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Thermal Conductivity and Heat Transfer Coefficient of Concrete

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Abstract: A very simple model for predicting thermal conductivity based on its definiensis was presented. The thermal conductivity obtained using the model provided a good coincidence to the investigations performed by other authors. The heat transfer coefficient was determined by inverse analysis using the temperature measurements. From experimental results, it is noted that heat transfer coefficient increases with the increase of wind velocity and relative humidity, a prediction equation on heat transfer coefficient about wind velocity and relative humidity is given.

Key words: thermal conductivity; heat transfer coefficient; relative humidity; wind velocity

1 Introduction

The temperature rise may lead to cracks in a concrete structure. To predict cracking response and cope with it, a systematic way to do analysis on the heat conduction is needed. However, temperature variation in a concrete structure due to the heat of hydration is remarkably varied with respect to the variation of concrete thermal properties, such as thermal conductivity, specific heat, density of concrete, and so on. It is widely accepted that the conductivity and the heat transfer coefficient have a relatively greater influence on temperature gradient along the concrete structure.

Thermal conductivity of concrete is greatly affected by mix proportioning, aggregate types and sources, as well as moisture status and unit weight in the dry state reported in [1-3], Kook-Han Kim [4] studied it and gave functions which have relationship between each of its constituents just for his test result, but it should be validated by other kinds of concretes and local test. So, it is urgent to find a simple and correct way to determine thermal conductivity. As for the heat transfer coefficient, few relatively studies on it. Branco *et al*[5] and Mendes [6] recommended that influencing factors should be verified by experimental results, proposed a prediction model as a function of the roughness of the concrete surface and the velocity of the wind. Yun Lee, *et al* [7] had reported all the key factors that effect heat transfer coefficient. BF Zhu[8] had also been studied many material thermal parameters, gave an empirical formula of thermal conductivity and a heat transfer coefficient model for preliminary design. Anyway, heat transfer coefficient should be obtained by local test. In present study, a method that obtains thermal conductivity based on its definiensis newly developed and at the same time, on the basis of the solution of a nonlinear diffusion equation with initial and boundary conditions, a transfer coefficient of heat in a concrete cube of different curing condition is found by minimization of a functional, who expresses error of the calculated temperature from their experimental values, experiments of concrete specimens at different curing condition were carried out to verify feasibility of inverse analysis and correctness of function of heat transfer coefficient.

2 Experimental

We performed a simulation of the thermal transfer on the basis of the nonlinear diffusion equation mentioned in [9]:

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$$\rho c \frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q_v \quad (\forall (x,y,z) \in R) \tag{1}$$

where, λ is the thermal conductivity, ρ the density; c the specific heat; and q_v the rate of heat generated per unit volume (exothermic heat of hydration).

The boundary condition associated with Eq. (1) is expressed as follows.

$$h(T_s - T_\infty) = \lambda\left(\frac{\partial T}{\partial x_v} n_x + \frac{\partial T}{\partial y} n_y + \frac{\partial T}{\partial z} n_z\right) \tag{2}$$

where, n_x, n_y, n_z are the direction cosines of the unit outward vector normal to the boundary surfaces, h the heat transfer coefficient, T_s, T_∞, T the temperature of boundary surface and ambient, respectively. Numerical solution of the Fourier equation may be accomplished by finite element analysis.

3 Results and Discussion

3.1 Thermal conductivity

According to the Ref.[4], thermal conductivity of concrete was represented in terms of the amount of aggregate, fine aggregate fraction; humidity condition of specimens and temperature, furthermore, aggregate volume fraction and moisture condition of specimen are revealed as mainly affect factors on thermal conductivity of concrete. Here, assuming concrete is consist of cement paste, fine aggregate, coarse aggregate and the interspaces between them is full with water, if water evaporated, its volume is substitute by the air. So, based on definiensis of thermal conductivity, an uniform flow of heat through a unit thickness of material between two faces subjected to a unit temperature difference during a unit time, we can assume that concrete was a kind of composite material in Fig.1, the heat flux from the upper to bottom can be show as follow:

$$\lambda = \lambda_c \omega_c + \lambda_w \omega_w + \lambda_{fa} \omega_{fa} + \lambda_{ca} \omega_{ca} \tag{3}$$

where, λ_c, λ_w, λ_{fa} and λ_{ca} denote thermal conductivity of cement, water, fine aggregate, as well as coarse aggregate, ω_c , ω_w, ω_{fa} and ω_{ca} are volume fraction in corresponding.

To verify correctness of this express, the experimental data of thermal conductivity were adopted from a study by Kook-Han Kim[4], in which ,influencing factors on thermal conductivity of concrete are quantitatively investigated by QTM-D3—that is, a conductivity tester developed in Japan and the two-linear parallel probe (TLPP) method, with which two probes are inserted into two parallel holes drilled in the sample, where one probe is used as a heating source and the other as a temperature sensor, parameters of materials of concrete selected from papers [10-12] are shown in Table 1. Table 2 shows different mix proportions of concrete, here, the thermal conductivity of water at saturation pressure is selected at 20 ℃, thermal conductivities of fine and coarse aggregate are using that of quartz and granite because the thermal conductivity of aggregates is largely affected by types of grounds. According to the above predict equation, the calculated concrete thermal conductivities can be

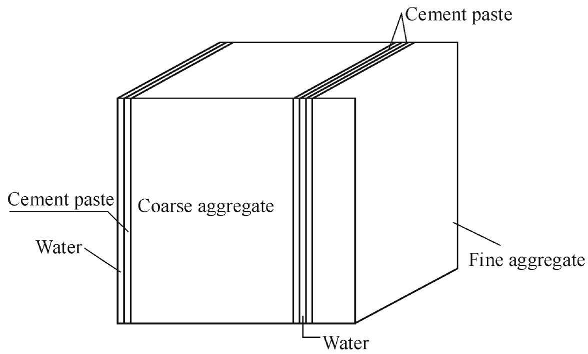

Fig.1 Constituents of concrete

Table 1 Parameters of materials

Parameters	Cement	Fine aggregate	Coarse aggregate	Water
Thermal conductivity /(kcal/mh℃)	0.260	4.450	2.500	0.521
Specific gravity /(kg/m^3)	3150	2550	2580	1000

Table 2 Mix proportions

Items	w/c	Unit content / (kg/m^3)				
		Cement	Fine aggregate	Coarse aggregate	Water	Admixture
C-GC1	40	350	702	1103	140	1.75
C-GC2	40	452	630	989	180	2.26
C-GC3	40	550	559	880	220	1.10
C-GC4	40	650	490	768	260	-
C-GC5	40	850	345	546	340	-
C-GC6	40	1050	206	321	420	-

Table 3 Thermal conductive of concrete predict by Eq.(3) and measured values

Items	Thermal conductive / (kcal/mh℃)	
	Measured	Calculated
C-GC1	2.12	2.40
C-GC2	2.00	2.19
C-GC3	1.93	1.98
C-GC4	1.69	1.79
C-GC5	1.47	1.38
C-GC6	1.20	0.98

compared with measured thermal conductivities from the test results (see Table 3), Table 3 reveals a closed relationship between them, The sample correlation coefficient R of 0.985 indicates that Eq.(3) is quite reasonable.

3.2 Heat transfer coefficient analysis

The heat pass through concrete surface and ambient air comes true by conduction, convection and radiation in [13, 14], so, heat transfer coefficient is influenced by geometric and aerodynamic parameters and self-characteristic, and is hardly to obtain. Usually, in the Ref.[15], prediction model related to the coefficient is proposed in situ experiments. In this paper, a prediction model about heat transfer coefficient thinking about wind velocity and relative humidity is given based on experiment results.

Considering the measuring temperature of concrete surface is difficult to explore, K-type thermo-couples for measuring temperature can influenced by ambient temperature, so it is necessary to explore a more accuracy method to determine the heat transfer coefficient. In this paper, an inverse analysis is used.

3.2.1. Experimental preparation

The mixture proportions combined to form 350 mm×350 mm×350 mm specimens to be investigated can be found in Table 4. 28-day compressive strength of the concrete is 34.9 MPa, its density is 2399 kg/m^3.

To make sure practical of the predict model of thermal conductivity, and to investigate the effect of the wind velocity as well as moisture condition on heat transfer coefficient, two types of concrete specimens were prepared for experiments. The first type of specimens were covered with bamboo plywood about 1.2 cm thick but the upper surface exposed to relative humidity of 60%, 80% to determine the effect of moisture on heat transfer coefficient. The second type of specimens (see Fig.3) was exposed to wind velocity of 1.8 m/s, 3.6 m/s. The wind blew only in one direction using a wind source installed at the front of the wind tunnel. A honeycomb and a wire screen were located inside the wind tunnel to create the laminar flow, which is essential for creating a consistent velocity condition. The magnitude of the wind velocity was measured at the same level as the top surface of the concrete specimen. For each condition, two identical specimens were tested.

3.2.2 Inverse analysis

For the inverse problem in the present study, the temperature of concrete T is regarded as unknown

Table 4 Composition of mixes/ (kg/m^3)

Water	Cement	Fine aggregate	Coarse aggregate	Fly ash	Admixture	*w/c*
141	250	582	1260	63	2.817	0.45

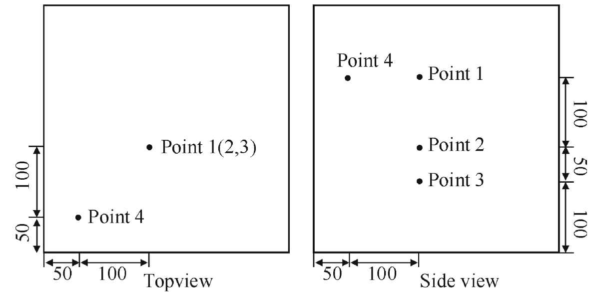

Fig.2 Locations of thermo-couples (Unit: mm)

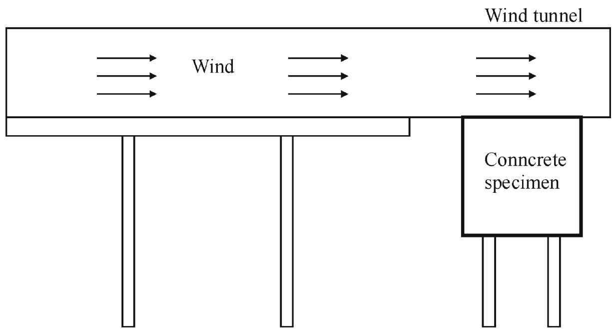

Fig.3 An overview of the test specimen set-up

and is to be estimated by using the temperature measurements of m sensors located at appropriate locations, detail procedures are as follow:

Firstly, setting the initial heat transfer coefficient, h_1 (surface of concrete) and h_2 (surface of bamboo). Accordingly, the calculated temperature can be determined from Eq.(1), then, we compare obtained solution of the problem with the measured temperature taken from the i th thermocouple at t=t_j. If obtained solution does not correspond to the measured temperature then we look for another set of heat transfer coefficient and so on. The iteration process is finished with the application of the least squares minimization technique, that is, the error in the estimates appeared in the Ref.[16] is to be minimized.

$$F = \sum_{i=1}^{m}\sum_{j=1}^{n} k_{ij}(T_{i,j} - T_{i,j}^{0})^2 \tag{4}$$

where, k_{ij} is associate parameter, $T_{i,j}$, $T^0_{i,j}$ the calculated and measured temperature at the j measurement locations at the time of i,m the number of measured points and n denotes the number of the discrete measurement times.

3.3.3 Results and discussion

Based on the predict model of thermal conductivity, the initial thermal conductivity was

2.33 kcal/(m・h・℃),thermal conductivity decreases with decrease of relative humidity. Specific heat considered in this study was 0.2072 kcal/(kg・℃). So, under relative humidity of 60%, 80%, the heat transfer coefficients of concrete are 9.598 kcal/ (m^2・h・℃), 11.07 kcal/ (m^2・h・℃) respectively. In the same way, the heat transfer coefficients of concrete are 11.843kcal/ (m^2・h・℃), 19.027 kcal/ (m^2・h・℃) under wind velocity of 1.8 m/s, 3.6 m/s. From experimental results, it is noted that heat transfer coefficient increases with the wind velocity and relative humidity. Figs.4-7 respectively show the comparison of the temperature between the calculated results and the measured results. It can be found that the agreement between them is very good, the max error is no more than 5%. This comparative result further shows that the thermal conductivity and heat transfer coefficient have good accuracy and good reliability, inverse analysis is feasible as well.

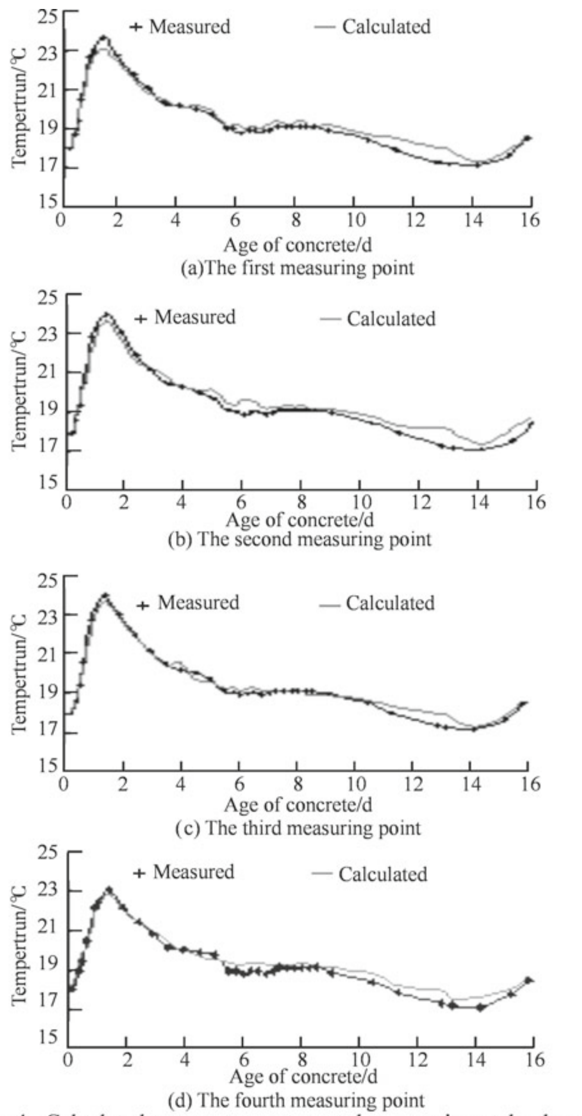

Fig.4 Calculated temperature compared to experimental values at RH=60%

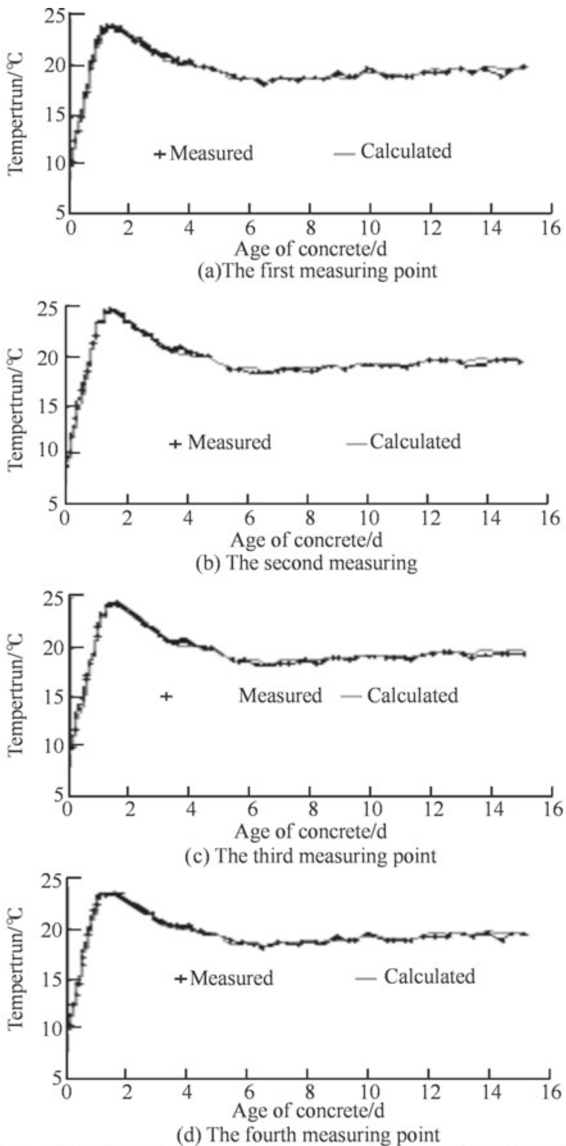

Fig.5 Calculated temperature compared to experimental values at RH=80%

So, in this paper, the dependence of relative humidity on heat transfer coefficients assumes linear relationship to simplify the prediction equation and the dependence of wind velocity assumes multinomial relationship to simplify the prediction equation. That is:

$$h = av^2 + bv + cR_h + d \tag{5}$$

where, v denotes wind velocity, m/s; R_h the relative humidity, %; a, b, c, d the constant parameters obtained by situ tests. By a regression equation using these data when v between 1.8 m/s and 3.6 m/s, the following equation was obtained to estimate heat transfer coefficient:

$$h = 0.9337v^2 - 1.15v + 7.365R_h + 3.937 \tag{6}$$

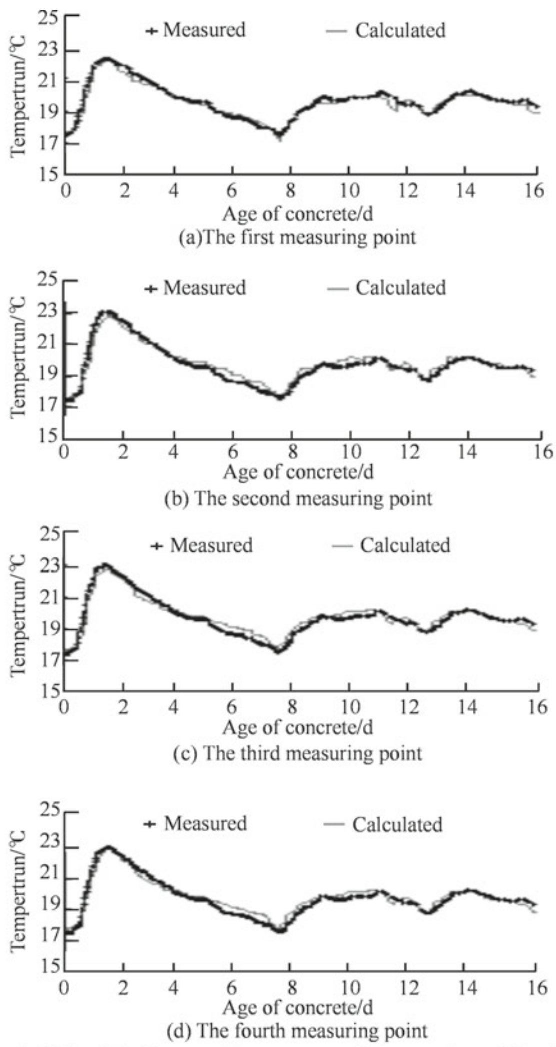

Fig.6 Calculated temperature compared to experimental values with wind velocity of 1.8 m/s

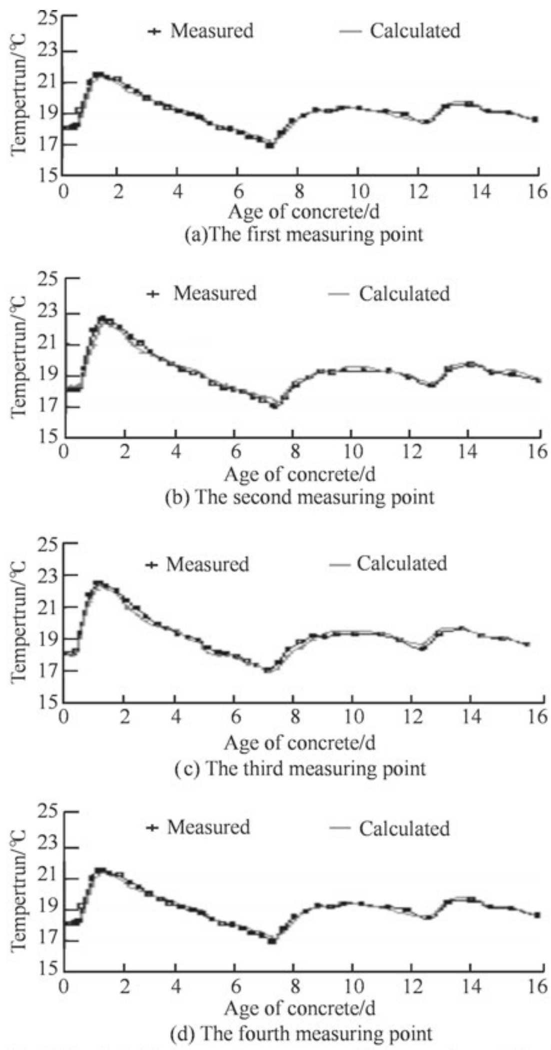

Fig.7 Calculated temperature compared to experimental values with wind velocity of 3.6 m/s

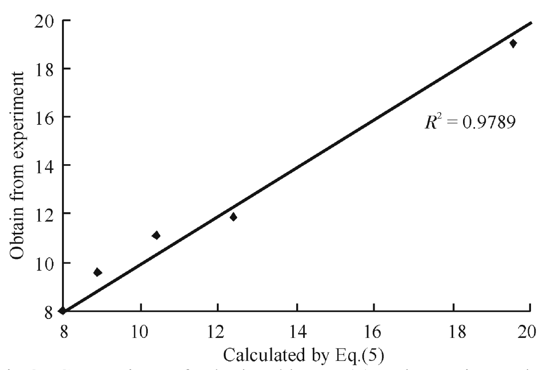

Fig.8 Comparison of calculated by Eq.(5) and experimental one (Unit: $m^2 \cdot h \cdot$ ℃)

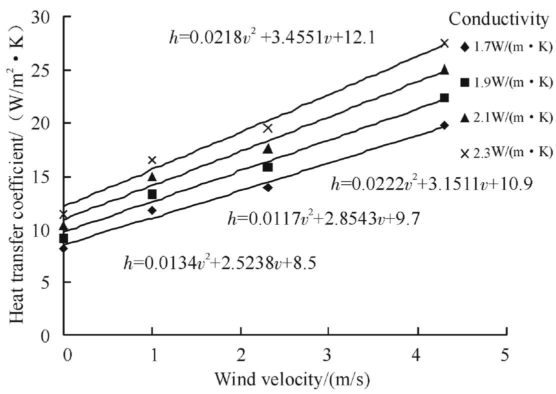

Fig.9 Relationship between wind velocity and heat transfer coefficient of the Ref. [7]

Fig.8 reveals a close relationship between heat transfer coefficient of concrete predicted from Eq. (6) and its measured values. The sample correlation coefficient R of 0.989 indicates that Eq. (6) is quite reasonable.

Fig.9 shows the quite agreement relationship between heat transfer coefficient and wind velocity at 20 ℃ regardless of humidity from the Ref.[7], where the heat transfer coefficient was obtained using Eq. (7),

$$h_a = \lambda_i \frac{A_i}{B_i} \tag{7}$$

where, h_a is the convective heat transfer coefficient; $A_i=(\mathrm{d}T/\mathrm{d}x)_i$, $B_i=(T_s-T_\infty)_i$, T_s the temperature at the specimen surface; T_∞ the temperature of ambient air; λ_i the thermal conductivity; and dT/dx is the thermal radiant at the surface, i refers to each location of temperature measurement. From Eq. (7), it is noted that the thermal conductivity directly influences the determination of the heat transfer coefficient. The thermal conductivities considered here were 1.7, 1.9, 2.1, and 2.3 W/(m K), which are adopted from a study by Kim *et al* [17]. So, if one applies Eq. (5) to the analysis of heat conduction in any concrete structures, one can make accurate evaluation of the spatial and temporal temperature distribution through any numerical techniques.

4 Conclusions

a) Predict model of thermal conductivity was presented in terms of the amount of aggregate, fine aggregate fraction, and cement paste of specimen, thermal conductivity obtained using the model and experimental results showed a closed relationship, and their correlation coefficient R of 0.989 indicated that Eq. (3) is quite reasonable and simple.

b) The temperature distribution of concrete by calculated heat transfer coefficient of inverse analysis showed an agreement with which of experimental results, and the max error is no more than 5%, which indicates that the predict model is feasible and heat transfer coefficient is accurate.

c) Heat transfer coefficient increases with the wind velocity as well as relative humidity, a predict equation on heat transfer coefficient about wind velocity and relative humidity is given. The proposed relationship correlates test results well by indicating the sample correlation coefficient of 0.994, but needs to be further examined with additional and precise experimental test results.

References

[1] Morabito P. Measurement of the Thermal Properties of Different Concretes [J]. *High Temp. High Press,* 1989, (21) :51– 59

[2] Nevile AM. *Properties of Concrete* [M]. UK: Longman, 1995:50-60

[3] ACI Committee 207. *Mass Concrete, ACI Manual of Concrete Practice,* Part 1[R]. Detroit: American Concrete Institute, 1994

[4] Kim Kook-Han, Jeon Sang-Eun, Kim Jin-Keun, *et al.* An Experimental Study on Thermal Conductivity of Concrete[J]. *Cement and Concrete Research,* 2003, (33) :363–371

[5] Branco FA, Mendes PA, Mirambell E. Heat of hydration effects in concrete structures[J]. *ACI Mater .J.* ,1992,89(2):139–145

[6] Mendes P. T*emperature Gradients for Concrete Bridges* [D]. Lisbon: Technical University, 1989: 89

[7] Lee Yun, Choi Myoung-Sung, Yi Seong-Tae, *et al.* Experimental Study on the Convective Heat Transfer Coefficient of Early-age Concrete[J]. *Cement & Concrete Composites*, 2009, (31): 60–71

[8] Zhu BF. *Thermal Stresses and Temperature Control of Mass Concrete* [M]. Beijing: China Electric Power Press,1998:12-17(in Chinese)

[9] MB Abd-el-Malek, MM Helal. Group Method Solution for Solving Nonlinear Heat Diffusion Problems [J].*Applied Mathematical Modeling*, 2006, 30(9):930–940

[10] Lanciani A, Morabito P, Rossi P. Measurement of the Thermo Physical Properties of Structural Materials in Laboratory and in site: Methods and Instrumentation [J]. *High Temp High Press,* 1989, (21): 391– 400

[11] Japan Concrete Institute. *The Measuring Methods of Conductivity, Diffusivity and Specific heat of Concrete and Their Application*[M]. J. Jpn. Concr, Inst. Mass Concr. Div,1982

[12] Liley PE. *Steam Table in SI Units, Private communication* [M]. West Lafayette: Purdue University, 1978

[13] Epifanov AP. Lukyanov AT, Rozenfeld GO, *et al*. Heat Transfer of Concrete Through External Surfaces [J]. *Power Technology and Enginee-ring,* 1974, 8(5): 438–440

[14] Dorignac E. Experimental Heat Transfer on the Windward Surface of a Perforated Flat Plate [J]. *International Journal of Thermal Sciences*, 2005, (44): 885-894

[15] Ozawa S. Study on the Early Age Cracking of Massive Concrete and Its Prevention Measure [J]. *Water Power for Electric Generation,*1962,(57): 254–261

[16] Holman JP, Gajda WJ Jr. *Experimental Methods for Engineers* [M]. New York: McGraw-Hill, 1989:37-83

[17] Kim KH, Jeon SE, Kim JK, Yang SC. An Experimental Study on Thermal Conductivity of Concrete[J].*Cement Concrete Research,* 2003,33(3):363–371