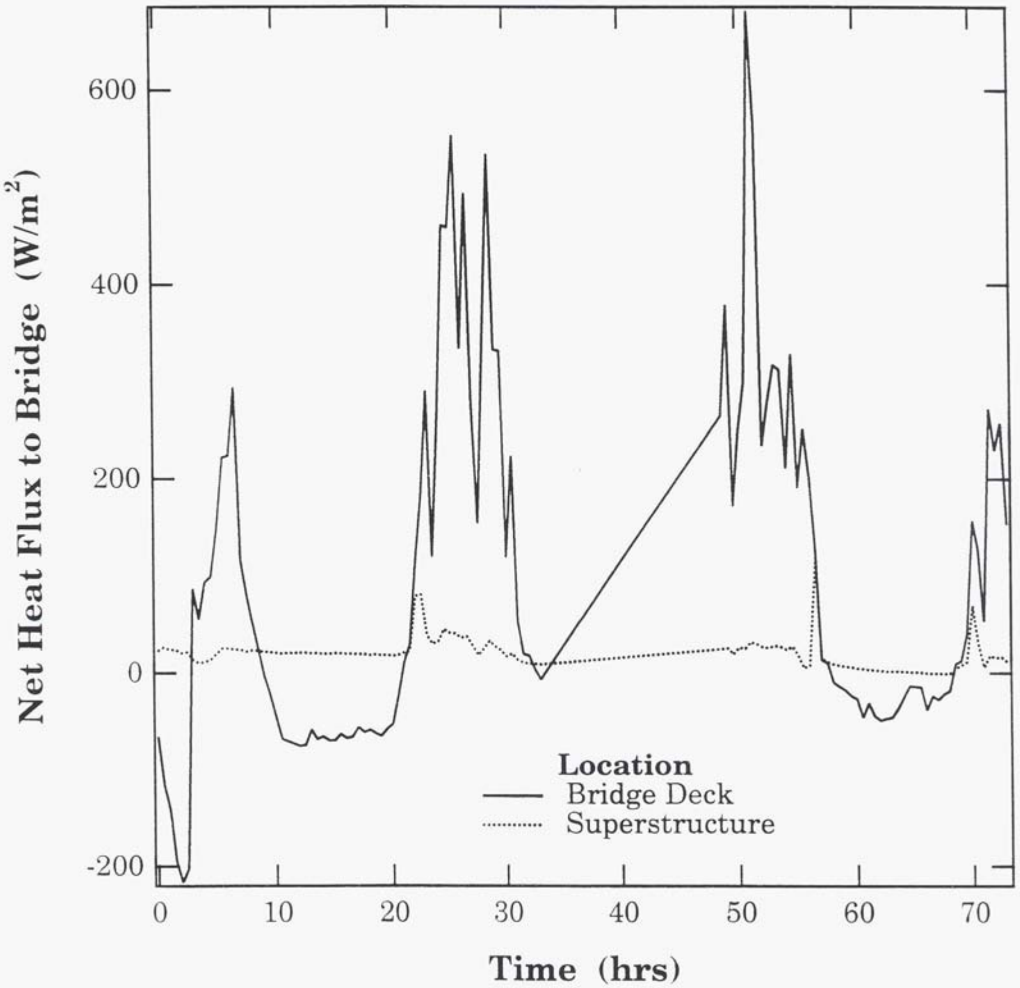

Figure 7 Net heat flux due to radiation above and below the bridge deck.

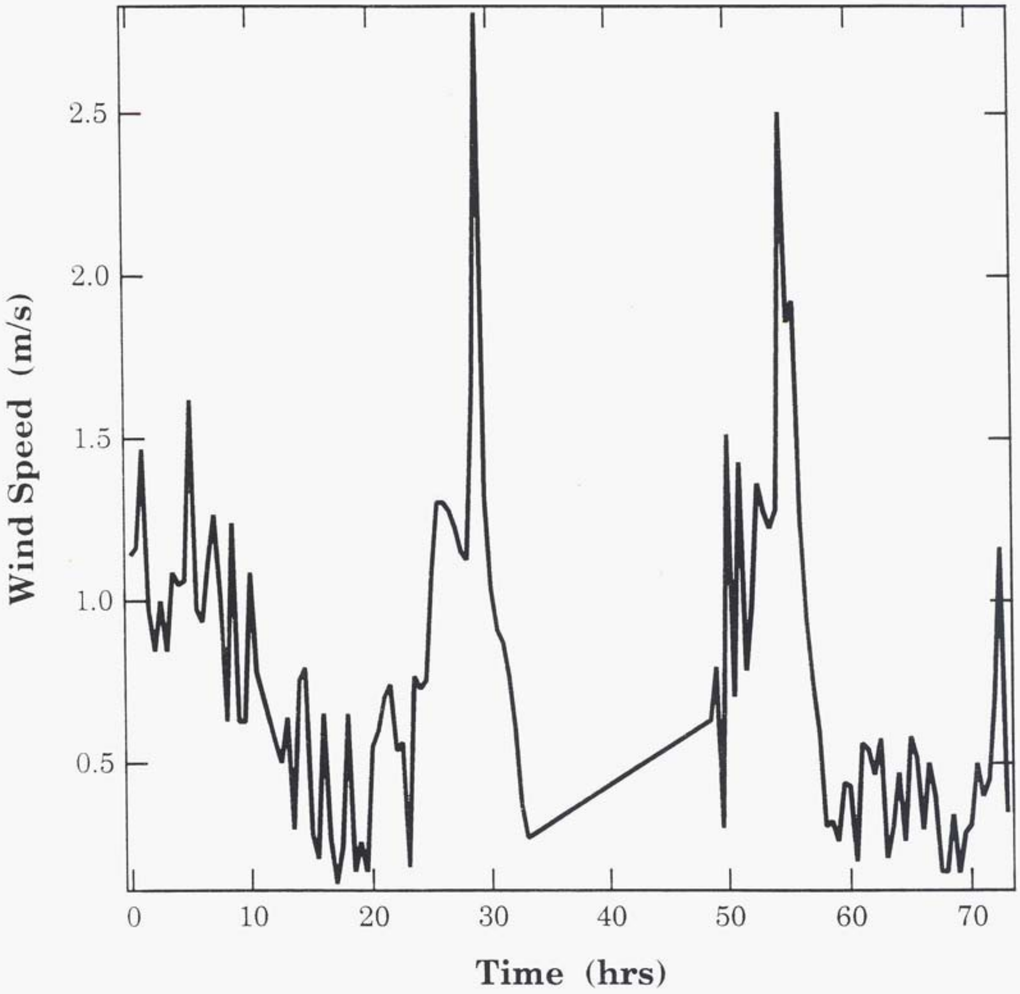

Figure 8 Windspeed at the surface of the bridge deck.

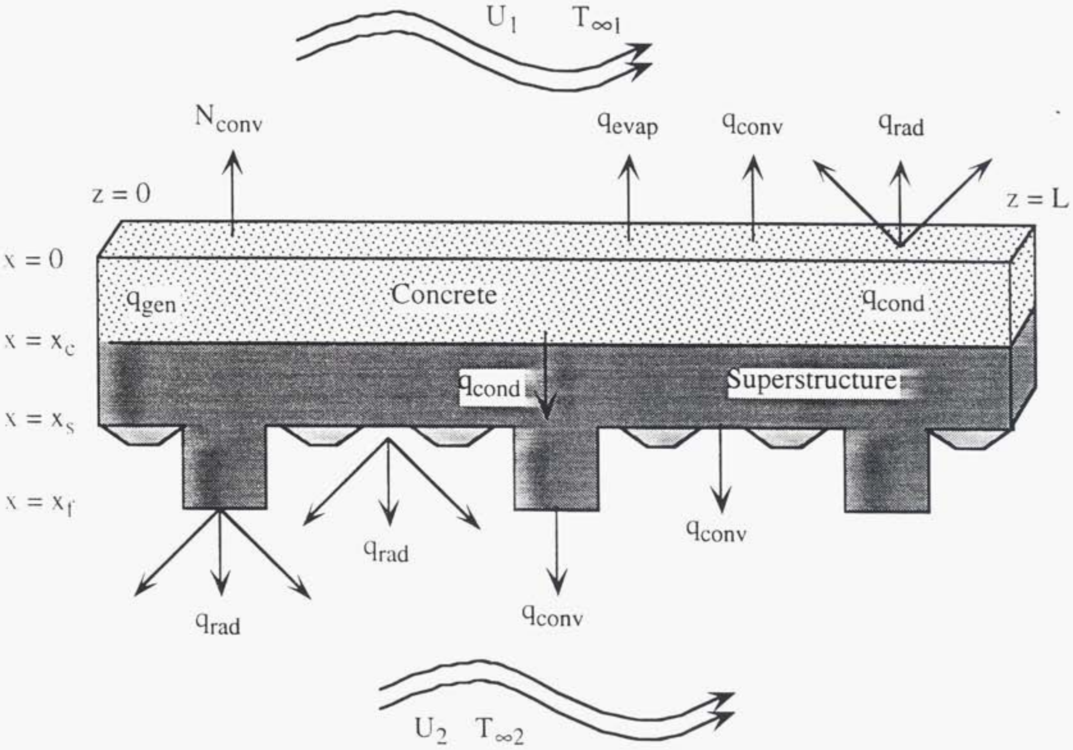

Figure 9 Standard, single-span, bridge deck with associated heat and mass transfer mechanisms.

The governing equations and associated boundary conditions were written as follows:

Concrete (c) layer:

$$\frac{\partial T_c}{\partial t} = \alpha_c\left(\frac{\partial^2 T_c}{\partial x^2} + \frac{\partial^2 T_c}{\partial z^2}\right) + \frac{(-\Delta H)k''C^2 y_{wc} y_{cem}}{\rho_c C_{p_c}} \tag{1}$$

$$\frac{\partial y_{wc}}{\partial t} = \frac{\partial}{\partial x}\left(\frac{D_{wc}}{1-y_{wc}}\frac{\partial y_{wc}}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{D_{wc}}{1-y_{wc}}\frac{\partial y_{wc}}{\partial z}\right) - k''\xi C y_{wc} y_{cem} \tag{2}$$

$$\frac{d y_{cem}}{dt} = -k''C y_{wc} y_{cem} \tag{3}$$

Superstructure (s) layer:

$$\frac{\partial T_s}{\partial t} = \alpha_s\left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial z^2}\right) \tag{4}$$

Boundary Conditions

At $x = 0$, y_{wc} = constant

$$-k_c \frac{\partial T_c}{\partial x} = \sigma\varepsilon T_c^{\,4} + h\left(T_c - T_\infty\right) + h_{vap}k_m\left(\frac{P^{sat}}{1\,atm} - y_{w\infty}\right) - \alpha_a\left(G_{dir} + G_{diff}\right) \qquad (5)$$

$$\text{At } x = x_c: \qquad T_c = T_s; \qquad k_c\frac{\partial T_c}{\partial x} = k_s\frac{\partial T_s}{\partial x} \qquad (6)$$

$$\text{At } x = x_s \qquad -k_s\frac{\partial T_s}{\partial x} = \sigma\varepsilon T_s^{\,4} + h_s\left(T_s - T_\infty\right) - \alpha_a G_{diff} \qquad (7)$$

$$\text{At } z = 0;\ z = L: \qquad \frac{\partial T_s}{\partial z} = 0; \qquad \frac{\partial T_c}{\partial z} = 0; \qquad \frac{\partial y_{wc}}{\partial z} = 0 \qquad (8)$$

We assumed in our boundary conditions at $z = 0, L$ that the sides of the deck are insulated and so allow no flow of heat or mass through them. The system was cut in half due to symmetry so that only one half of the bridge deck need be simulated.

We used the Galerkin formulation and the finite element method to solve the set of equations. The computer program includes automatic mesh generation and mesh renumbering so that changes in geometry are easily incorporated and the matrix of equations is as compact as possible.

The modeling work concentrated on developing 2-D model simulations corresponding to an experimental system that consisted of an actual bridge deck placement over the Mourninglull in Saratoga County. Since the support structure of the bridge consisted of steel beams we needed to include those in the model. Their dimensions are such that it would be impractical to mesh the beams themselves and so we modeled those beams as infinite fins. We could then calculate the heat loss from those fins and incorporate those losses as boundary conditions within our model. All other convective and radiative interactions with the environment were accounted for.

The simulations were based on using the same concrete parameters we used for our pavement work. This is not strictly valid since high performance concrete containing a significant quantity of flyash was used in this bridge deck. The flyash alters the reaction rate and the heat evolved and we are still searching for reliable data for both accounts. Figures 11-14 show the temperature profiles within the deck over a 48 hrs period in twelve hour intervals. We can see the initial rise in temperature and the falloff that occurs as the cement reaction proceeds. We also pick up the effect of the support beams and their increased heat transfer in the region directly above them. In this simulation we incorporated the experimental data recorded at the Mourningkill into our calculations. The data was smoothed and fit to fourth oder polynomials for each 12 hrs period. Unfortunately. due to storms. we had a blackout period in the data between 33 and 48 hrs that makes some of our later predictions a bit more suspect. However, a preliminary comparison with the data shows that we are in the right ballpark and need some minor improvements in the reaction rate and heat evolved to get a better representation to reality. As soon as we obtain more reliable data on the effect of flyash on the reaction rate and heat evolution we will incorporate that into the model. We have some recent data on the thermal conductivity of concrete as it cures and will include this in the model as well.

Next year we plan to run some further experiments with NYDOT's new bridge deck composition incorporating flyash and microsilica. This will entail further modifications to the model and a search for more data on how microsilica dn flyash affect the reaction rate and heat evolution in the concrete.

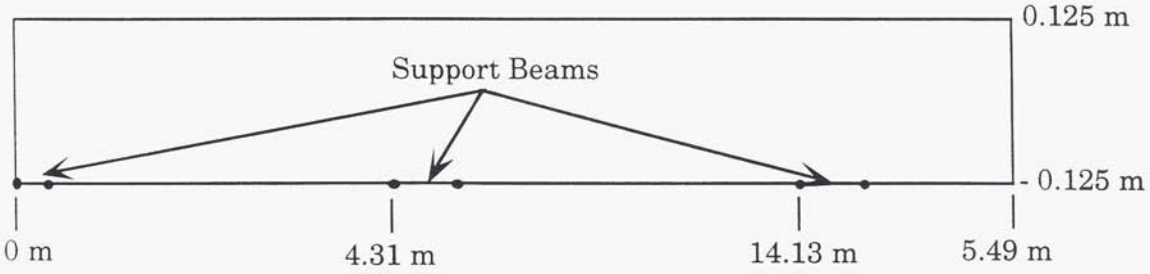

Figure 10 Actual bridge deck design. Figure shows the location of the support beams. In figures 11 - 14 the length coordinate has been shifted by 4 meters.

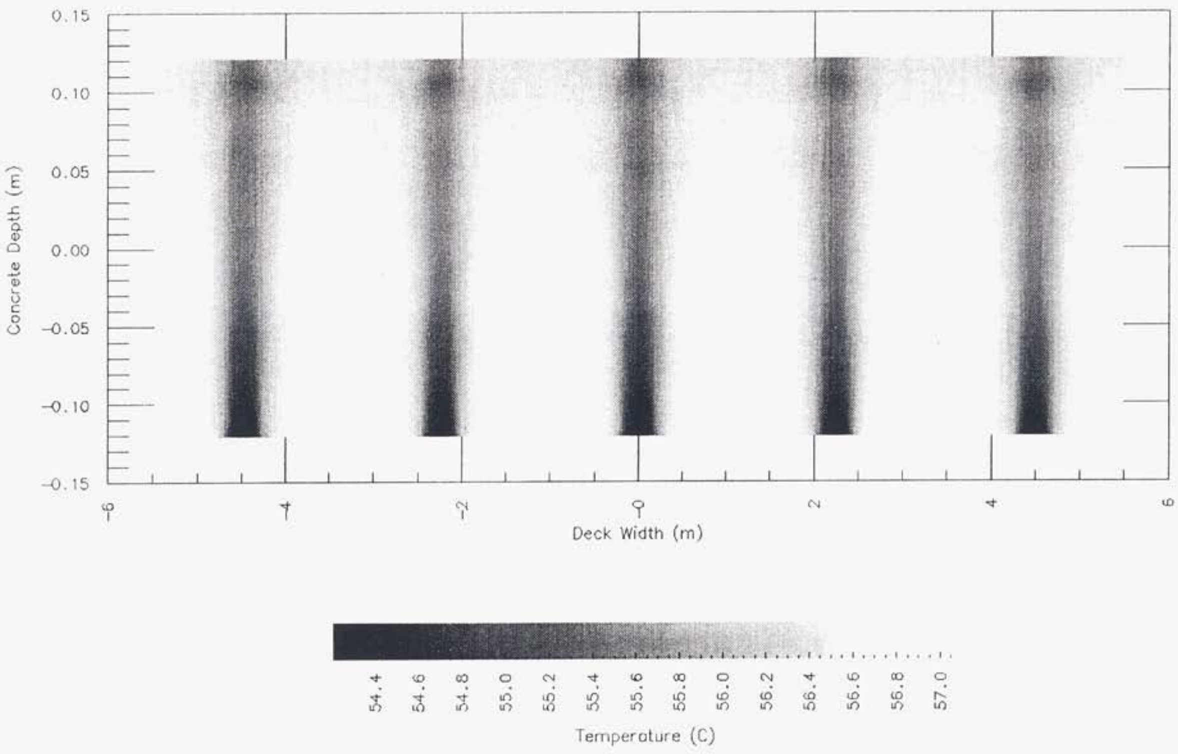

Figure 11a Temperature profile in the bridge deck at 12 hrs. Parameters were set to match the experimental temperature at this time.

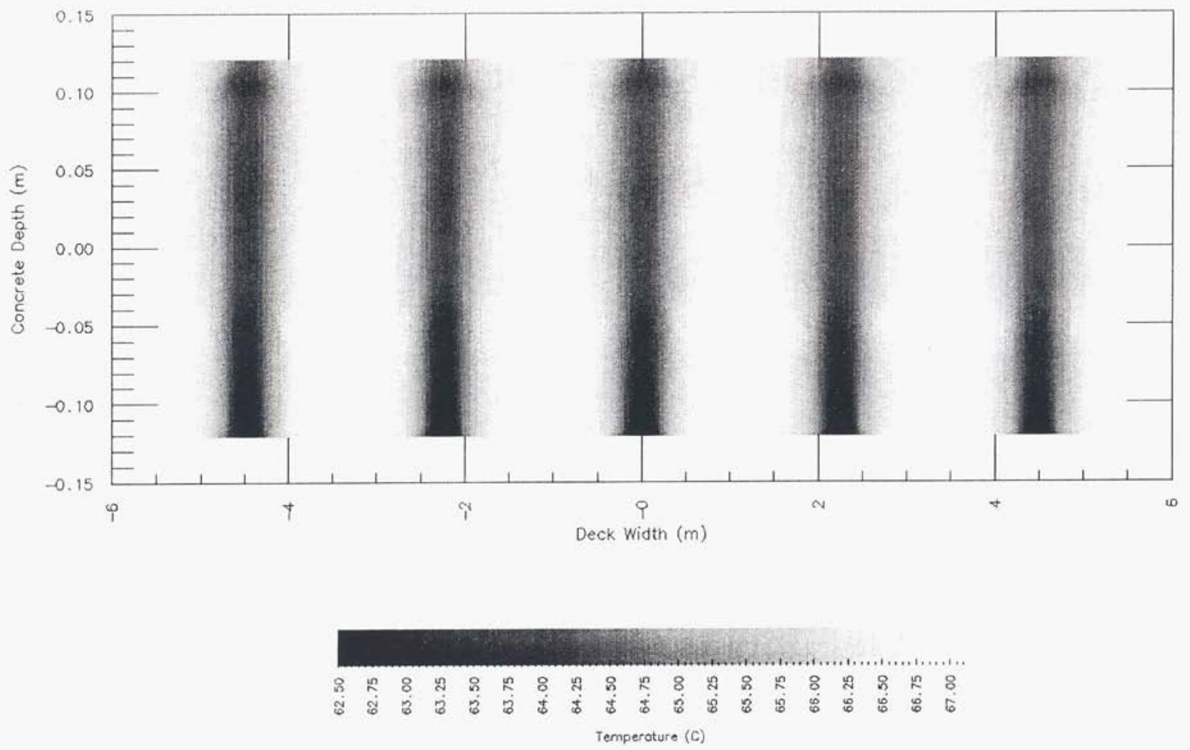

Figure 11b Temperature profile in the bridge deck at 24 hrs. Temperature keeps rising in disagreement with experimental data. We had no measurement of cooling water rate to assist us in determining the heat removal rate from the upper surface. Better kinetic data for flyash is needed.

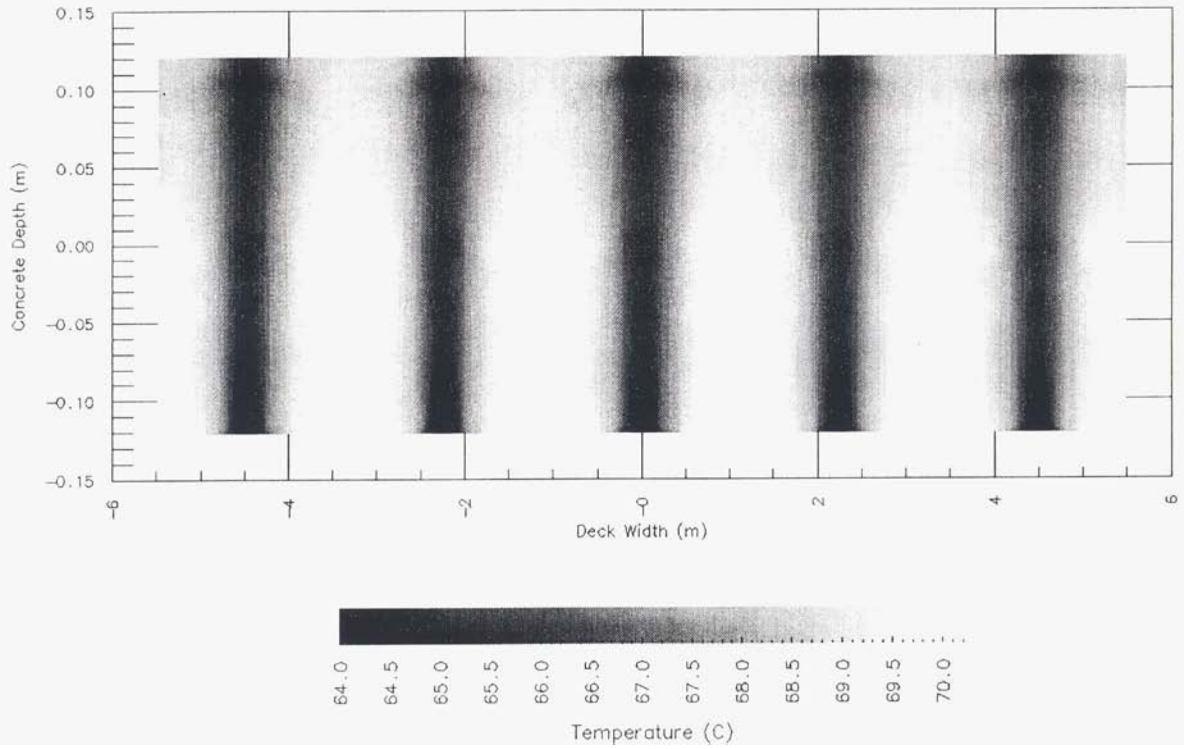

Figure 11c Temperature profile in the bridge deck at 36 hrs. Temperature has begun to stabilize as reaction dies off.

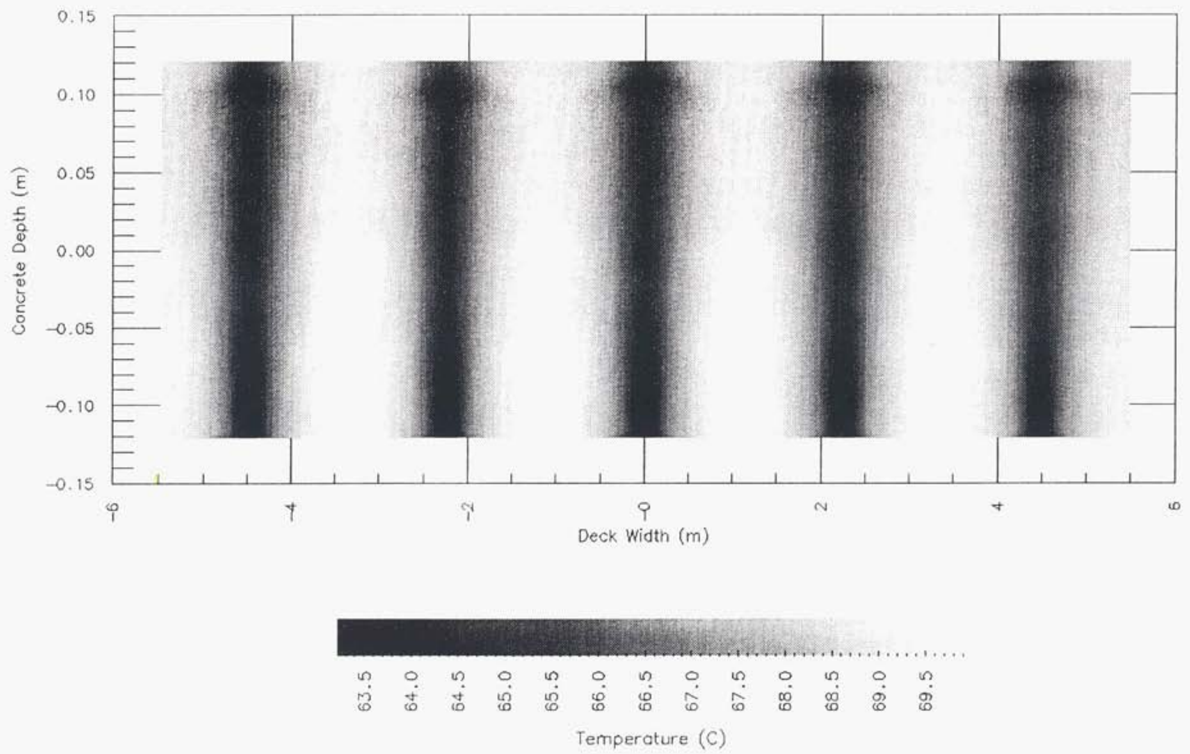

Figure 11d Temperature profile in the bridge deck at 48 hrs. Temperature begins to drop as reaction dies off and heat removal rate is greater than generation rate.

IV. Nomenclature

A_f - surface area of the bridge deck superstructure lying underneath the fins (m^2)
A_s - surface area of the flat portion of the bridge deck superstructure (m^2)
C - total concentration of all species (mol/m^3)
C_p - heat capacity of the concrete (J/kgK)
D_w - diffusivity of water (m^2/s)
k'' - reaction rate constant ($m^6/mol\ s$)
L - road width
N_{conv} - molar flux of water from concrete due to convection (mol/m^2s)
N_{diff} - molar flux of water through concrete due to diffusion (mol/m^2s)
N_{rxn} - molar flux of water in concrete due to reaction (mol/m^2s)
p^{sat} - vapor pressure of water (N/m^2)
q_{cond} - heat flow due to conduction (W)
q_{conv} - heat flow due to convection (W)
q_{evap} - heat flow due to water evaporation (W)
q_{gen} - heat generated by chemical reaction in the concrete (W)
q_{rad} - heat flow due to radiative transfer (W)
q_s - radiative heat fow from the concrete (W)
q_{sky} - radiation heat flow to concrete from the sky (W)
q_{sun} - radiative heat flow to concrete from the sun (W)
r - overall reaction rate (mol/s)
T - temperature (K)
t - time (s)
U - air velocity (m/s)
x - depth coordinate in concrete (m)
y_{cem} - mole fraction of cement
y_w - mole fraction of water in the concrete

Greek

α - thermal diffusivity (m^2/s)
α_a - absorption coefficient
ε_s - emissivity of concrete surface
σ - Stefan-Boltzmann constant (W/m^2K^4)

Subscripts

c - concrete
g - ground
ref - reference
s - sublayer
∞ - ambient value

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