Cement & Concrete Composites 31 (2009) 60–71

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Experimental study on the convective heat transfer coefficient of early-age concrete

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ARTICLE INFO

Article history:
Received 3 September 2007
Received in revised form 17 September 2008
Accepted 19 September 2008
Available online 30 September 2008

Keywords:
Thermal property
Convective heat transfer coefficient
Wind velocity
Curing condition
Ambient temperature
Evaporation effect

ABSTRACT

During the process of setting and hardening in concrete, the temperature profile shows a gradual nonlinear distribution due to the development of heat of hydration in cement. At early ages of concrete structures, this nonlinear distribution can have a large influence on crack evolution. It is thus important to obtain an accurate temperature history, and to do this, it is necessary to examine the thermal properties of the concrete. In this study, the convective heat transfer coefficient, which represents the heat transfer between a concrete surface and ambient air, was experimentally investigated with test variables such as the velocity of wind, the curing conditions, and the ambient temperature.

For analyses using the thermal equilibrium boundary condition, it is generally noted that most of the heat release by the evaporation of moisture occurs at an early stage. To consider this phenomenon, the existing thermal equilibrium boundary condition has been modified so as to consider the evaporation quantity due to the evaporation effect. Convective heat transfer coefficients for a specific case were then calculated from the modified thermal equilibrium boundary condition using experimental results.

1. Introduction

Thermal cracking problems due to the heat of hydration of cement in concrete structures were first noted in the many large-sized concrete dams that were constructed in the United States in the 1930s. Since this time, many studies concerning thermal cracking have been performed. In particular, a number of numerical tools using the finite element method (FEM) have been developed. Currently, however, input data related to the thermal properties of the concrete have not been thoroughly investigated. For structures located at coastal regions or areas under the influence of strong winds, however, thermal damage by convective heat transfer may also be prevalent. In order to more accurately evaluate such thermal damage, it is necessary to consider thermal properties such as the convective heat transfer coefficient.

The convective heat transfer coefficient associated with air convection (designated as 'the convective heat transfer coefficient' in this study) is one of the most important thermal properties, representing the heat transfer between a concrete surface and ambient air. In contrast to other thermal properties such as thermal conductivity and the specific heat of the concrete, however, relatively few studies on this coefficient have been performed. Furthermore, as several well-known factors such as roughness of the concrete surface, materials of the formwork, and flow characteristics influence the heat transfer coefficient, it is difficult to determine the coefficient. Nevertheless, some experimental results and prediction models that have been presented are worth noting. Rastrup [1] has reported that the convective heat transfer coefficient typically ranged from 5 to 35 W/(m^2 K). Other researchers [2,3] also agreed with this range. Branco et al. [4] and Mendes [5] recommended that influencing factors that affect the coefficient should be verified through experimental results, and proposed a prediction model as a function of the roughness of the surface of the concrete and the velocity of the wind. Furthermore, in Japan, prediction models related to the coefficient have been proposed from in situ experiments. According to the experimental results obtained from the Ohbayashigawa Dam [6], the coefficient has a value of 14–15 W/(m^2 K) when the wind velocity ranges from 2 to 3 m/s. Experiments by Yamagawa et al. [7] suggest that the coefficient has a value of 9–13 W/(m^2 K) for the same range of wind velocity as used in the Ohbayashigawa Dam study. Finally, Ozawa [8] proposed a prediction model with wind velocity by analyzing these experimental results.

Although several studies concerning the heat transfer coefficient have been carried out as briefly summarized above, existing prediction models show different results according to the experimental conditions. Furthermore, the effects of the curing condition, the ambient temperature, and the evaporation effect on the coefficient were not reflected in these studies. In the present study,

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0958-9465/$ - see front matter
doi:10.1016/j.cemconcomp.2008.09.009

these effects are considered and a testing method that obtains the coefficient is newly developed and a modified thermal equilibrium equation is suggested.

2. Experimental program

2.1. Mixture proportion

The concrete mixture proportions selected for the prismatic and 28-day compressive strength cylindrical specimens are given in Table 1. For good workability and consolidation of the concrete, two kinds of admixtures, which meet the ASTM C 494 requirements for a Type F admixture [9], were also used. The proportion is similar to that of a mixture used in the containment structure of at least one nuclear power plant (NPP) in South Korea.

2.2. Test variables

To investigate the effect of the curing conditions and ambient temperature as well as the wind velocity on the convective heat transfer coefficient, the wind velocity, curing conditions, and ambient temperature are selected as the main parameters, as shown in Table 2. To calibrate the initial convective heat transfer coefficient, evaporation effect tests were additionally conducted.

2.3. Experimental method

An overview of the test specimen set-up is shown in Fig. 1. Each experiment on several wind velocities was simultaneously performed for three sets of curing conditions (i.e., without a curing cover, with a curing blanket, and with a curing blanket and a plastic sheet). 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.

To determine the effects of cross-sectional area of specimens used in this study, two sizes of specimens (i.e., 200 mm × 200 mm × 500 mm and 500 mm × 500 mm × 500 mm, Fig. 2a) were selected; the convective heat transfer coefficients for a specific case (e.g., a wind velocity of 1.0 m/s, without a curing cover, and a temperature of 20 °C) were obtained and compared. A 500 mm × 500 mm × 500 mm specimen was also used for edge effect tests of the same case. To measure the temperature distribution within the specimen with specimen size, K-type thermo-couples were embedded at the center of the cross-section (the first and second figures of Fig. 2a) and seven positions along the longitudinal direction of the specimen (Fig. 2b). For edge effect tests, K-type thermo-couples were embedded at distances of 20 mm, 50 mm, 100 mm, 200 mm, and 500 mm from the surface exposed first to the wind (the third figure of Fig. 2a). In order to simulate one-dimensional heat transfer, the specimen was surrounded by insulating materials with a thickness of 300 mm, except at the upper surface of the specimen (the fourth figure of Fig. 2a). To perform the evaporation test, an electro-scale, used to measure the specimen's weight with time, was installed slightly below the insulating materials.

Table 1
Mixture proportion of the concrete

w/c[a] (%)	Unit weight (kg/m^3)					
	W	C	S	G	Admixture	
					AE	WR
44.4	169	381	746	959	0.034	0.62

[A] Water-cementitious materials ratio.

Table 2
Test variables

Wind velocity (m/s)	Curing condition	Ambient temperature (°C)
0–5	w/o curing cover Curing blanket Curing blanket + plastic sheet	20, 30

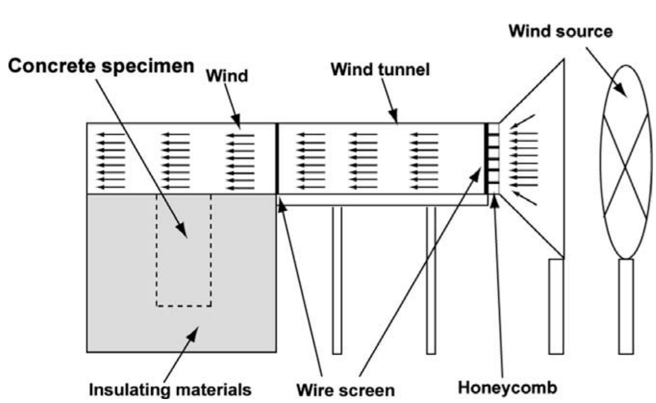


Fig. 1. An overview of the test specimen set-up.

3. Analysis method of experiment results based on the thermal equilibrium equation

3.1. Thermal equilibrium condition on the surface

The convective heat transfer coefficient is related to the boundary condition of a concrete surface that is in contact with ambient air. In this boundary condition, the thermal equilibrium condition can be expressed as the following one-dimensional equation:

$$h_a(T_s - T_\infty) = \lambda\left(\frac{dT}{dx}\right) \quad (1)$$

where h_a is the convective heat transfer coefficient; T_s is the temperature at the specimen surface; T_∞ is the temperature of ambient air; λ is the thermal conductivity; and dT/dx is the thermal gradient at the surface.

3.2. Convective heat transfer coefficient

Using Eq. (1), experimental results of the convective heat transfer coefficient were analyzed. The given time was determined using the concept of maturity, as shown in Eq. (2), to identify development time of the thermal characteristics of each concrete specimen. The equation is as follows:

$$M = \sum(T_s - T_o)\Delta t \quad (2)$$

where M is the maturity; T_o is the datum temperature (−10 °C); and Δt is the time interval. Saul [10] stated the principle of the maturity concept as, "concrete of the same mixture at the same maturity has approximately the same strength whatever combination of temperature and age goes to make up that maturity".

Regression analyses using temperature distributions within the specimen at times having the same maturity were performed. Fig. 3 shows the temperature distribution lines of four specific cases with maturity of test results for a wind velocity of 0.0 m/s

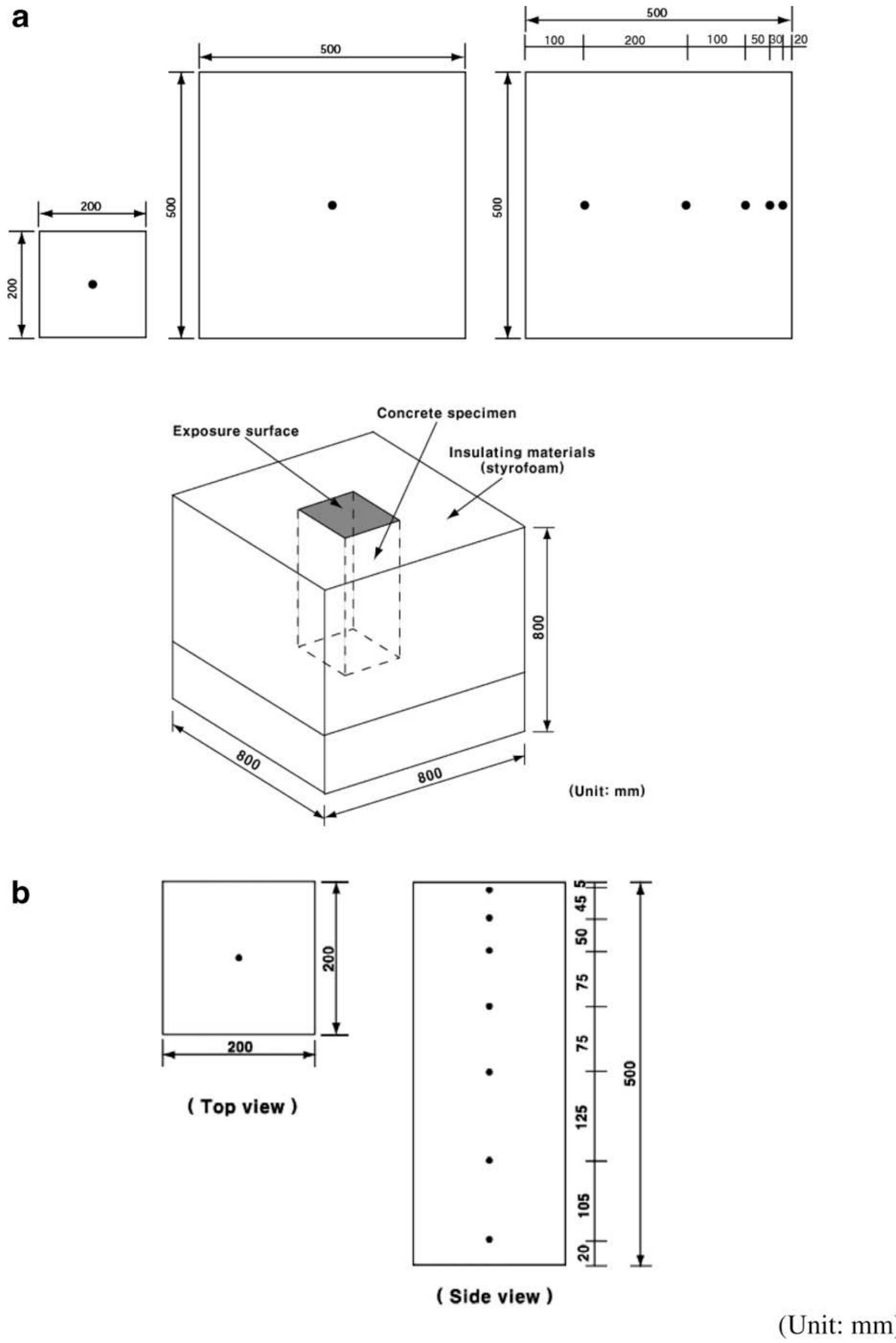


Fig. 2. (a) Sizes and shape of specimens and insulating materials and (b) locations of thermo-couples.

and for those without a curing cover. In Eq. (1), thermal gradients dT/dx and temperatures at the specimen surface T_s were obtained using the equations from the regression analyses. In this paper, Eq. (3) is viable, as it is assumed that the convective heat transfer coefficient is constant at the same wind velocity, as previously mentioned. To obtain the heat transfer coefficient using Eq. (4), knowledge of the surface temperature is needed

$$\lambda_{i+1} = \lambda_i \frac{A_i B_{i+1}}{A_{i+1} B_i} \tag{3}$$

$$h_a = \lambda_i \frac{A_i}{B_i} \tag{4}$$

where $A_i = \left(\frac{dT}{dx}\right)_i$ and $B_i = (T_s - T_\infty)_i$; i refers to each location of temperature measurement.

From Eq. (4), it is noted that the thermal conductivity directly influences the determination of the heat transfer coefficient. The thermal conductivities considered in this study were 1.7, 1.9, 2.1, and 2.3 W/(m K), which are adopted from a study by Kim et al. [11]. Among the concrete mix proportions that Kim et al. [11] tested, 2.1 W/(m K) was reported as the thermal conductivity of the concrete mix assigned with C-GC1, which had a very close mix proportion with our concrete mix. Therefore, we divided the thermal conductivity values reported in Kim et al. [11] into four groups and obtained the convective coefficient according to these values, as shown in Table 3. Additionally, among four thermal conductivities, we took 2.1 W/(m K) as the thermal conductivity of our concrete mix and proceeded to the consideration of evaporation effect as mentioned in the following section.

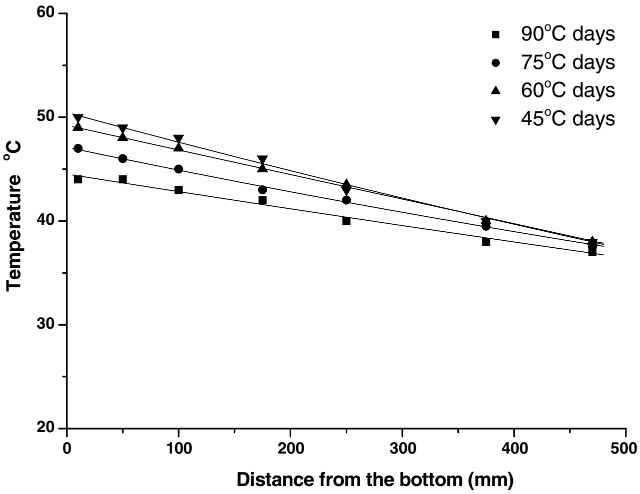


Fig. 3. Temperature distribution lines with maturity.

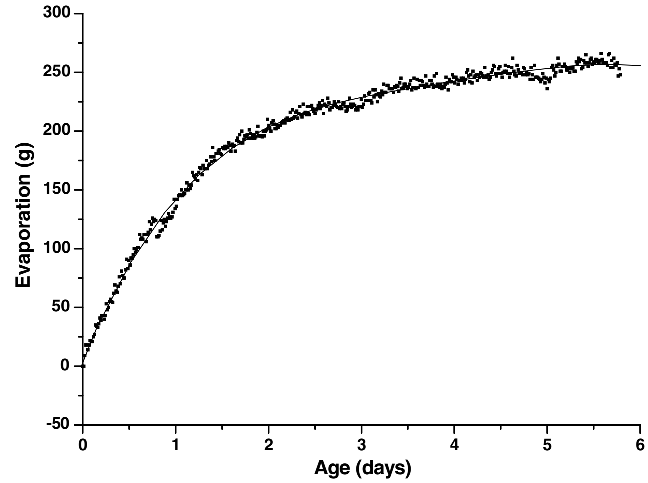


Fig. 4. Evaporation curve with age (wind velocity of 0.0 m/s and without a curing cover).

3.3. Consideration of the evaporation effect

When the experimental results for the case without a curing cover are analyzed using the existing thermal equilibrium equation, it can be seen that the convective heat transfer coefficient is large at an early stage (cf. Fig. 10 in chapter 4). This phenomenon is assumed to be due to the evaporation of moisture within the concrete by the evaporation effect.

To evaluate the evaporation effect, an evaporation quantity test with time was performed for a specific case (i.e., a wind velocity of 0.0 m/s and without a curing cover). The results are shown in Fig. 4. The evaporation heat of moisture at the surface can be obtained from the thermal properties tabulated in a heat transfer book [12]. For example, if the temperature is 20 °C, the evaporation heat has a value of 2450 J/g. In performing the tests, it is found that the temperature change at the surface is generally influenced by the occurrence of the heat of hydration, heat transfer due to convection, and heat release due to the evaporation effect. Detailed explanations of these factors are provided in the following subsections.

3.3.1. Heat of hydration

The prediction of the heat of hydration is complicated by the size and geometry of the specimen. When the analyses are carried out, however, the amount of heat of hydration occurring at a given time is assumed to be minimal.

3.3.2. Heat transfer due to convection

Heat transfer due to convection (i.e., heat flux) occurs because there is a temperature difference between the concrete surface and the ambient air. The heat transfer can be calculated by

$$q_{\text{convec}} = h_a(T_s - T_\infty) \quad (5)$$

where q_{convec} is the heat transfer due to convection in W/m^2.

3.3.3. Heat release due to the evaporation effect

To predict the evaporation heat with time, variances in evaporation heat were determined by a regression analysis of the test results, as shown in Fig. 4. At an early stage, the variance increased, and the rate of increase decreased incrementally as time passes. After a certain amount of time elapses, however, the difference becomes less distinct.

3.3.4. Modified thermal equilibrium equation considered the evaporation effect

The convective heat transfer coefficients determined using the existing thermal equilibrium condition at an early stage show that there is a danger of overestimation of the results. This is attributed to the absence of consideration of the evaporation effect by the evaporation of moisture. To address this problem, a modified thermal equilibrium condition (Eq. (6)) that takes into account the evaporation effect before the hardening of concrete has been suggested

Table 3
Analytical results for $T = 20$ °C and $T = 30$ °C

Ambient temperature		Convective heat transfer coefficient, h_a (W/(m^2 K))							
Curing condition	Conductivity W/(m K)	$T = 20$ °C				$T = 30$ °C			
		0 m/s	1 m/s	2.3 m/s	4.3 m/s	0 m/s	1 m/s	2.3 m/s	4.3 m/s
w/o curing form	1.7	8.1	11.7	13.9	19.7	8.3	13.0	14.7	20.9
	1.9	9.1	13.3	15.8	22.3	9.5	14.8	16.7	23.7
	2.1	10.3	15.0	17.6	25.0	10.7	16.6	18.7	26.5
	2.3	11.3	16.5	19.5	27.5	11.7	17.7	20.7	29.3
Curing blanket	1.7	3.1	3.6	4.0	4.3	3.6	3.8	4.4	5.1
	1.9	3.4	4.0	4.7	5.6	4.0	4.3	5.0	5.8
	2.1	3.9	4.6	5.2	6.3	4.5	4.8	5.5	6.5
	2.3	4.3	5.1	5.6	6.9	5.0	5.3	6.1	7.2
Curing blanket + plastic sheet	1.7	1.8	2.0	2.3	3.3	1.9	2.3	3.3	3.6
	1.9	2.2	2.3	2.6	3.8	2.2	2.5	3.4	4.0
	2.1	2.4	2.6	3.0	4.3	2.4	2.9	3.9	4.5
	2.3	2.6	2.9	3.3	4.7	2.6	3.2	4.4	5.0

$$\lambda\left(\frac{dT}{dx}\right) = h_a(T_s - T_\infty) + \frac{dE}{dt} \times \frac{l_b}{A} \tag{6}$$

where E is the evaporation quantity (g) and A is the cross-sectional area in which evaporation occurs.

4. Experiment and analysis results

Figs. 5 and 6 illustrate the relationships between the temperature and age with the wind velocity, curing condition, and ambient

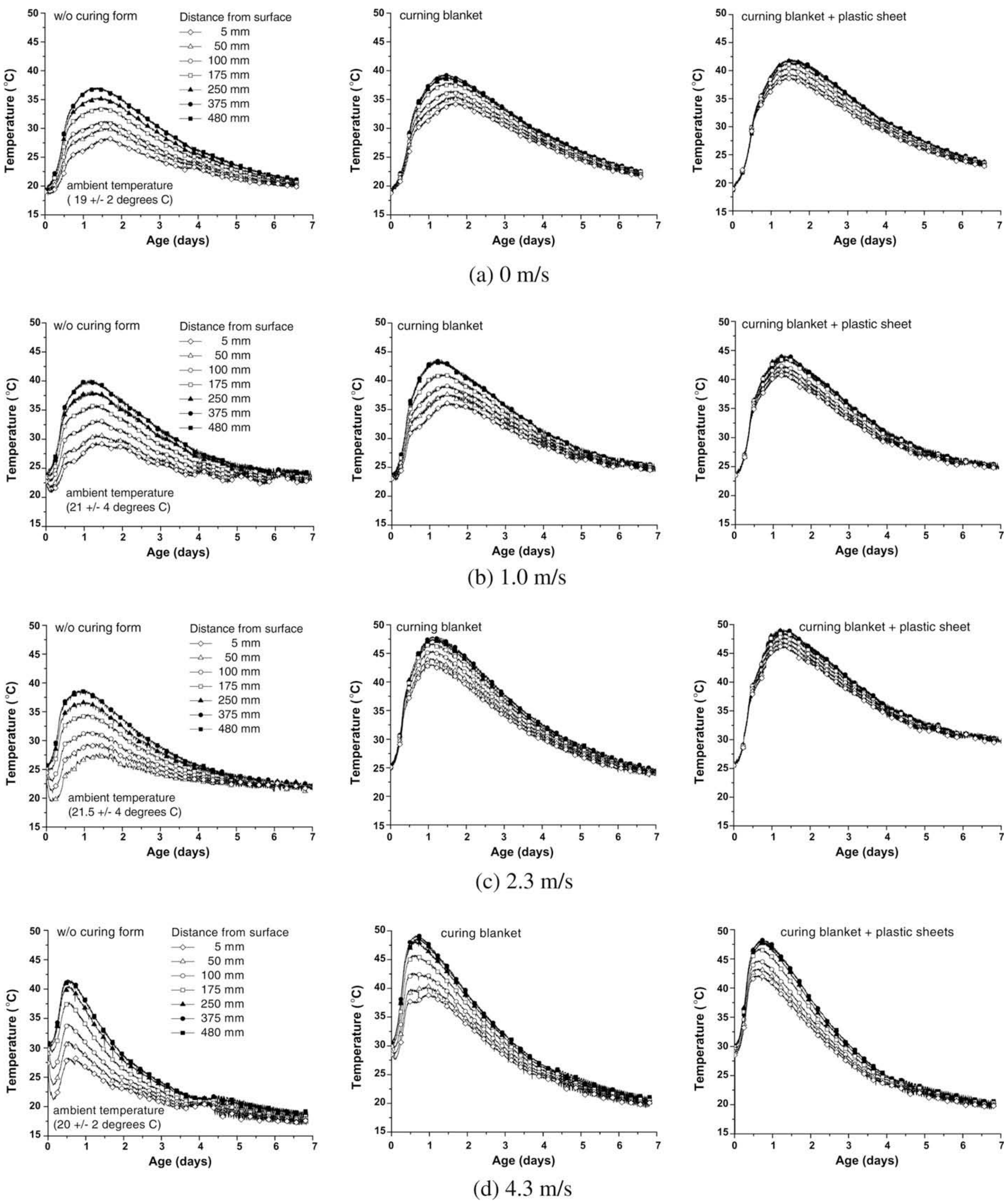


Fig. 5. Experimental results for $T = 20\,^{\circ}C$.

temperature. Table 3 shows the heat transfer coefficients as they relate to the wind velocity, curing condition, ambient temperature, and thermal conductivity.

4.1. The specimen size and edge effect

Fig. 7a, which shows the relationship between convective heat transfer coefficients and ages, indicates that there are no apparent

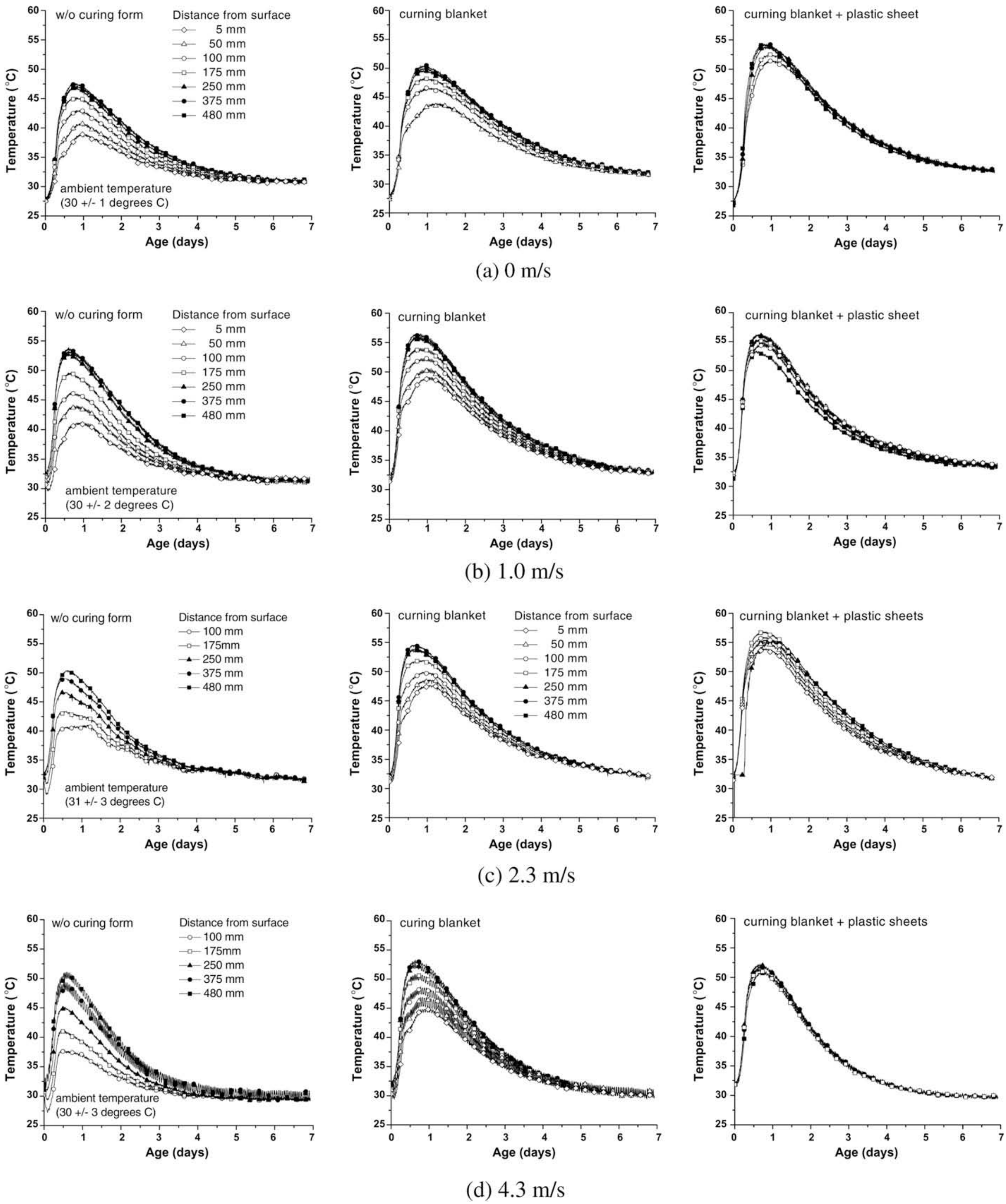


Fig. 6. Experimental results for $T = 30$ °C.

differences in the heat transfer coefficients. Fig. 7b, which shows the results of edge effect tests, illustrates that when the distance from the surface is greater than 100 mm, the convective heat transfer coefficients have similar values. When the thermo-couples were located 20 mm and 50 mm from the surface, however, some differences between the heat transfer coefficients were observed. This variation is attributed to the heat released to insulating materials (Styrofoam) and end effects according to the location of the thermo-couples. Finally, the concrete specimen was determined to have dimensions of 200 mm × 200 mm × 500 mm assuming the isotherm condition in a given cross-section. Namely, it was concluded that when the cross-section noted above was used the temperature difference with location from one side of the specimen to the other side is minor.

4.2. Effect of the wind velocity

From Fig. 8, it is noted that the convective heat transfer coefficient increases as the wind velocity increases, regardless of the curing condition, as the heat release rate by convection from the concrete surface to ambient air increases with the wind velocity. This tendency is more pronounced in the case without a curing cover compared to that with a curing blanket and with a curing blanket and a plastic sheet, respectively. This indicates that curing materials reduce the heat release at the surface of the specimen. Accordingly, when curing materials are used the difference in the temperature between the surface and the center of the concrete specimen is reduced compared to the case without a curing cover.

The rate of temperature reduction of the specimen's center is less than that of the specimen surface (Figs. 5 and 6). This signifies that the heat release rate through convection (from the surface to ambient air) is larger than that by conduction (from the center to the surface) as the wind velocity increases. Therefore, it can be concluded that the convective heat transfer coefficient, which represents the heat release, increases with the wind velocity.

Fig. 9 shows a comparison of convective heat transfer coefficients calculated using the existing models with the test results obtained in this study in the case without a curing cover and with $T = 20$ °C. From this figure, it is noted that the convective heat transfer coefficient in this study is larger than that obtained from the existing models. In spite of the discrepancy with test results from other models, the convective heat transfer coefficient increases with wind velocity in accordance with the overall trend of other models. The differences in the convective heat transfer coefficients among the test results and existing models are affected by minor differences in the testing methods, testing conditions during the installation processes, and the analysis methods selected for each study.

4.3. Effect of the curing condition

Fig. 8 also shows the difference in convective heat transfer coefficients with curing materials. When curing materials are used, the temperature difference between the center and the surface of the specimen decreases, as the heat release rate into ambient air is reduced (Figs. 5 and 6). Comparisons of the convective heat transfer coefficients with type of curing materials are also shown for the same case. More specifically, when only a curing blanket was used, the heat release rate into ambient air increased compared to the use of a curing blanket and a plastic sheet. Accordingly, when only a curing blanket was used, the difference in the temperatures increases and the adiabatic effect decreases compared to the cases where a curing blanket and a plastic sheet are used.

4.4. Effect of the ambient temperature

Under the same wind velocity and curing conditions, the test results (Fig. 10) concerning the ambient temperature (i.e., $T = 20$ or 30 °C) reveal that the variance of the convective heat transfer coefficients is not significant. That is, the difference in the heat release rate with ambient temperature was minimal. This is due to the fact that when the ambient temperature changes, the individual temperature at each location within the concrete varies. However, the relative difference between temperatures at different locations is nearly consistent. Considering the data as a whole, it is concluded that the ambient temperature has no apparent effect on the convective heat transfer coefficient, which represents the heat release at the surface.

4.5. Effect of the evaporation effect

The evaporation effect is a phenomenon in which evaporation occurs at the interface between a solid and a liquid. In this study, at an early age of concrete hardening (approximately within 12 h after casting), a large amount of water evaporated due to the heat release caused by the evaporation of moisture within the concrete (Fig. 4).

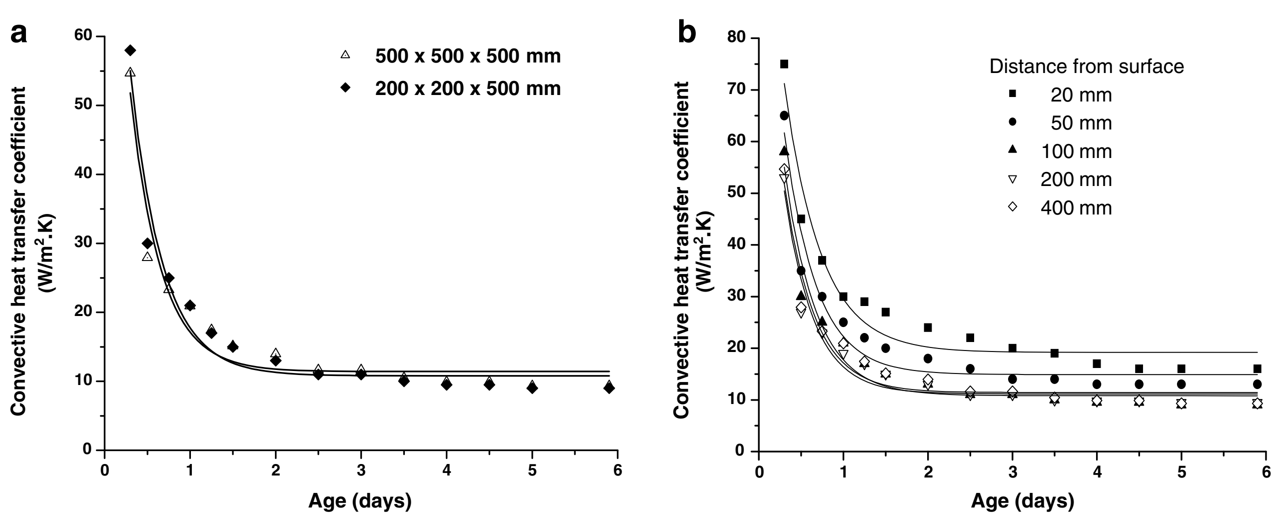
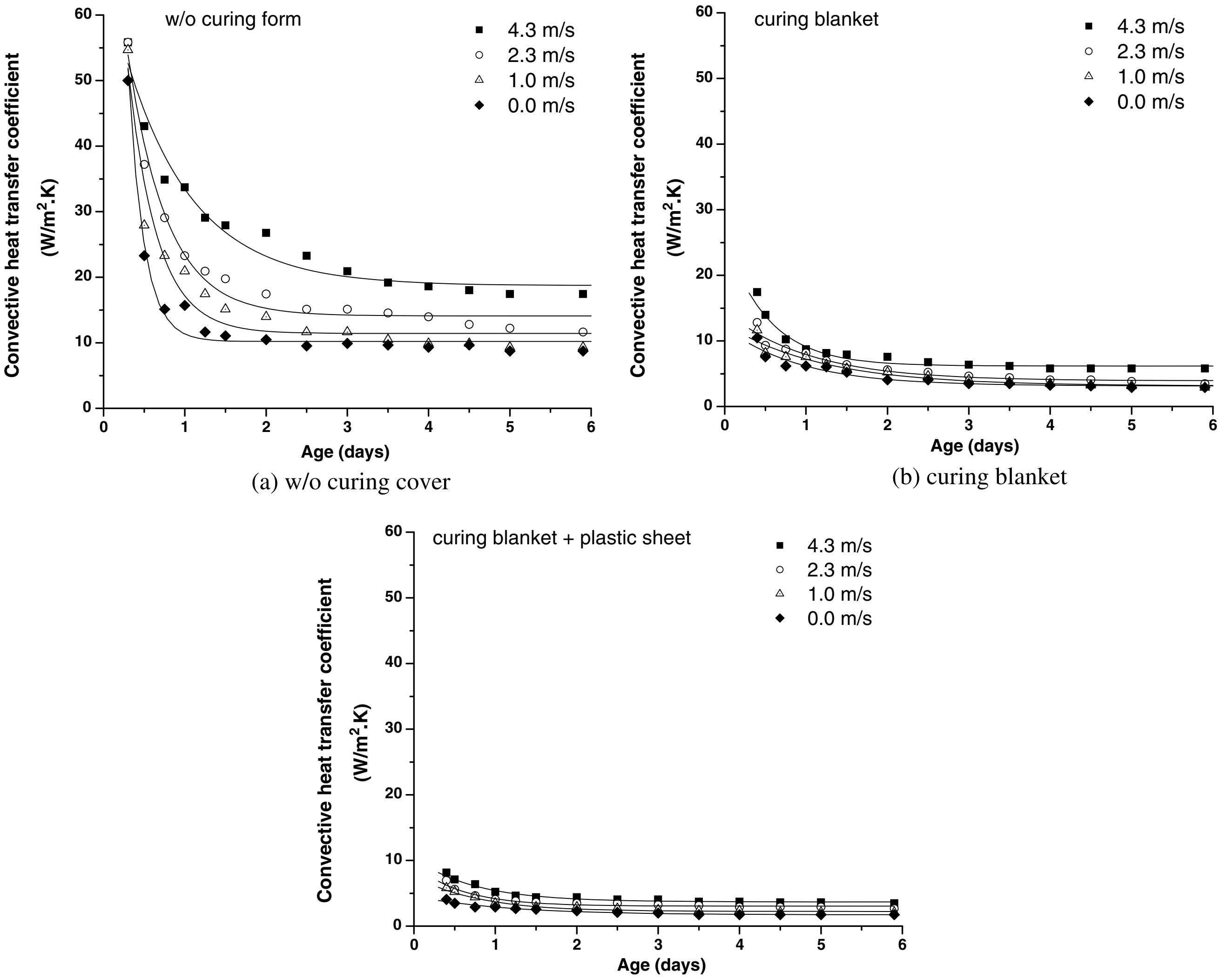


Fig. 7. Effect of the specimen type: (a) size effect test results and (b) edge effect test results.



(a) w/o curing cover

(b) curing blanket

(c) curing blanket + plastic sheet

Fig. 8. Convective heat transfer coefficients with wind velocity and curing condition.

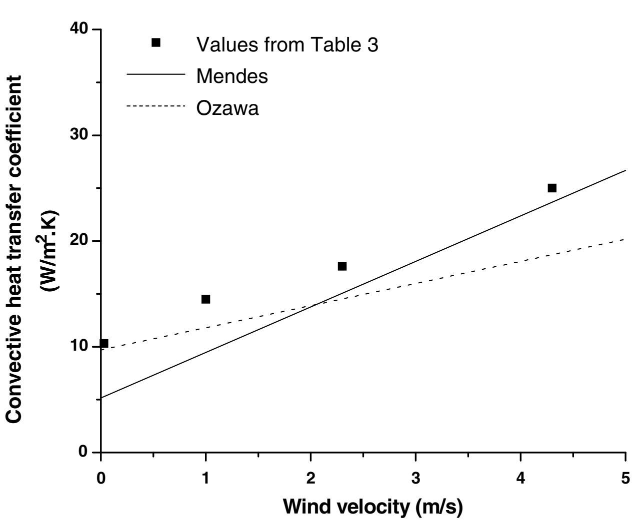
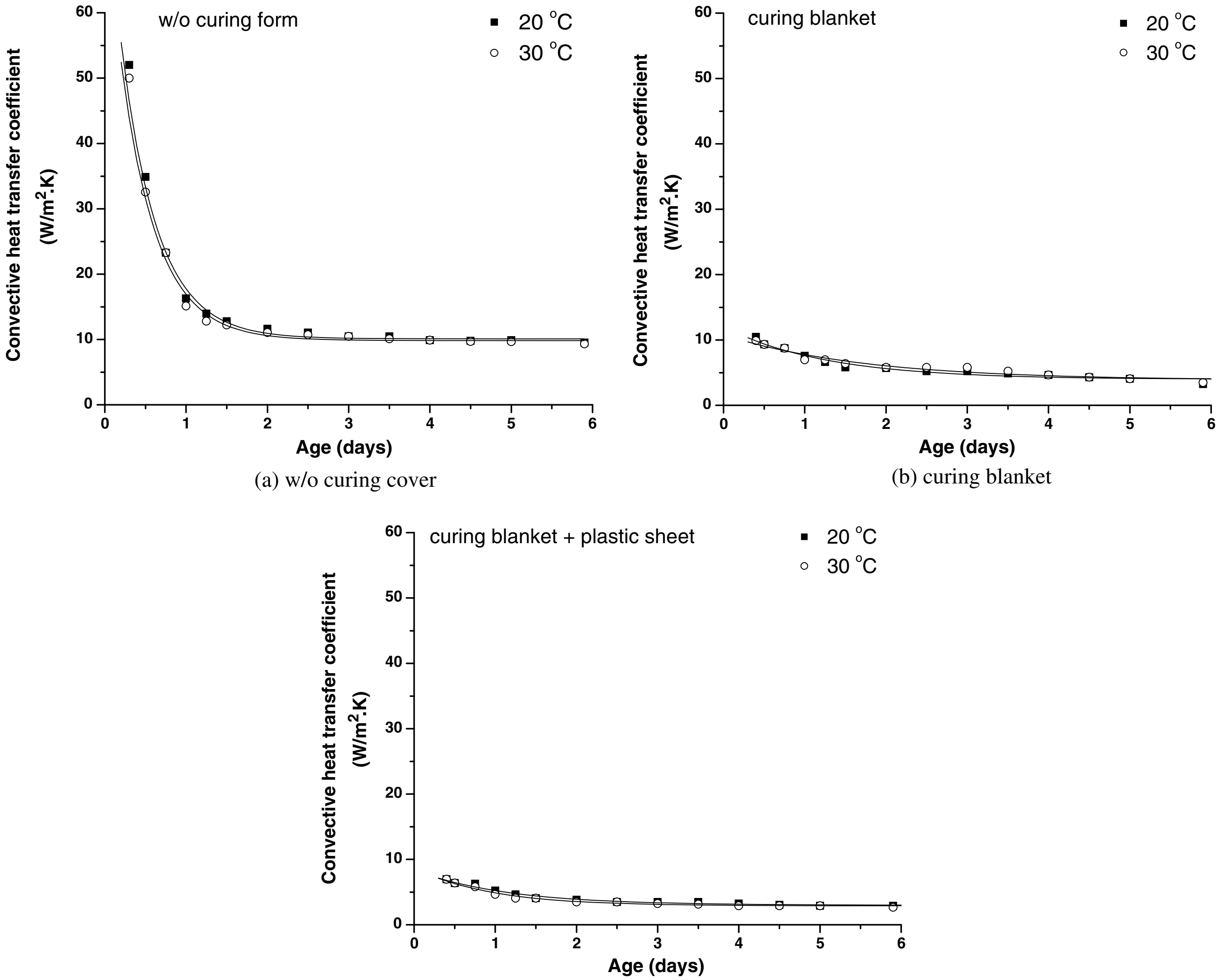


Fig. 9. Relationship between convective heat transfer coefficient data obtained in this study and previous models.

From the analysis of the test results concerning the wind velocity, it is noted that in the case without a curing cover, most of the heat release occurs at an early stage. This phenomenon is related to the evaporation of moisture within the concrete before hardening, and this affects the initial convective heat transfer coefficient (Fig. 11). The heat release by the evaporation of moisture at an early stage of curing can play an important role in the temperature distribution within the concrete. Accordingly, when the convective heat transfer coefficient is determined, the evaporation effect caused by the evaporation of moisture should be considered.

Fig. 12 shows the analysis results obtained using the modified and existing thermal equilibrium conditions on the test results. From this figure, it is noted that the variances of coefficients with time are not apparent when the evaporation effect is considered.

Comparisons of convective heat transfer coefficients obtained for both cases (i.e., cases when the evaporation effect is considered and when it is not considered) and for a specific case (i.e., a wind velocity of 0.0 m/s and without a curing cover) are shown in Table 4. From this table, it is noted that the difference between convective heat transfer coefficients for both cases is approximately 30–



(a) w/o curing cover

(b) curing blanket

(c) curing blanket + plastic sheet

Fig. 10. Convective heat transfer coefficients with ambient temperature and curing condition (wind velocity of 0.0 m/s).

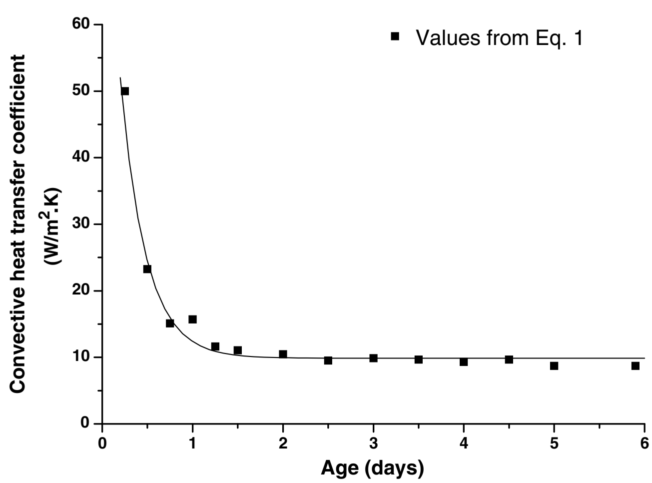


Fig. 11. Convective heat transfer coefficients with age ($T = 20$ °C, wind velocity of 0.0 m/s and without a curing cover).

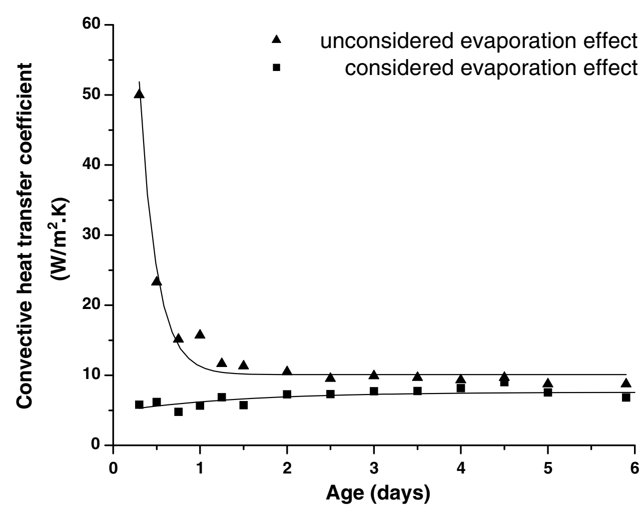


Fig. 12. Relationship between convective heat transfer coefficient and age with evaporation.

40%. Accordingly, when determining the convective heat transfer coefficient, the evaporation effect caused by the evaporation of moisture should be considered. In future studies, more experiments involving other cases are required.

Table 4
Comparisons of convective heat transfer coefficients

Curing condition	Wind velocity (m/s)	Ambient temperature (°C)	Conductivity (W/(m K))	Convective heat transfer coefficient, h_a W/(m^2 K)	
				w/o evaporation effect	w/evaporation effect
w/o curing form	0	20	1.7	8.1	4.9
			1.9	9.1	6.1
			2.1	10.3	7.2
			2.3	11.3	8.3

5. Effect of the convective heat transfer coefficient on thermal stress evolution in structural concrete

In this chapter, a thermal stress analysis for concrete structure is performed to investigate the effect of the convective heat transfer coefficient on the thermal cracking behavior in real concrete structure. The type of structure selected as a numerical example for the thermal stress analysis is a massive concrete wall of a nuclear power plant (NPP) intake structure. Only a quarter of the total structure needs to be considered due to symmetry, as shown in Fig. 13. Input data for the thermal stress analysis of the concrete wall are shown in Table 5. To consider the effect of various curing conditions (i.e., without a curing cover, with a curing blanket, and with a curing blanket and a plastic sheet), three types of convective heat transfer coefficients were selected from Table 3, as shown in Table 5. For the adiabatic temperature rise curve with w/c, the equation (i.e., Eq. (7)) of the Korea Concrete Institute (KCI) Code [13] was used

$$T = K[1 - e^{-\alpha t}] \quad (7)$$

where T is the adiabatic temperature rise at time t (°C), K is the maximum adiabatic temperature rise (50.18 °C), α is the temperature increasing velocity (1.25), and t is the time (day).

The temperature distributions for three types of curing conditions at 3.0 days are shown in Fig. 14. It looks as if the maximum temperature in the center of the concrete wall is similar to 66.7 °C, but the temperature distributions of the upper surface are different among the three cases. Fig. 15 shows the temperature history at the six points displayed in Fig. 13. As shown in Figs. 14 and 15, the temperature of the upper surface in Figs. 14 and 15a shows a rather low value in contrast with the other two cases due to the fast heat release of the with out curing cover case with high convective heat transfer coefficient. The fast release of heat at the surface of the concrete structure may cause the excessive tensile stress at the early age stage of concrete casting.

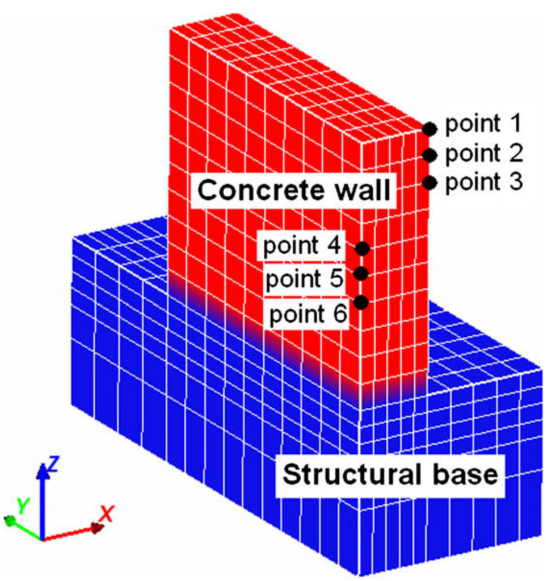


Fig. 13. Structural configuration and mesh modeling.

Table 5
Input data for thermal stress analysis of the concrete wall

Parameter		
Cement content (kg/m^3)	338	
Thermal conductivity (W/(m K))	2.1	
Ambient temperature (°C)	20	
Convection heat transfer coefficient (W/(m^2 K))	w/o curing cover	10.3
	Curing blanket	3.9
	Curing blanket + plastic sheet	2.4

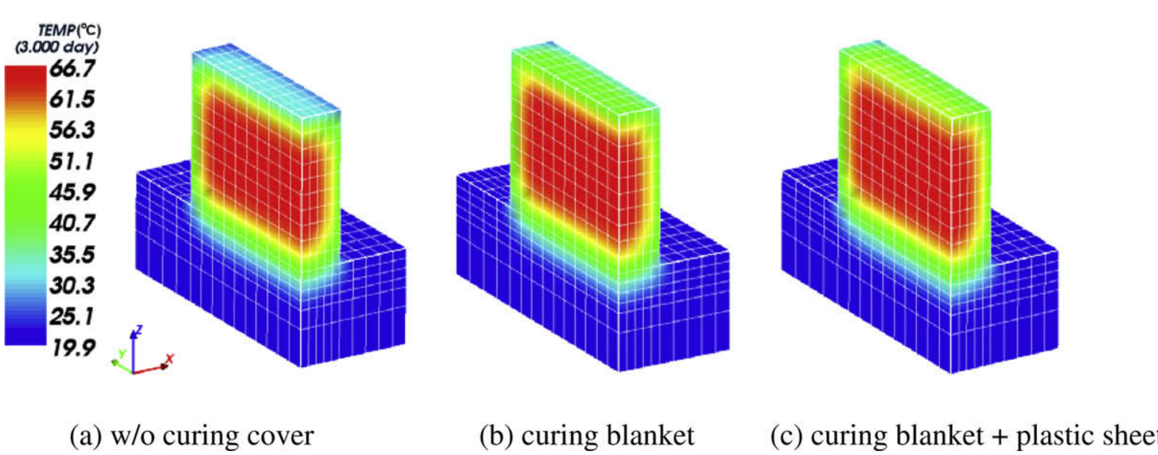
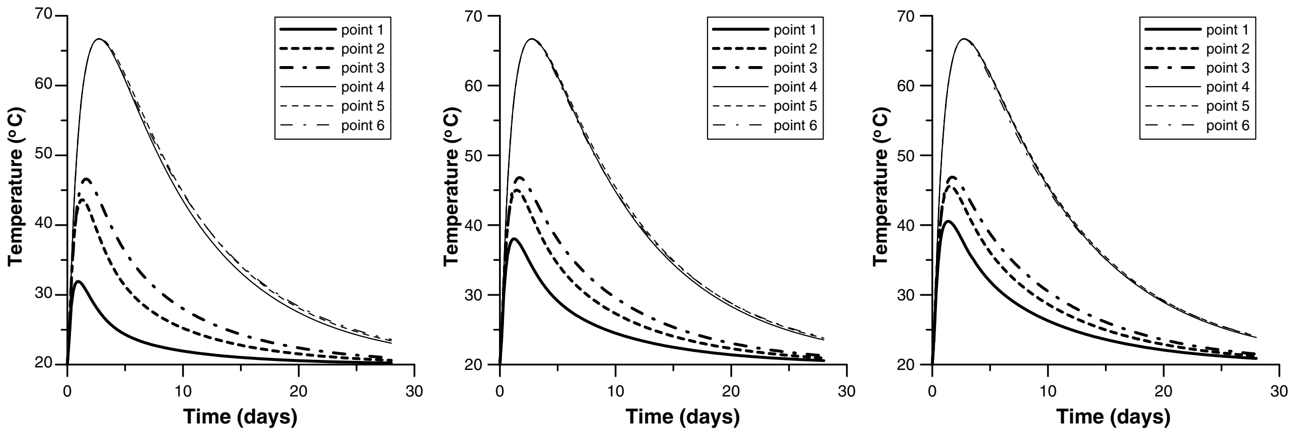


Fig. 14. Temperature distributions at 3.0 days.

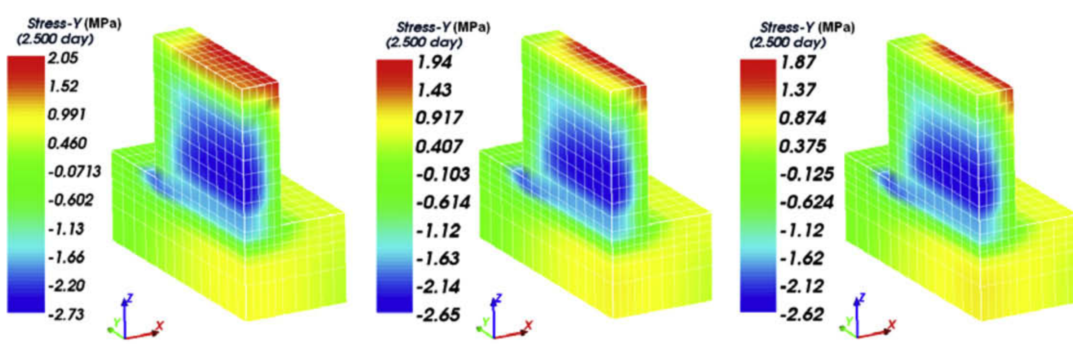


(a) w/o curing cover (b) curing blanket (c) curing blanket + plastic sheet

Fig. 15. Temperature history at six points in the concrete wall.

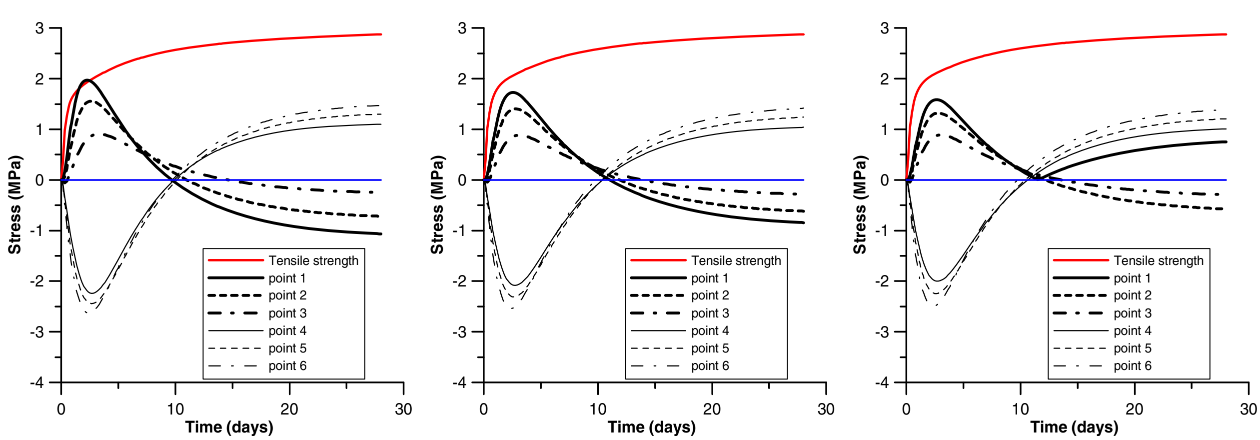
Fig. 16 shows the stress distributions for three types of curing conditions at 2.5 days. Fig. 16a shows that maximum tensile stress at 2.5 days is 2.05 MPa, which is the maximum value among the three types of curing conditions. This is because the internal restraint effect of the with out curing cover condition is the most pronounced due to the largest temperature difference between the inner and outer surfaces, as shown in Figs. 14 and 15. The tensile stress because of the large temperature difference between the inner and outer surfaces can cause surface cracking if the tensile stress exceeds the tensile strength on the concrete surface.

Fig. 17 shows the stress history at the six points displayed in Fig. 13. In Fig. 17, tensile strength evolution, which is influenced by concrete age and temperature variation, is shown at point 1, where the thermal cracking is predicted. As time increases after



(a) w/o curing cover (b) curing blanket (c) curing blanket + plastic sheet

Fig. 16. Stress distributions in Y-direction at 2.5 days.



(a) w/o curing cover (b) curing blanket (c) curing blanket + plastic sheet

Fig. 17. Stress history at six points in the concrete wall.

casting the concrete wall, the tensile stresses at points 1–3, which are representatives of the upper surface, develop and gain positive values at early age stage. For the with out curing cover case shown in Fig. 17a, tensile stress at point 1 exceeded tensile strength at around 2–3 days. The excess of tensile stress may cause tensile cracking on the concrete surface. In the other two curing conditions, tensile stress is lower than tensile strength, and, therefore, it is predicted that cracking in concrete wall will not happen at an early age stage.

In summary, the convective heat transfer coefficient influences the temperature profile in concrete structure and the tensile stress produced by the temperature difference causes cracking on the concrete surface. Therefore, it is noted that the convective heat transfer coefficient is the crucial material property of concrete in the prediction of temperature and thermal cracking.

6. Conclusions

In this study, a series of experiments was carried out to evaluate the effect of the wind velocity, curing condition, and ambient temperature on the convective heat transfer coefficient. From the test results, the following conclusions can be drawn.

1. The convective heat transfer coefficient, which represents the tendency for heat transfer between a concrete surface and ambient air, changes with factors such as the wind velocity, curing condition, and thermal conductivity.
2. The heat transfer coefficient is calculated through the use of the thermal equilibrium condition. From the results, it is noted that the effect of the wind velocity and curing condition on the coefficient is apparent. These results show a similar trend to that of results from existing models. However, the influence of ambient temperature was found to be negligible within a range from 20 °C to 30 °C.
3. In analyses using the existing thermal equilibrium condition, it is found that the convective heat transfer coefficient is large at an early stage. This phenomenon is caused by the evaporation of moisture within the concrete by evaporation effect. To consider this, a modified thermal equilibrium condition that takes into account evaporation by the evaporation effect before the hardening of concrete was suggested. The coefficients showed a nearly constant value when the modified boundary condition was applied.
4. The difference between convective heat transfer coefficients for both cases (i.e., when the evaporation effect is considered and convective heat transfer coefficient is determined, the evaporation when it is not considered) is approximately 30–40%. Accordingly, when the effect caused by the evaporation of moisture should be considered.
5. In structural concrete, the convective heat transfer coefficient influences the temperature distribution, which naturally produces tensile stress. Therefore, the convective heat transfer coefficient can be regarded as the crucial material property of concrete with respect to the prediction of thermal cracking.

7. Further study

In order to accurately perform thermal analyses due to the development of heat of hydration, studies on thermal characteristics, such as the heat transfer coefficient dealt with in the present paper, are required. Accordingly, in further experimental work, studies involving different curing materials and thicknesses should be carried out. In addition, the authors plan to develop a general prediction model that includes various factors that affect the heat transfer coefficient associated with air convection on the bases of theoretical background and experimental results.

Acknowledgements

The authors would like to thank the Infra-Structures Assessment Research Center (ISARC) funded by the Korea Ministry of Construction and Transportation (MOCT) for financial support.

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