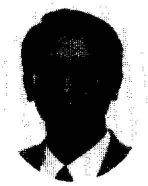
콘크리트재료의 열특성 및 수화열 해석

Characterization of Thermal Properties of Concerete and Temperature Prediction Model



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요 약

콘크리트의 열해석은 콘크리트 초기온도, 환경조건 및 시멘트의 수화 등에 의해 특징지워진다. 이러한 상호관계를 모두 고려한 프로그램을 만들어서, 콘크리트재료의 열특성과 환경조건을 감안한 콘크리트 구조물의 온도해석을 하였다. 시멘트 수화의 특성으로는 활성화에너지, 단위열량, 수화열이 있으며 이러한 인자들에 의해 콘크리트의 내부열 발생이 영향을 받는다. 본 연구에서는 활성화에너지와 수화열을 상대강도-등가재령모델에 의해 구했으며, 단위열량은 등온열량측정법에 의해 실험적으로 구하였다. 또한 콘크리트 구조물의 온도분포를 실험적으로 구하여 수치해석모델과 비교하였다. 먼저 위에서 제시된 모든 조건들에 대한 parametric 해석을 실시하여 프로그램의 신뢰성을 확보하였다. 그리고 원주형시편을 만들어서 온도분포 및 변화를 측정하여 수치해석에 의해 예측된 온도분포와 비교하였다.

Abstract

The thermal behavior of concrete can be characterized from a knowledge of concrete

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• 본 논문에 대한 토의를 1997년 6월 30일까지 학회로 보내주시면 1997년 8월호에 토의회답을 게재하겠습니다.

temperature at early ages, environmental conditions, and cement hydration in the mixture. To account for those interactions, a computer model was developed for predicting the temperature profile in hardening concrete structure in terms of material and environmental factors. The cement hydration characteristics such as the activating energy, total heat liberated, and the degree of hydration, can represent the internal heat generation. In this study, the activating energy and the degree of hydration curve were determined well from the mortar compressive strength tests while total amount of heat liberated was determined by the isothermal calorimeter method. The main purpose of this study is to correlate measured temperature distributions in a concrete structure during the hardening process with the results computed from theoretical considerations. Using two-dimensional heat transfer model, first, the importance of several parameters will be identified by a parametric analysis. Then, the temperature distribution of the cylindrical concrete specimen in the laboratory was measured and compared with that yielded by the theoretical considerations.

Keywords : heat of hydration, degree of hydration, activating energy, total heat liberated, equivalent age, heat transfer

1. Introduction

The interaction between temperature conditions in concrete structure within the first few days after the concrete is placed can influence the quality of the concrete over its lifetime. This means that processes occurring in concrete at an early age have an important influence on concrete quality. Therefore, planning of concrete placement should account for monitoring of temperature as well as strength development in the concrete during and within the first few days after the concrete is placed. To supplement construction quality in the field, temperature distributions of the concrete structure can be estimated using a numerical scheme of solving a boundary value equation where all the environmental factors (such as air temperature, wind velocity, solar gain, and solar radiation) and cement heat of hydration are considered.

In the heat transfer problem of a newly placed concrete structure, it is necessary to know the rate of heat generated, Q_H. This important parameter can be measured in adiabatic or heat of solution methods and determined from relative strength-equivalent age relationship[1]. This study presents methods to determine three material properties for the heat of hydration: activating energy, total amount of heat developed, and the degree of hydration.

The purpose of this study is also to correlate measured temperature distributions in a concrete specimen during the hardening process with the results computed from theoretical considerations developed subsequently in sections 2 and 3. Two-dimensional heat transfer models in both plane systems and axisymmetric systems will be used to validate the heat conduction model. Using the model, first, the importance of several parameters will be identified by a parametric analysis. Then, temperature distribution of the cylindrical concrete specimen in the laboratory (which is controlled at constant temperature and constant heat transfer coefficient neglecting solar radiation) was measured and compared with that yielded by the theoretical considerations.

2. Models for temperature prediction

Temperature development in concrete due to hydration and ambient temperature conditions can be determined from the general differential equation for heat transfer.

The governing equation of heat transfer, due to conduction in a two dimensional domain can be expressed as below:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + Q_H = \rho c_p \frac{\partial T}{\partial t} \qquad (1)$$

where k_x, k_y = thermal conductivities of concrete, W/m · ℃
ρ = concrete density, kg/m³
c_p = specific heat, J/kg · ℃
t = time, hour
T = temperature, ℃
Q_H = generated heat from heat of hydration of cement, W/m³

It should be noted that the thermal conductivity of cementitious materials may be expressed using the heat of hydration, α as $k_o(2-\alpha)$ where k_o is a reference conductivity.[2]

2.1 Environmental variables

Heat energy is transferred between a concrete surface and the environment through convection, solar gain, and solar radiation. Figure 1 presents heat transfer between a concrete slab on the ground and the surrounding environment.

At the concrete surface,(Γ_1) heat transfer is affected by all the heat mechanisms such as wind (convection), solar gain, and solar radiation through the environment. At 1~2 m below bottom of the concrete slab,(Γ_2) a Neumann condition may be imposed because of the rapid attenuation of heat into the soil.[5] These two conditions are summarized as follows:

$$k\vec{\nabla}T \cdot \vec{n} + q_c + q_r - q_s = 0 \quad on \;\; top$$

$$k\vec{\nabla}T \cdot \vec{n} + q_c + q_r - q_s = 0 \quad on \;\; \Gamma_1 \qquad (2)$$

$$k\vec{\nabla}T \cdot \vec{n} = 0 \quad on \;\; bottom$$

$$k\vec{\nabla}T \cdot \vec{n} = 0 \quad on \;\; \Gamma_2 \qquad (3)$$

where q_c = heat flux due to convection, W/m²
q_r = heat flux due to surroundings, W/m²
q_s = solar radiation absorption, W/m²
n = unit direction of heat flow by vector notation

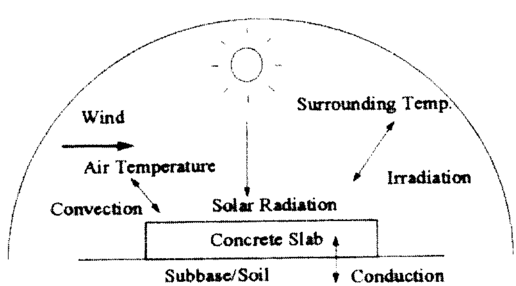

Fig. 1 Heat transfer between a concrete surface and the environment

2.1.1 Wind

The flux of heat transfer by convection, q_c, is associated with the movement of air fluid, i.e. wind. The rate of heat transfer by wind is expressed by Newton's law of cooling stated as the heat rate absorbed or dissipated depends on the difference of air temperature, T_e, and the concrete surface temperature, T_s. Also involved in the flux expression is the proportionality constant which is known as the convective heat transfer coefficient, h_c. The appropriate rate equation is of the form:

$$q_e = h_e(T_s - T_e) \tag{4}$$

The empirical convective heat transfer coefficient, h_c, is somewhat complicated to determine because of the many variables which affect it. It is a complex function of the composition of the air, the roughness of the concrete surface, and the nature of the fluid motion. A typical range of the heat transfer coefficient extends from 5 to 35 W/m^2 · ℃.[2,4]

Attempts have been made to relate convection heat transfer coefficient to wind velocity of the air and concrete surface roughness.[5] It is useful to consider the following empirical formula to estimate a value of h_c:

$$h_c = (6 + 3,7\nu) \tag{5}$$

A value of 6 W/m^2 · ℃ for h_c represents an average concrete surface roughness without any contribution from wind effects.

The latter portion of the above expression is added to adjust the value of h_c as a function of wind (m/sec), ν.

2.1.2 Solar gain

In terms of a concrete surface and its distant field surroundings, some incidents of radiation are emitted and absorbed and radiative exchange between the concrete surface and its surroundings takes place.

These solar gain rates are affected by a material property of the concrete surface and represented using an emissivity which ranges from 0.8 to 0.9 for the cementitious materials. In general, the Stefan-Boltzmann's law explains solar gain transfer mechanism between a concrete surface and its surroundings as follows:

$$q_r = \varepsilon\sigma(T_s^4 - T_\infty^4) \tag{6}$$

where ε_t = surface emissivity of concrete
σ = Stefan-Boltzmann constant, 5.670 × 10^{-8} W/(m^2 · K^4)
T_∞ = surrounding temperature, K

2.1.3 Solar radiation

Solar radiation represents a calculated rate related to the thermal energy that is incident upon a concrete surface. The sun's rays which are absorbed directly by the concrete surface cause the concrete surface to be heated more rapidly than the interior region of a concrete structure. This effect may contribute to a temperature gradient through the slab.

As discussed before, the important parameters for a heat transfer analysis of a concrete slab are the thermal properties (conductivity, density, and specific heat), heat transfer coefficient, ambient temperature of the air, solar absorptivity and emissivity. Besides these factors are other important factors such as initial concrete placement temperature and the heat of hydration. Table 1 lists useful information as various input data for heat transfer analysis based on literature review.[2-4,6-11] As observed in Table 1, a wide range exists in possible values of concrete thermal conductivity. The coefficients range from 49 to 101 J/cm · ℃ · hr.

Table 1 Concrete thermal properties and heat transfer coefficient from others(2-4, 6-11)

Source	Conductivity (J/cm · °C · hr)	Specific heat (J/g · °C)	Heat transfer coefficient (J/cm² · °C · hr)	
Hsieh	48.6	0.905	Winter	12.3
			Summer	8.2
			Free	1.8
Emborg	57.6-90	0.8-1.2	-	
Truman	73.1	0.879	with form	1.7
			w/o form	8.3
Johnson	50.5	0.963	4.01	
Brebbia	50.4	0.96	Top	8.28
			Bot	2.52
			Left	5.40
			Right	3.24
			Inside	0.72
Machida	72.1	0.983	Room	3.77
Tan	79-101	-	-	
Rastrup	-	1.07	-	
Chapmann	61.2	0.81	-	

3. Methods to determine heat of hydration of concrete

In the heat transfer problem of a concrete structure, concrete not only conducts heat but also generates heat because of hydration of cement. To solve the heat transfer problem and determine the temperature development, it is necessary to know the rate of heat generated, Q_H in a unit volume of concrete. This important parameter can be measured in adiabatic or heat of solution methods and determined from relative strength-equivalent age relationship. This section presents methods to determine three material properties for the heat of hydration.

3.1 Basic relations in heat of hydration

The generated heat rate per unit volume and time (heat of hydration) can be expressed as follows[7]:

$$Q_H = \frac{dW}{dt} \tag{7}$$

where

$$W = H_u C \alpha(t_e) \tag{8}$$

$$t_e = \sum \exp\left[-\frac{E}{R}\left(\frac{1}{T+273}\right)-\left(\frac{1}{T_r+273}\right)\right]\Delta t \tag{9}$$

where W = generated heat of a unit volume of concrete, J/cm³

H_u = total amount of heat liberated at complete hydration of a unit weight of cement, J/g

C = cement content per unit volume of concrete, g/cm³

α = degree of hydration

t_e = equivalent age, hr

E = activation energy, J/mol

R = the universal gas constant, 8.3144 J/(mol · ℃)

T_r = reference temperature, ℃ (usually 23 ℃)

The degree of hydration is a function of the equivalent age as follows:

$$\alpha = \exp\left[-\lambda_1 (\ln_\tau)^{-x_1}\right] \tag{10}$$

where λ_1 and k_1 are material constants and $\tau = 1 + (t_e / t_1)$ using an additional material constant, t_1. Equation (10) is well-known expression for the degree of hydration commonly used in Europe. Combining above equations, one obtains:

$$Q_H = H_u C \alpha \frac{\lambda_1 x_1}{t_1} \frac{[\ln(\tau)]^{-(1+x_1)}}{\tau} \times \exp\left[-\frac{E}{R}\left(\frac{1}{T+273}-\frac{1}{T+273}\right)\right] \tag{11}$$

It is seen from Eq.(11) that the heat of hydration at any equivalent time, te, can be calculated from the total amount of heat liberated at complete hydration, H_u, cement content, C, the degree of hydration, α, and the activating energy, E.

3.1.1 Activation energy

The activation energy can be determined by ASTM test C1074.[12] The ASTM standard procedure is based on the relationships of temperature sensitivity and rate of strength gain of cementitious specimens. To determine the activation energy, E, the Arrhenius equation is used as follows:

$$\ln(k_T) = \ln(A) - \frac{E}{R}\frac{1}{(T+273)} \tag{12}$$

where k_T is a rate constant at curing temperature T and A as a constant.

According to ASTM 1074, the strength of the mortar cube can be plotted in terms of age at each curing temperature after conducting mortar cube strength tests. The following strength-maturity relationship can be used to determine the activation energy of a concrete mix:

$$\sigma = \sigma_u \frac{k_T(t-t_o)}{1+k_T(t-t_o)} \tag{13}$$

where σ is strength at a certain age, σ_u as ultimate strength, t as curing age at a constant temperature, and t_o as initial age when strength is developed. Least-squares regression analysis is used to determine the values of k_T for the mixture at each curing temperature.

Then, the slope of the line, E/R in Eq.(12) is determined from the natural logarithm of the quotients (k_T values) as a function of the reciprocal absolute temperature. The activation energy, E can be found by multiplying E/R by the universal gas constant, R.

3.1.2 Total amount of heat developed

It is necessary to know the heat produce at complete hydration but it is difficult to determine. According to Emborg[7], some researchers have used fictitious value of total amount of heat developed, H_u. This is because it requires at least 2 days or more to obtain adiabatic temperature rise from the adiabatic calorimetry. However, the total amount of heat liberated can be determined easily by the heat of solution method which is described in ASTM C186.[13]

3.1.3 Degree of hydration

Change in the values of the degree of hydration for concretes can be determined by cement samples from the calorimetry. This is what most engineers do. If cement samples are tested at the isothermal condition, change in their degree of hydration with equivalent time exhibits a S-shape curve. However, the plot in the degree of hydration versus equivalent time has a similar trend to the trend exhibited in the plot of the relative strength curve with equivalent time from the cement mortar tests. Therefore, the degree of hydration in Eq. (10) will be represented by the relative strength data from the cement mortar tests. Least-squares regression analysis is again used to determine the constants of λ_1 t_1 and k_1.

3.2 Experimental program for heat of hydration

Mortar mix in the laboratory was made to determine activation energy, E, and the degree of hydration, α which is composed of three constants of λ_1 t_1 and k_1. Also, a cement sample wasused to determine total amount of heat, H_u, developed by the heat of the solution method.

3.2.1 Mix designs and specimen preparation

Table 2 shows the concrete mixtures proportions. However, the mortar mixture for the mix design had cement-to-sand proportions equal to the cement-to-coarse aggregate proportions in the concretes.[13] Mortar cube specimens were prepared using the brass mold which has three 51 mm cube compartments. All the specimens were demolded at the time of the first strength test and cured into temperature-controlled water baths until the day of testing.

Table 2 Mix design(1m^3 of concrete)

Material	Weight or Volume
Cement, type I	251
Fly ash, type C	68
Crushed limestone	684
Siliceous and 1	399
Siliceous and 2	765
Water	135
Conrtete unit weight	2301kg/m^3

3.2.2 Tests and data analysis

The strength-age data for each mixture were used to determine the parameters ofthe strength-age relationship in Eq. (13). From those strength-age data, each constant of k_T at each isothermal condition in Eq. (13) are determined by the regression analysis and given in Table 3. Using the relations of the rate constant, k_T and curing temperature, T, value of activation energy, E was obtained using Eq. (12). Table 3 lists activation energy value as 47.8 kJ/mol. Presently, there is not much published data on the effect of activation energy of mortars which contain different replacement of cement by fly ash. Carino and Tank[11] reported 40-60 kJ/mol of activating energy for mortar specimens made with Type I cement.

Next, the empirical coefficients of Eq. (10) were determined by the relative strength data of the cement mortar tests, using the least squares analysis. Table 3 summarizes the values of λ_1, t_1, and k_1 for the mix.

The degree of hydration versus equivalent age values, obtained using Eq. (10), is shown in Fig. 2. There is relatively good agreement between the degree of hydration equation (Eq. (10)) and the data.

Finally, the total amount of heat liberated, H_u was determined using the isothermal calorimeter (heat of solution method). As seen in Table 3, test value was 483.0 J/g.

This value is reasonable since it was noted that Type I cement has average value of 497 J/g.[7]

Table 3 Input data for heat of hydration

T (°C)	k_T (1/day)	E (kJ/mol)	λ_1	t_1	k_1	H_u (J/g)
10	.153					
25	.389	47.8	1.65	13	1.21	483
50	1.867					

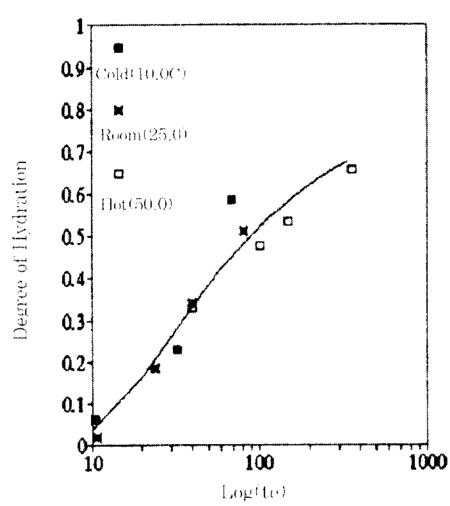

Fig. 2 Degree of hydration versus equivalent age

4. Prediction of temperature distribution

The purpose of this section is to correlate measured temperature distributions in a concrete specimen during the hardening process with the results computed from theoretical considerations developed in sections 2 and 3. In order to account for the heat of hydration, a heat transfer analysis of the exothermic phenomenon is considered with heat conduction. Two-dimensional heat transfer models in both plane systems or axisymmetric systems will be used to validate the heat conduction model. As discussed before, the importance of several parameters will be identified by a parametric analysis. Then, temperature distribution of the cylindrical concrete specimen in the laboratory (which is controlled at constant temperature and constant heat transfer coefficient neglecting solar radiation) was measured and compared with that yielded by the theoretical considerations.

4.1 Sensitivity analysis of heat transfer in concrete structure

In order to study the significance of the various parameters, temperature change at the surface of a concrete slab (Fig. 3) was calculated. By keeping the rest of the variables in Table 4, one variable at a time was increased by 10 percent.

A summary of comparisons is given in Table 5. It can be seen that the most significant factors with respect to the environmental variables are air temperature and initial concrete temperature. Also of importance is the absorptivity of the surface to the solar radiation.[6] However, an increase in the thermal conductivity, specific heat, and density of concrete reduces the temperatures at the concrete surface.[6] An increase in the thermal conductivity, specific heat, and density of soil does not seem to change the temperature at the concrete surface.

With respect to the heat of hydration of cement properties, an increase in the total amount of heat developed, H_u, the cement content, C, and the activating energy, E does not amplify the predicted temperature at the

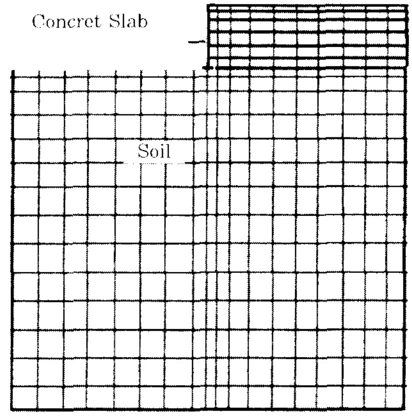

Fig. 3 Typical concrete slab idealization in 2-D model

Talble 4 Input date for parametric analysis

	Input date	Values
Concrete	k, (J/cm · hr · °C)	61.1(2-α)
	ρ, (g/cm^3)	2.357
	c_p, (J/g · °C)	1.044
	α_s	0.5
	ϵ	0.9
Soil	k, (J/cm · hr · °C)	50.0
	ρ, (g/cm^3)	1.632
	c_p, (J/g · °C)	0.800
	α_s	0.5
	ϵ	0.9
Heat of hydration of cement	H_u, (J/g)	440.3
	C, (g/cm^3)	0.32
	E, (J/mol)	47755
	λ_1	1.65
	t_1	13
	k_1	1.21

Note: α_s denotes absorptivity

Table 5 Parametric study results (Weather Data from Waller County in Texas was used)

Variables	% ΔT at top
Concrete k	-0.7
Concrete c_p	-1.3
Concrete ρ	-1.3
Soil k	0.0
Soil c_p	0.0
Soil ρ	0.0
Air temperature	4.7
Wind velocity	-0.6
Solar absorptivity	3.2
Emissivity	-0.5
Initial concrete temp.	3.4
Initial soil temp.	0.5
Thickness of slab	0.0
H_u	0.5
C	0.5
E	0.7
λ_1	-1.2
t_1	-1.0
k_1	-0.5

concrete surface. However, material constants of the degree of hydration properties such as λ_1, t_1, and k_1 decrease the temperature at the concrete surface by 1.2%, 1.0%, and 0.5%, respectively.

As proceeded before, each 10 percent increase of each variable at a time was adopted for the sensitivity analysis. However, rather than using by 10 percent increase of average value of each variable, sensitivity analyses using by 10 percent of deviatoric limits of the variables will provide more realistic sensitivity results.

4.2 Experimental temperature distribution of cylindrical specimen

A cylindrical concrete specimen(diameter=26.0cm and height=25.4cm) was prepared with thermocouples at five different locations along the axis of the specimen in the laboratory. The laboratory was controlled by constant room temperature(32℃). The mix design(in Table 2) was used as the concrete materials. Five channels in the data logger were used to record the temperature at five different depths in the cylinder : 2.54cm(1 inch), 7.62cm(3inches), 12.7cm(5 inches), 17.8cm(7inches), 22.9cm(9inches), and room temperature. The measurement time interval was 30 minutes.

This analysis uses a two-dimensional axisymmetric heat transfer model. The finite element mesh is shown in Fig. 4. In this analysis, a half model of the total structure is used to take advantage of symmetry along the center line axis.

Adiabatic temperature conditions are assumed to exist at the boundary condition on the axis and can be defined:

$$k\vec{\nabla}T \cdot \vec{n} = 0 \tag{14}$$

For the other surfaces, the mixed boundary condition is applied as follows:

$$k\vec{\nabla}T \cdot \vec{n} + h_c(T_s - T_e) = 0 \tag{15}$$

The top surface is exposed to an ambient temperature of 32℃, and the convective heat transfer coefficient of 4 J/cm^2 · hr · ℃. For the right-hand side vertical surface, the heat transfer coefficient of 2 J/cm^2 · hr · ℃ is applied. On the bottom surface, the heat transfer coefficient is 0.5 J/cm^2 · hr · ℃. Based on experimental research, the cement heat of hydration characteristics which were determined from concrete mix are used as input data(Table 3). However, a total amount of heat liberated at complete hydration Hu was used as 440.3 J/g instead of 483.0 J/g since the comparison of the measured and predicted temperatures(as will be subsequently in Figs. 5 and 6) was satisfactory. This may be attributed to the fact that the mix contains 21 percent of Type C fly ash and fly ash liberates less heat. It should be noted that the laboratory samples (cement samples for the heat of solution method) did not contain fly ash. In the analysis, a time increment of 0.1 hours was selected. An initial temperature of 19℃ was used for the analysis.

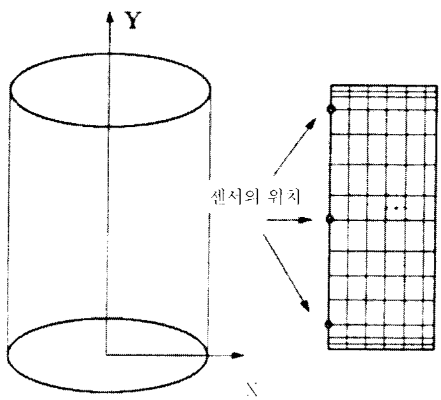

Fig. 4 Concrete cylinder and meshes in the 2-D axisymmetric model

Figure 5 shows temperature measurements of the concrete cylinder specimen at various different locations. The maximum temperature at 2.54cm(1inch) below the top surface(called top 2.54cm, for brevity) was 37.4℃ after 23.5hours. On the other hand, the maximum temperature at 2.54cm above the bottom surface(called bottom 2.54cm) was 41.3℃ after 20.5hours. Between the top 2.54cm and bottom 2.54cm, temperature gradient was 3.7℃.

The predicted concrete temperatures at the five different depths (which are the same depths as for the experiments) are shown in Fig. 6. From the analysis, maximum temperatures occurred at 23.5 hours and were 39.4 ℃ and 41.8 ℃ at the top 2.54 cm and the bottom 2.54 cm, respectively.

The comparison between measured and predicted temperatures was found to be satisfactory. Based on test results, concrete conductivity was 45(2-α) J/cm · hr · ℃ where α being the degree of hydration and concrete specific heat as 1.05 J/g · ℃.

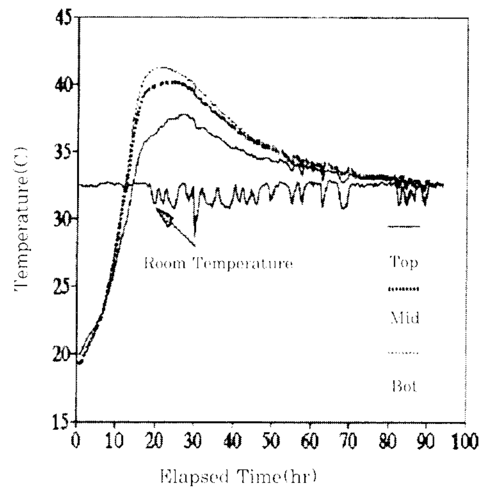

Fig. 5 Measured concrete temperatures from the cylinder (laboratory)

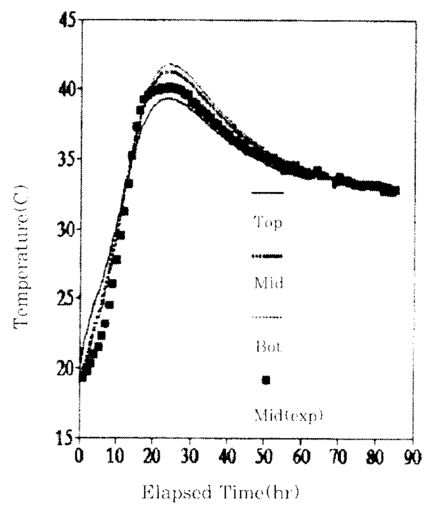

Fig. 6 Predicted concrete temperatures from the cylinder

5. Conclusions

The following conclusions and recommendation could be made from this study:

1. This study provides a concise review of current information and knowledge of

several significant factors affecting the development of temperature and heat of hydration as it would pertain to hardening concrete slab materials.

2. Several parameters relative to the characterization of climatic conditions (convection, solar gain, and solar radiation) were identified. Although limited information is available for the transfer of heat by convection and solar gain, the relationships provided in the text of this study provide the necessary input in which to assign values to these parameters for the analysis portion of this study. The importance of those variables in the overall analysis has been addressed by the parametric analysis.
3. The cement hydration characteristics can be determined by the solution method. Three necessary material properties such as the activating energy, E, total heat liberated, H_u, and the degree of hydration, α, can represent the internal heat generation of the heat transfer equation. In this study, the activating energy and the degree of hydration curve are determined well from the mortar compressive strength tests while total amount of heat liberated from the hydration of the cement is determined by the isothermal calorimeter method.
4. A concrete slab structure is unlike most other structures because they possess very large surface to volume ratios causing significant variations in temperature and moisture. As a result, thermal properties such as concrete conductivity or thermal diffusivity would affect the heat transfer of the concrete slabs at an early age. Thus, concrete conductivity can be back-calculated from the best fit value between the computed and measured laboratory process with a cylindrical specimen. Then, temperature distribution of the newly placed concrete slab on the ground can be accurately predicted with environmental data by the theoretical considerations.

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