CONCRETE TEMPERATURE MODELING AND STRENGTH PREDICTION USING MATURITY CONCEPTS IN THE FHWA HIPERPAV SOFTWARE

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ABSTRACT

HIPERPAV (HIgh PERformance concrete PAVing) is a concrete paving software product sponsored by the FHWA intended to serve as a tool in the proper selection and control of the factors affecting concrete pavement behavior at early ages. This paper serves to describe two key components of the HIPERPAV system. The first is the core concrete temperature prediction model, which consists of a transient two-dimensional finite-element model. This model includes the effects of thermal conduction, convection, solar radiation, irradiation, and the heat of hydration of the cementitious materials. The second topic of this paper is the concrete strength development model, which is based on the equivalent age maturity concept. This model allows for an accurate prediction of the strength development in the concrete during the early-age period.

INTRODUCTION

Background

Concrete pavement early-age behavior is primarily influenced by temperature and moisture variations. Fluctuations in temperature and moisture produce expansion and contraction movements in the concrete pavement that are restrained by the subbase and the slab weight. The mix placement and curing temperatures affect the concrete's rate of hydration and heat liberation. As a result, the development of concrete properties are different from the standard lab curing conditions. In the field, stresses are generated that can significantly affect the pavement's performance in the long term. Thus, predicting the magnitude of these temperature and moisture changes is essential in understanding the pavement's early-age behavior.

Objectives

Prediction of the pavement temperature at early ages is the main focus of this paper. Models for predicting temperature of concrete structures have been previously developed. However, the relevance of this paper strives in presenting an innovative model for prediction of temperature in concrete pavements by selection of the appropriate boundary conditions. In addition, a recent field validation of this temperature model is presented. Finally, a number of applications where prediction of the concrete pavement temperature is of interest are described.

CONCRETE TEMPERATURE PREDICTION

Cement Hydration

The hydration reaction of cement is an exothermic process, in which heat is liberated during the reaction of the cementitious materials with water. There are a number of factors that affect the hydration of the cement, and the interactions of all these factors are quite complex. Most of the factors that influence the hydration process will also influence the rate of heat development, and need to be accounted for in any mechanistic modeling procedure. The influencing factors considered in the HIPERPAV temperature model are as follows: amount and type of cement (composition), water/cement ratio, admixtures, placement and curing temperatures, thermal characteristics of the concrete (transmissivity and specific heat), thickness of the section, and the pavement boundary conditions.

Temperature development in concrete due to hydration and ambient temperature conditions can be determined from the general differential equation for heat transfer. The governing model of heat transfer in two dimensions can be expressed as follows [1]:

$$k_x \bullet \frac{d^2T}{dx^2} + k_y \bullet \frac{d^2T}{dy^2} + Q_h(t,T) = \rho \bullet C_p \bullet \frac{dT}{dt} \quad (1)$$

where,

- k_x,k_y = thermal conductivities of concrete (W/m/°C),
- ρ = concrete density (kg/m³),
- C_p = specific heat (J/kg/°C),
- Q_h = generated heat (cement hydration and external sources) (W/m³),
- T = nodal temperature (°C), and
- t = time (seconds).

The heat of hydration of the maturing concrete is characterized by the Q_h term in Equation 1. The heat of hydration is the amount of heat that is released into the system due to the hydration processes of the cementitious materials. It is mathematically defined as follows [2]:

$$Q_h = H_u C \psi \frac{\lambda_1 \kappa_1}{t_1} \bullet \frac{\left[\ln(\tau)\right]^{-(1+\kappa_1)}}{\tau} \bullet e^{\left[-\frac{\Phi}{R}\left(\frac{1}{T+273}-\frac{1}{T_r+273}\right)\right]} \quad (2)$$

where,

H_u = total heat of hydration (J/g),
C = cementitious materials content (g/cm²),
λ_1 , κ_1 = adiabatic hydration shape parameters,
t_1 = adiabatic time parameter (hour),
τ = age parameter, defined as: $1 + t_e/t_1$ (3)
ψ = degree of hydration, defined as: $e^{-\lambda_1(\ln\tau)^{-\kappa_1}}$ (4)
t_e = equivalent age at the reference curing temperature, defined as [3]:

$$t_e = \sum_{t=0}^{age}\left[e^{\left[-\frac{\Phi}{R}\left(\frac{1}{T+273}-\frac{1}{T_r+273}\right)\right]} \bullet \Delta t \right] \quad (5)$$

Φ = activating energy (J/mol),
R = universal gas constant (8.3144 J/mol/°C),
T = nodal temperature (°C), and
T_r = reference temperature, 20°C.

The degree of hydration is a measure of the quantity of the hydration products formed, which is also related to the growth of strength. Byfors presented data that showed that a linear relationship exists, for the most part, between the growth of compressive strength and the degree of hydration [2]. The degree of hydration is a function of the equivalent age, as shown in Equation 5, with ψ varying between 0.0 at the start of hydration, and 1.0 when hydration is fully completed.

The rate of cement hydration and the temperature development of a hydrating concrete mix is dependent upon a number of factors including the concrete temperature, cement composition and fineness, admixture type and quantity, aggregate types, and water/cement ratio. [4,5]. It is, therefore, rather complex to incorporate all these factors in a mechanistic hydration model in such a way that the temperature development can accurately be predicted. This problem is overcome by submitting the concrete to an experimental heat signature test, where there is no interchange of heat with the surroundings. The parameters λ_1, κ_1, and t_1 in Equation 4, which define the rate of heat evolution with progressive hydration for a specific concrete mixture are determined through such heat signature tests. In HIPERPAV, various adiabatic hydration curves are used to characterize the temperature generation as a function of the cement type and mineral admixtures used in the concrete.

The heat of hydration varies greatly with the cement composition. The quantities of C_3A and C_3S are primarily responsible for heat evolution at early ages. The four clinker minerals have different characteristics with regard to the development of heat. As a result, the total heat of hydration (H_u) can be estimated directly from the cement chemistry [6,7]. Each cement constituent has been found to have a unique heat of hydration. To estimate the total heat of hydration of cementitious materials, the percentage of the total mass of each constituent is multiplied by its individual heat of hydration.

Boundary Conditions

In concrete placed under field conditions, heat will be transferred to and from the surroundings. The temperature development in the concrete structure is, therefore, determined by the balance between heat generation in the concrete and heat exchange with the environment. Heat transfer with the surroundings may take place via four different mechanisms: conduction, convection, irradiation, and solar absorption. Figure 1 illustrates the exchange of heat in a pavement system. Factors considered for this purpose include conduction, convection, solar absorption, and irradiation. The models that will be used to characterize each of these factors are discussed below in more detail.

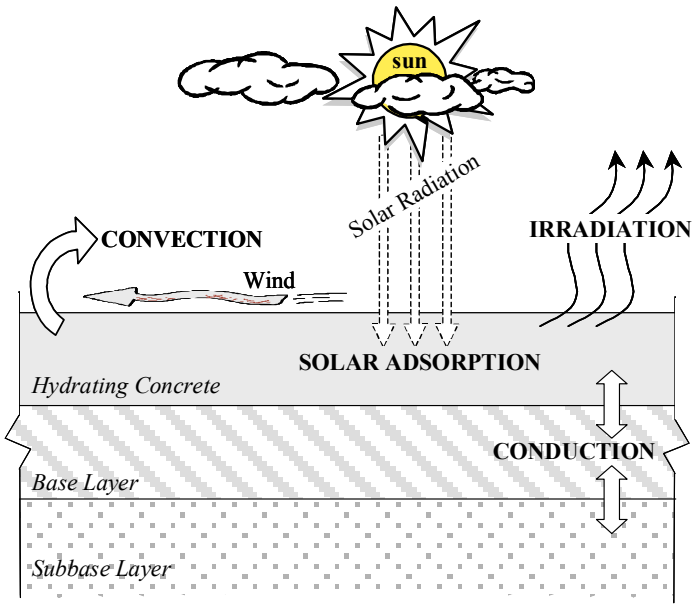


Figure 1: Heat transfer mechanisms between pavement and its surroundings

Conduction

Thermal conduction is defined as heat transport in a material by transfer of heat between portions of the material that are in direct contact with each other. In a pavement system, conduction occurs between the different pavement layers. Conduction also occurs at the interface between the concrete slab surface and the surface protection (insulation) used at early age. Typical insulation methods include plastic sheets, blankets, and urethane foams.

The governing equation for thermal conduction reveals that heat transfer is a function of the thermal conductivity, density, and specific heat of the materials in contact. Based on test data, it was shown that the average thermal conductivity of maturing concrete is between 33%[8] and 21%[9] higher than that of the hardened concrete. From this information, assuming that the decline in this parameter is linear with the degree of hydration, a relationship that considers these initial and final values could be expressed as:

$$k = k_{\infty}(1.33 - 0.33 \cdot \psi) \qquad (6)$$

where,

k = current thermal conductivity (W/m/ºC),
k_∞ = thermal conductivity of mature concrete (W/m/ºC), and
ψ = current degree of hydration.

The temperature and the thermal properties of the base underlying the concrete slab may have a significant influence on the temperature development of the hardening concrete. Table 1 provides typical thermal characteristics of some typical base materials:

Table 1: Thermal characteristics of various base materials [10, 11]

Base Material	Density (kg/m^3)	Thermal Conductivity (W/m/ºC)	Specific Heat (J/kg/ºC)
Gravel, dry	1703	0.52	838
Gravel, moist	1898	2.42	1047
Asphalt	2302	1.38	1047
Stabilized Base	2,339	3.32	1,005
Cohesive Subgrade	2,066	1.59	1,214

Conduction further transpires between the surface coverings of the concrete slab, commonly placed during construction. These include insulation blankets, curing compound, plastic sheets, urethane foams, closed cell polystyrene foam, and many other products. The steady-state heat transfer, excluding any radiation, can be expressed as follows [12]:

$$q = h_0 \cdot (T_s - T_a) \tag{7}$$

where,

q = Heat flux (W/m^2),
h_0 = overall heat transfer coefficient ($W/m^2/°C$),
T_s = surface temperature (°C), and
T_a = air temperature (°C).

Where more than one layer of insulation is used, the overall heat transfer coefficient can be calculated, which is a single coefficient that defines the thermal resistance of all the materials. The overall heat transfer coefficient can be calculated as follows [12]:

$$h_0 = \left(\frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots + \frac{d_n}{k_n} \right)^{-1} \tag{8}$$

where,

h_0 = overall heat transfer coefficient ($W/m^2/°C$),
$d_1, d_2, \ldots d_n$ = thickness of n successive layers (m), and
$k_1, k_2, \ldots k_n$ = thermal conductivity of n successive layers (W/m/ºC).

Convection

Thermal convection is the heat transferred from a surface to a fluid or gas, where convection is the movement of a mass of gas or liquid due to the temperature difference, and physical contact

of the gas or liquid is the actual method of heat transfer [12]. Convection is, therefore, the mechanism of heat transfer between the concrete surface and the environment. This is illustrated in Figure 1, via the effect of the wind. For pavements, wind velocity across the concrete surface determines whether convection is forced or free. In HIPERPAV, convective heat transfer is modeled through the use of the following equation [12]:

$$q_c = h_c \cdot (T_s - T_a) \tag{9}$$

where,

q_c = Heat transferred due to convection (W/m^2),
h_c = surface convection coefficient (W/m^2/°C),
T_s = surface temperature (°C), and
T_a = air temperature (°C).

The rate of heat flow from a horizontal surface is controlled by the magnitude of the temperature difference, the wind speed, and the surface texture of the member [12,13]. As heat is transferred from the warmer horizontal member to the adjacent air, the air is heated, its density decreases, and it tends to rise. As the heated air rises, it is replaced by cooler air that, in turn, is heated and rises. This is a continuous recurring process, repeating itself until the heat balance is eliminated. This complex phenomenon has been thoroughly investigated by numerous researches in the heat transfer field. From combinations of experimental work, a model is available for use on a smooth horizontal surface that is valid for both forced and free convection [13,14,15]. However, this model does not include any modification due to surface roughness and it is recommended that the surface convection coefficient above be increased by 6% to account for this effect [12]. Therefore, the following model is recommended for use in HIPERPAV:

$$h_c = 3.727 \cdot C \cdot \left(0.9 \cdot \left(T_s + T_a\right) + 32\right)^{-0.181} \cdot \left(T_s - T_a\right)^{0.266} \cdot \sqrt{1 + 2.857 \cdot w} \tag{10}$$

where,

h_c = surface convection coefficient (W/m^2/°C),
C = constant depending on the shape and heat flow condition,
1.79 for horizontal plates warmer than air,
0.89 for horizontal plates cooler than air,
T_s = surface temperature (°C),
T_a = air temperature (°C), and
w = wind speed (m/s).

As the heat transfer due to convection on the surface could occur simultaneously with the presence of surface insulations over the pavement top surface, the overall heat transfer coefficient has to be determined that includes both of these effects. Equation 8 can be modified to calculate the overall heat transfer coefficient as follows (with all parameters as defined elsewhere):

$$h_0 = \left(\frac{1}{h_c} + \frac{d_1}{k_1} + \frac{d_2}{k_2} + \ldots + \frac{d_n}{k_n} \right)^{-1} \tag{11}$$

Solar Absorption

Solar absorption or insolation, is the flux absorbed by the pavement surface through exposure to the incoming sunrays. In HIPERPAV, the following simplified equation for solar absorption is used:

$$q_s = \beta_\varepsilon \cdot q_{solar} \quad (12)$$

where,

q_s = solar absorption heat flux (W/m^2),
β_ε = solar absorptivity, and
q_{solar} = instantaneous solar radiation, (W/m^2) as defined in Table 2.

Table 2: Solar radiation values used in HIPERPAV (McCullough)

Sky Conditions	Solar Radiation, J, (W/m^2)
Sunny	1,000
Partly Cloudy	700
Cloudy (Overcast)	300

Note that in Table 2, the solar radiation is a function of the cloud cover, and even with an overcast sky some of the longer wavelengths can still penetrate the sky and be a source of heat. During nighttime, the solar radiation is negligible. The solar absorptivity of Portland cement concrete is a function of the surface color, with typical values ranging from 0.5 to 0.6. An ideal white-body would have a value of 0.0, and an ideal black-body would have a value of 1.0.

Irradiation

Irradiation heat transfer is accomplished by electromagnetic waves between a surface and its surroundings. The Stefan-Boltzmann law is commonly used for this type of heat transfer, which is defined as follows [13]:

$$q_r = \varepsilon \cdot \sigma \cdot (T_c^4 - T_\infty^4) \quad (13)$$

where,

q_r = heat flux of heat emission from the surface (W/m^2),
c = Stefan-Boltzmann radiation constant (5.67x10-8 W/m^2/°C^4),
ε = surface emissivity of concrete,
T_c = concrete surface temperature (°C), and
T_∞ = surrounding air temperature, (°C).

The surface emissivity is a function of the concrete surface color. An "idealized" black surface would have a value of 1.0. A value of 0.88 was selected for use in HIPERPAV [21]. However, note that in the above equation T_∞ is the temperature of the surrounding environment, and this value cannot arbitrarily be assumed to be equal to the ambient temperature. The following simplified equation is used in place of the original equation [16]:

$$q_r = \varepsilon \cdot [4.8 + 0.075 \cdot (T_a - 5)] \cdot (T_s - T_a) \quad (14)$$

where,

T_s = concrete surface temperature (°C), and
T_a = the air temperature (°C).

STRENGTH DEVELOPMENT PREDICTION

In this section, the equivalent age maturity method for prediction of strength development in the concrete pavement is described. However, before the prediction of strength can be made, the concrete set time has to be determined.

Concrete Set Time

Concrete set time is of great importance in the analysis of concrete pavement behavior at early ages. Set time is defined as the time the concrete transitions from a plastic material to a solid one. Before final set, it is assumed that no strength or stiffness have developed in the concrete, but thereafter the concrete's mechanical properties such as strength and stiffness develop. It is at this point that pavement stresses also develop as a function of temperature and moisture volumetric changes in the concrete that are restrained by subbase friction and the own weight of the slab.

It is known that set time is affected by the development of cement hydration. According to Byfors [2], final set occurs at a critical degree of hydration which is a function of the water-cement ratio and can be predicted with the following relationship:

$$\psi_{critical} = 0.40 \text{ to } 0.46 \times {}^{W}/_{CM} \quad (15)$$

where,

$\psi_{critical}$ = degree of hydration at final set of PCC, and
${}^{W}/_{CM}$ = water-cementitious materials ratio of the concrete mix.

Concrete Strength and Modulus of Elasticity Prediction

Maturity methods have been used extensively in recent years to predict the in-place strength of concrete [3,6]. The basis for this method is simple: the concrete strength and modulus of elasticity are directly related to the quantity of heat developed from the hydrating cement. The practical benefit of this method is that field evaluations of strength gain can be made from temperature measurements of the concrete over time. The theoretical benefit is the ability to predict both the strength and modulus of elasticity of concrete over a wide range of conditions based simply on the temperature development in the pavement.

Maturity is a measure of the thermal history of a concrete specimen. Under cold conditions, if a concrete specimen is cured with insulating materials that prevent heat loss to the environment, it will gain strength faster than an exposed concrete specimen. The detriment of curing at high temperatures is that environmental stresses are later induced in the pavement, which could ultimately make it more vulnerable to premature failures.

The Arrhenius method of maturity was selected for this project [3]. The basis for this method is the prediction of the equivalent age, t_e, as defined in Equation 5. The equivalent age can then be used to calculate the degree of hydration. The degree of hydration is then used to predict the strength or modulus of elasticity. The prediction of these properties requires a benchmark value. For convenience, 28-day values are used for this purpose. In order to calculate the early-age strength, the degree of hydration is used with the following equation:

$$\widetilde{S}_{current} = \widetilde{S}_{28-day}\left(\frac{\psi_{current} - \psi_{critical}}{\psi_{28-day} - \psi_{critical}}\right)^{k} \tag{16}$$

where,

$\widetilde{S}_{current}$ = tensile strength for current time (age) (kPa),
$\widetilde{S}_{28-day}$ = tensile strength at 28-days (kPa),
$\psi_{current}$ = degree of hydration at specific time,
$\psi_{critical}$ = degree of hydration at final set (see Equation 15),
$\psi_{28\text{-day}}$ = degree of hydration at 28-days using t_e = 672 hrs in Equation 5, and
k = power curve parameter = 1.0.

The above equation can also be applied to predict the compressive strength and the modulus of elasticity by changing the *k* exponent on the strength equation to 0.67 for the modulus of elasticity or 1.5 for the compressive strength [17].

FIELD VALIDATION

Validation Plan

A field validation of the HIPERPAV system and the individual models that comprise it was recently performed. During this field validation, the pavement temperature prediction model was extensively evaluated. A summary of the validation procedures are described herein.

Five construction sites were selected from around the United States for field instrumentation and data collection. These sites were located in Arizona, Minnesota, Nebraska, North Carolina, and Texas. At each site, an average of four slabs were instrumented and monitored. For a typical location, two of the slabs were placed in the morning and the other two in the afternoon. The data was obtained between October 1998 and May 1999. A total of nineteen slabs were instrumented and ten of these were selected for validation: three in Arizona, two in Minnesota and North Carolina, and one in Nebraska. The remaining nine slabs were used for model calibration. Table 3 summarizes the most pertinent variables for each site.

To predict changes in pavement temperature, two separate mechanisms were considered: environmental effects and the heat of hydration. Environmental conditions monitored included air temperature, solar radiation, wind speed, relative humidity, and cloud cover. Characterizing the heat of hydration required adiabatic calorimeter tests that were performed in the laboratory. The effects of both mechanisms are reflected in the actual concrete temperatures measured by thermocouples that were embedded at seven different depths throughout the slab thickness.

Pavement Temperature Prediction

To validate the temperature model, the concrete temperatures measured in the field were compared to the theoretical concrete temperatures as predicted with the temperature model, as shown in Figure 2. The measured versus predicted temperatures throughout the depth of the slab were compared, as well as the temperature gradient from the top of the slab to the bottom.

To assess the fit of the theory to the experimental values, a least square regression fit was performed. A summary of the r^2 values for the slabs at the five sites is presented in Table 4. A reasonably good fit was obtained for all the experimental slabs with r^2 ranging between 0.76 and 0.90. The r^2 value in Table 4 is the average of fit for the prediction of temperature throughout the slab depth. The lowest individual r^2 value was 0.65 for the middle temperature sensor in the North Carolina slab. The low r^2 value for that slab may be attributed to differences in that particular mix to the one used to determine the experimental hydration parameters. Comparison to the 45º-line was considered in the analysis of predicted versus measured responses for every model validated since the coefficient of determination with this procedure takes into account possible systematic trends in over-prediction or under-prediction. The coefficient of determination with this procedure is determined with only two variables, which allows the use of the simple linear regression model, that guarantees appropriate use of the r^2-value.

Table 4: Statistical summary for the HIPERPAV temperature model

Minnesota	r^2
Slab 1	**0.78**
Slab 4	**0.81**
Nebraska	
Slab 2	**0.86**
Arizona	
Slab 1	**0.84**
Slab 3	**0.76**
Slab 6	**0.81**
Texas	
Slab 2	**0.90**
Slab 3	**0.80**
North Carolina	
Slab 2	**0.80**
Slab 3	**0.82**

RECOMMENDED APPLICATIONS

Prediction of the pavement temperature, as affected by the environment and cement hydration, has a number of applications during the early age and in the long term. These applications include the following:

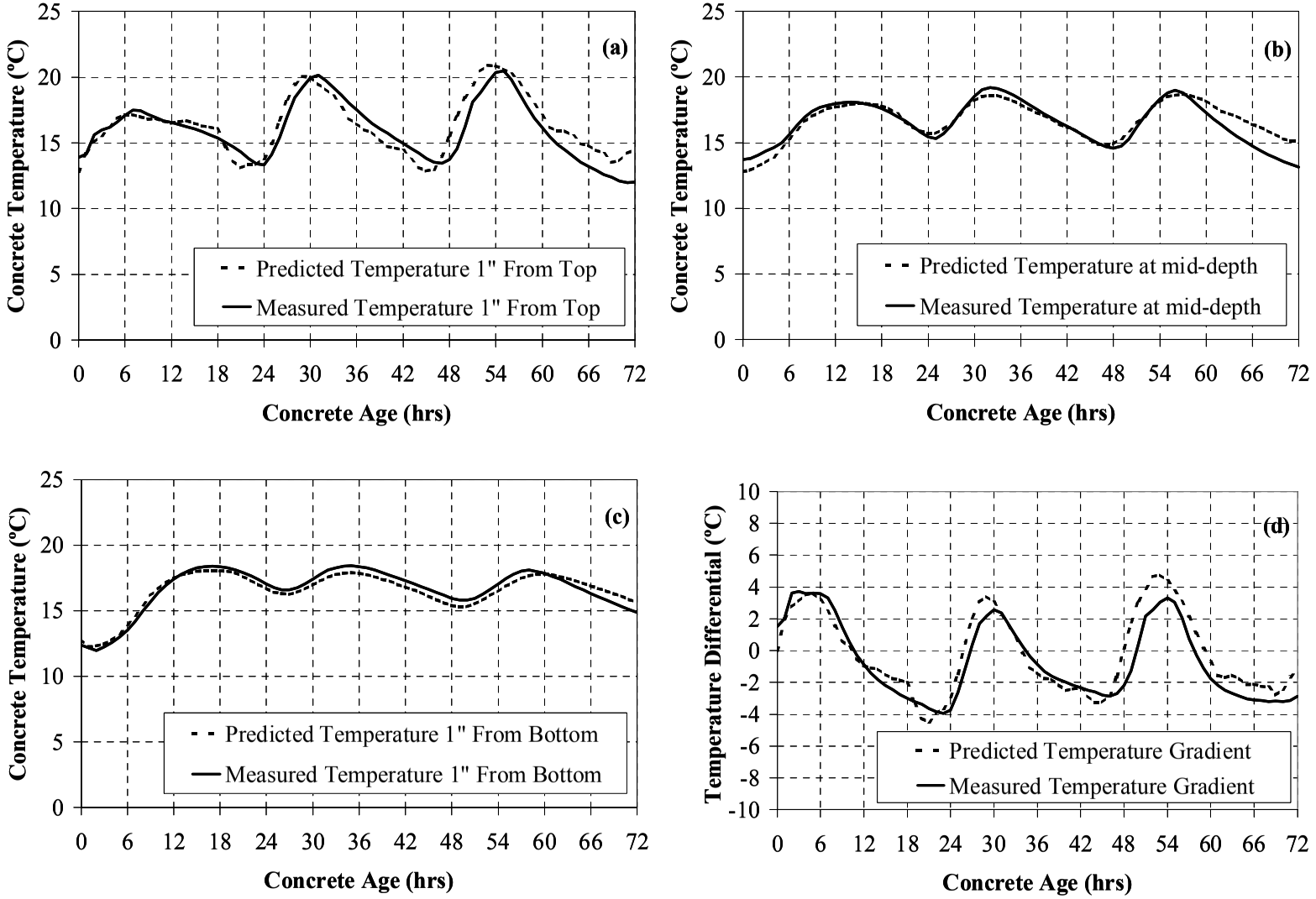


Figure 2: Predicted concrete temperature by HIPERPAV versus in-situ measured temperature for Arizona Slab #5

Table 3: Various HIPERPAV variables for the instrumented sites

Variable Class and Type	Minnesota				Nebraska		Arizona					Texas				North Carolina			
Pavement Design and Materials																			
Transverse Joint Spacing (m)	4.57				5.00		4.57					4.57				Variable from 4.88 to 6.71 m			
Pavement Thickness (mm)	305				254		254					305				279			
Subbase type	Granular				Crushed Concrete Base		AC Base					AC Base				AC leveling course			
Subbase friction (kPa) - movement (mm)	14.6 - 0.305				11.17 - 1.194		124.1 - 0.381					20.75 - .0.178				86.9 - 1.092			
28-day PCC Tensile Strength (MPa)	3.34				3.59 (51-day)		2.36 (7-day)					2.77 (7-day)				2.25 (7-day)			
28-day PCC Compressive Strength (MPa)	30.75				47.41 (51-day)		25.92					20.08 (7-day)				22.94			
28-day PCC Modulus of Elasticity (MPa)	28,200				38,660 (51-day)		23,720					29,720 (7-day)				21,325			
Concrete Mix Design																			
Cement Type	I/II				IP		II					I/II				I/II			
Aggregate Type	*19 mm - Natural Gravel 19 mm + Crshd Limestone*				*Crushed Limestone*		*River Gravel*					*Limestone*				*Phyllite*			
Aggregate CTE (μm/mºC)	*8.4 x 10-06*				*7.9 x 10-06*		*6.8 x 10-06*					*7.9 x 10-06*				*7.88 x 10-06*			
Cement Content (kg/m^3)	267				312		285					247				250			
Cementitious Materials (kg/m^3)	Fly ash Class "C"				Fly ash Class "C"		Fly ash Class "F"					Fly ash Class "F"				Fly ash Class "F"			
Cementitious Materials Content (kg/m^3)	71				23		61					67				75			
Water Content (kg/m^3)	122				135		128					113				141			
Coarse Aggregate Content (kg/m^3)	(19 mm +) 544 (19 mm -) 559				530		1102					1143				1149			
Fine Aggregate Content (kg/m^3)	776				1,223		802					588				836			
Chemical Admixtures:	W.R. - A.E.				W.R. - A.E.		W.R. - A.E.					W.R. - A.E.				W.R. - A.E.			
Water Reducer	KB-1000 - 1,315				Master Pave-N 613.7		WRDA 64 - 889.6					Master Builders 322N - 595.7				Monex LR - 1,060			
Air Entrainer	Polychem VR - 213				Pave Air 90 323.7		Daravair1000 - As needed @ 2.0%					Master Builders AE-90 - 139.2				Monex Air 40 - 104.4			
W/CM	0.36				0.40		0.37					0.36				0.44			
Weather Conditions	S1	S2	S3	S4	Slab 1	Slab 2	S1	S3	S4	S5	S6	S1	S2	S3	S4	S1	S2	S3	S4
Air temperature range (ºC)	0.5 to 22				8 to 24.5		-1.1 to 23					8 to 30				8 to 28			
Air Temperature at placement (ºF)	8.9	11.1	3.9	5.6	20.6	24.4	7.8	5.6	12.8	7.8	13.9	13.9	15.6	9.4	8.3	16.1	22.2	12.2	22.2
Relative Humidity (%)	29 - 100				54 - 100		15 - 99					30-100				28-99			
Wind Speed (kph)	0 - 25.7				0 - 29		0 - 52.29					0 - 27				0 - 24			
Overcast Conditions at placement *	S	PC	PC	PC	Sunny	Overcast	S	S	S	S	S	OC	OC	S	S	S	S	C	OC
Construction Operations																			
Curing Method	Curing compound				Curing Compound		Curing compound and Polyethylene Sheeting					Curing Compound				Curing Compound			
Time of Day of Construction (hh:mm)	9:05	13:08	9:05	10:25	10:20	15:10	9:20	10:25	15:00	9:50	13:35	8:35	9:30	8:10	11:30	12:00	14:05	10:20	12:30
Saw cutting time after placement (hh:mm)	20:00	17:30	18:00	17:30	18:30	13:20	16:40	23:10	21:30	26:25	26:35	14:15	12:50	12:30	9:50	7:00	6:55	8:40	9:30
Initial Concrete Mix Temperature (ºC)	57	15.0	10.0	11.1	24.7	24.4	17.2	13.3	17.2	12.8	16.7	20.6	20.0	22.2	26.7	27.8	28.9	27.2	27.2
Initial Subbase Temperature (ºC)	60	14.4	11.1	11.7	15.6	23.9	15.6	11.7	15.6	8.9	11.7	18.3	18.3	18.3	22.8	30.6	28.9	25.6	26.1
Measured pavement thickness (mm)	12 1/8	305	308	302	248	257	248	260	254	267	273	305	305	305	305	276	274	284	281
Measured slab length (m)	15'	4.5	4.5	4.6	5.0	5.8	4.6	4.7	4.6	4.6	4.6	4.5	4.5	4.3	4.5	6.4	6.8	5.2	5.2

** S - Sunny, PC - Partly Cloudy, C - Cloudy, OC - Overcast*

Strength Prediction

Prediction of concrete strength development using maturity methods requires information on the curing temperature of the concrete. As illustrated in the concrete strength prediction section, this can be accomplished with the use of the temperature prediction model. In turn, prediction of the concrete strength at early ages can serve a number of purposes including evaluation of earliest sawcutting time, evaluation of opening to traffic, and evaluation of cracking risk among other applications.

Sawcutting time

Previous investigations provide guidelines on earliest sawcutting time based on concrete strength gain criteria and other factors such as coarse aggregate type, and desirable raveling conditions [18].

Early Opening to Traffic

Early opening of pavements after construction is becoming a necessary strategy to minimize user costs during rehabilitation and reconstruction operations of congested streets and highways. As opening to traffic criteria rely primarily on the concrete strength gain, the temperature model can be used to predict the time for a specified strength threshold for opening to traffic.

Cracking Risk

Prediction of the concrete strength gain along with the prediction of stress development using a number of models has shown to be helpful in evaluating the potential for concrete pavement cracking under a variety of weather conditions and different construction strategies [19].

Plastic Shrinkage

Prediction of evaporation rate is a function of concrete temperature, wind speed, air temperature, and relative humidity [4]. With the temperature model, evaporation rate can be predicted to control plastic shrinkage cracking in concrete pavements. This provides knowledge to the construction industry as to the occurrence of adverse paving conditions so that measures can be taken to have the necessary equipment and slab protection on site prior to the occurrence of these critical conditions.

Temperature Gradients

Temperature and moisture transport in the concrete result in gradients that can lead to curling and warping movements and stresses. It has been observed in recent investigations that the initial thermal gradient at set plays a major roll in the performance of the pavement in the long term [20]. Prediction of the initial thermal gradient and subsequent curling state of the slab can be accomplished with the use of the temperature model presented in this paper.

CONCLUSIONS

The early-age temperature development of concrete can be estimated from knowledge of cement composition, cement factor, admixtures, thermal characteristics of the concrete, slab thickness, and the environmental conditions during paving and curing.

Major findings encountered during the validation effort are as follows:

- The HIPERPAV temperature model showed a good prediction of the temperatures measured in the field for a number of climatic conditions and pavement sites throughout the US.
- Heat signature tests provide a means of characterizing concrete hydration with time. With the parameters determined through these heat signature tests, HIPERPAV can account for the effect different mixture proportions and constituents have on the hydration of concrete.
- Prediction of concrete strength development using maturity methods requires information on the curing temperature of the concrete.
- The prediction of the concrete strength at early ages can serve a number of purposes including: evaluation of earliest sawcutting time, evaluation of opening to traffic, and evaluation of cracking risk.

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