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PROCEDURES FOR EVALUATION OF VARIOUS FACTORS AFFECTING THE TEMPERATURE RISE IN MASS CONCRETE

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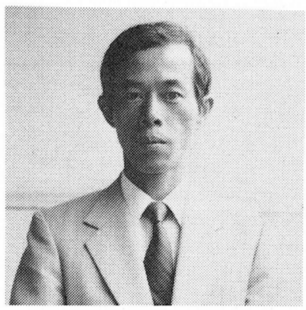

Sadamu ONO

SYNOPSIS

This paper discusses various factors affecting the temperature rise characteristics of massive concrete structures during construction on the basis of analyses of numerical values and actual measurements. Pertient factors are concrete adiabatic temperature rise, thermal properties of concrete, placing temperature, ambient temperature, thickness of member, coefficient of heat transfer, and curing. The following became clear after the investigation on various factors affecting the temperature rise. The effect of concrete temperature rise appears clearly. If we show characteristics of it by an empirical equation $Q(t)= Q\infty (1-e^{-\gamma t})$, the effect of $Q\infty$ and γ on temperature rise is independent. Further, in the paper I wish to propose a simple method which permits us to arrive at a solution of sufficient accuracy by means of results obtained through the investigation on various factors affecting the temperature rise.

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1. INTRODUCTION

Cracks induced by thermal stresses (hereinafter called thermal cracks) due to heat of hydration of cement during mass concrete construction have been studied for the past several decades.

From the viewpoints of structural safety and functional performance of the structure, the thermal crack control has been placed a great importance not only to various structures as concrete dams but also to large size concrete structures for substructures of recent long span bridges, a side wall and bottom slab of LNG ground tank or a base mat of a nuclear power plant.

Before thermal crack control can be implemented, the concrete temperature due to the heat of hydration of the cement after placing must be estimated. The studies related to temperature rise in mass concrete originated from the study of Boulder Dam[1] in 1930's and since then a number of studies have been carried out up to the present as they are represented by Carlson, McHenry, R.E. Glover and A.D. Ross. But the majority of studies has been concentrated upon the analytical aspects of concrete temperatures. Although the studies on the factors influencing the concrete temperatures or on the problems of assessing their precisions are of practical importance, these studies are unexpectedly few and far between. Recently, with the increasing applications of computers, a finite element method for an analysis of the integrated system has been widely used for the temperature analysis of mass concrete due to heat of hydration. When these analyses are performed, of course the results should be verified. However, the boundary condition can so far be considered only by the Carlson method. And the analytical precision and the simplicity cannot be satisfied by simple method of ACI[2], Yanagida[3] or Nojiri[4]. It is the status quo that there is no plactically effective simple calculation method.

This paper examinesthe seven factors — an adiabatic temperature rise of concrete, a thermal characteristic of concrete, a placing temperature, an ambient atmospheric temperature, member dimensions, a heat transfer rate and effects of curing procedures — each effects the temperature of mass concrete. Analyses were carried out on the basis of the numerical procedures and the measured values. Furthermore authors proposes the calculation method of the temperature rise for mass concrete. The procedure is based on the relation between the adiabatic temperature rise characteristic of concrete and the concrete temperature.

2. VARIOUS FACTORS AFFECTING THE TEMPERATURE OF CONCRETE

2.1 Adiabatic Temperature Rise Characteristics [5]

When the adiabatic temperature rise is expressed by $Q(t)=Q_\infty(1-e^{-\gamma t})$, influence of the adiabatic temperature rise characteristics affecting the temperature of concrete can be determined by substitution to the effect of the empirical constant Q_∞ and γ . Where, $Q(t)$ is the adiabatic temperature rise in °C at age t, t is in days. Q_∞ is the final adiabatic temperature rise in °C and γ is the empirical constant related to the temperature rising rate. To examine experimentally the effect of Q_∞ and γ, however, these should be un-coupled. The experimental examination of these factors during the hydration of cement poses a considerable difficulties. This study gave an expression of the empirical constant γ in terms of the final adiabatic temperature rise Q_∞ due to the numerical experiment influence to the temperature of concrete.

Table 1 shows the levels of various factors that were allowed to change. The levels of factors other than those shown in Table 1 are shown in Table 2. The numerical

Table.1 Factor and level

Factor	Level
Final adiabatic temperature rising amount Q_∞ (℃)	25.8, 29.4, 33.1, 36.8* 40.5, 44.2, 47.8
Empirical constant on temperature rising rate r	0.105, 0.262, 0.366, 0.418, 0.471, 0.523* 0.575, 0.628, 0.680, 0.941, 1.0, 1.5, 2.0
Dimension of member D (m)	0.75, 1.5, 3.0

Note) * : reference

Table.2 Reference factor and level in numerical experiment

	Factor	Level		Factor	Level
1.	Concrete placing temperature (℃)	0	14.	Empirical constant (Q_∞) (℃)	36.8
2.	Ground (or old concrete) temperature (℃)	0	15.	〃 (r)	0.523
3.	Minimum member thickness (m)	0.75～3.0	16.	Ambient temperature (℃)	0
4.	Unit volume weight of concrete (kg/m³)	2278	17.	Coefficient of heat transfer kcal/m²hr℃ (w/m℃)	20 (23.26)
5.	Specific heat of concrete kcal/kg℃ (J/kg℃)	0.318 (1.332)	18.	Reservoir thickness (m)	0
6.	Thermal conductivity of concrete kcal/mhr℃ (w/m℃)	2.094 (2.435)	19.	Sheet thickness (m)	0
7.	Thermal diffusivity of concrete (m²/hr)	0.0029	20.	Air thickness (m)	0
8.	Unit volume weight of ground(or old concrete) (kg/m³)	2278	21.	Thermal conductivity of water kcal/mhr℃ (w/m℃)	0.518 (0.602)
9.	Specific heat of ground kcal/kg℃ (J/kg℃)	0.318 (1.332)	22.	Thermal conductivity of sheet kcal/mhr℃ (w/m℃)	0.8 (0.930)
10.	Thermal conductivity of ground kcal/mhr℃ (w/m℃)	2.094 (2.435)	23.	Thermal conductivity of air kcal/mhr℃ (w/m℃)	0.022 (0.026)
11.	Thermal diffusivity of ground (m²/hr)	0.0029	24.	Curing days (日)	3.0
12.	Unit cement content (kg/m³)	280	25.	Time interval (△t) (hr)	3.0
13.	Type of concrete adiabatic temperature rise equation		26.	Space interval (△x) (m)	0.25

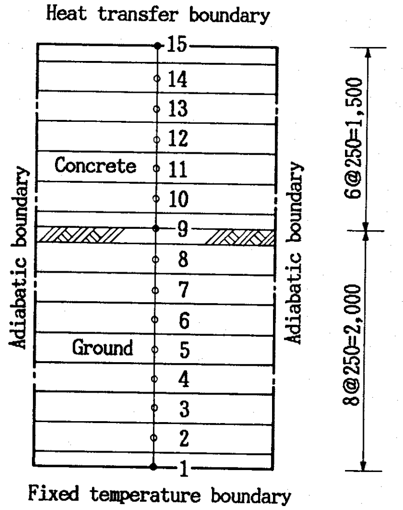


Fig.1 Temperature analysis model (Case of member dimension D=1.5m)

Table.3 Effect of thermal characteristics of ground affecting to concrete temperature

Case No.	Member thickness D (m)	Specific heat of ground Cg (Kcal/Kg℃)	Thermal conductivity of ground λg (Kcal/mhr℃)	Unit volume weight of ground ρg (Kg/m³)	Maximum of internal temperature rising amount Tr, max (℃)	Maximum of surface temperature rising amount Ts, r, max (℃)	Time to arrive at Tr,max Day max (日)
1	0.75	0.54	0.108	1,300	12.7	3.5	1.6
2	0.75	0.14	2.52	2,870	14.4	3.6	1.9
3	1.5	0.54	0.108	1,300	23.3	4.4	2.9
4	1.5	0.14	2.52	2,870	24.3	4.2	3.6
5	3.0	0.54	0.108	1,300	32.4	3.9	5.3
6	3.0	0.14	2.52	2,870	32.7	3.9	5.5

calculation was conducted by an one-dimentional finite difference method. A case of the heat transfer analysis model is shown in Fig. 1. In this analysis, the thermal characteristic of the existing foundation was kept constant. The result shows its effect on the fresh concrete temperature for members with small thickness as shown in Table 3. However the effect is almost negligible for members with large thickness.

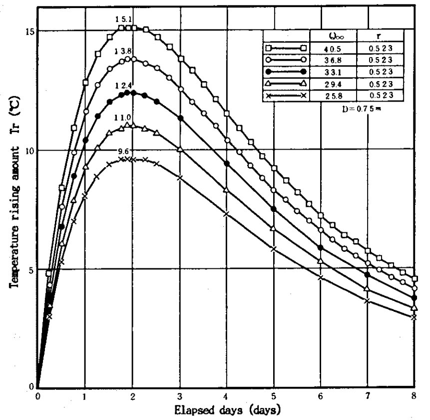


Fig.2 Effect of Q∞ affecting to internal temperature rising amount (Calculated value)

Fig. 2 shows the time dependent change in the temperature rise for D=0.75. The maximum value $T_{\gamma,max}$ of the internal temperature rise with reference to the placing temperature increases with the increase in Q∞. The effect of Q∞ is recognized.

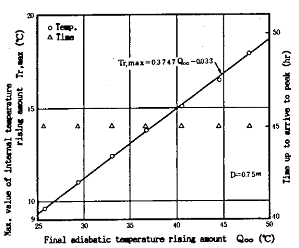


Fig.3 Relation between Tr,max, DAYmax and Q∞ (D=0.75m, calculated value)

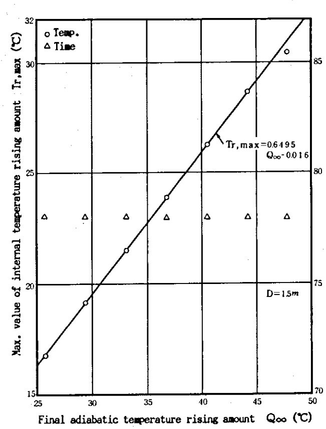


Fig.4 Relation between Tr,max, DAYmax and Q∞ (D=1.5m, calculated value)

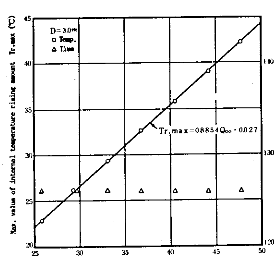


Fig.5 Relation between Tr,max, DAYmax and Q∞ (D=3.0m, calculated value)

Fig. 3, Fig. 4, and Fig. 5 show the relations between Q∞ and T_{γ}, max or the time to reach T_{γ}, max (DAY max) for different member dimensions. A strong positive correlation is recognized between Q∞ and $T_{\gamma,max}$. It is proved that T_{γ}, max increases linearly with the increase in Q∞. And its rate increases proportionaly to the member dimension.

On the other hand, DAYmax, as clearly shown in Fig. 3 to Fig. 5, is almost constant though Q_∞ changes, therefore Q_∞ has no influence on DAYmax.

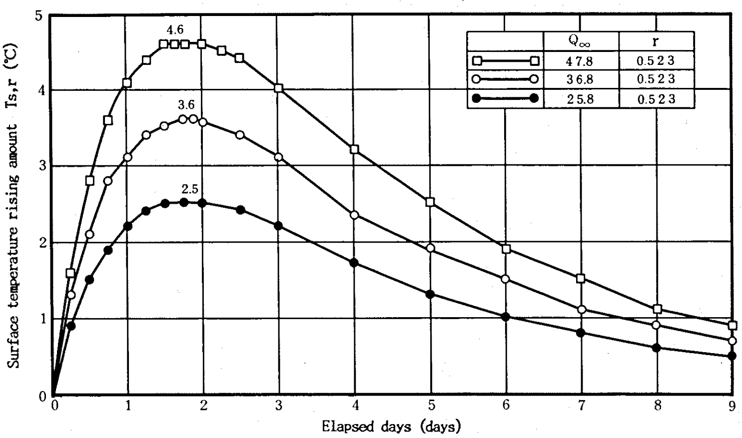


Fig.6 Effect of Q_∞ affecting to surface temperature rising amount (Calculated value)

Fig. 6 shows the result of ±30% change in the Q_∞ reference at Q_∞=36.8 for the case of the member dimension of 0.75m. The Maximum value of the surface temperature rise $T_{s,\gamma}$ increases or decreases by ±1°C corresponding to the change in Q_∞. This increase or decrease in $T_{s,r}$ is approximately equal to the change in Q_∞. Although Q_∞ changes, the time to reach the maximum value of $T_{s,\gamma}$ does not change. This result is similar to the tendency of the internal temperature rise. Fig. 7 shows the effect of the empirical constant γ on the temperature of concrete. The result is more complicated in comparison with the effect of Q_∞. The characteristics possiblly induced from this result is that the $T_{\gamma,max}$ increases and the DAYmax decreases with the increase in γ. Fig. 8 shows the relation between

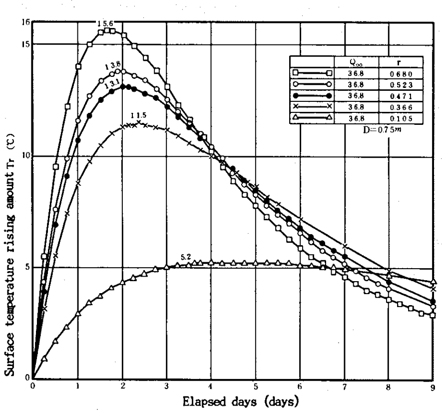


Fig.7 Effect of r affecting to internal temperature rising amount (Calculated value)

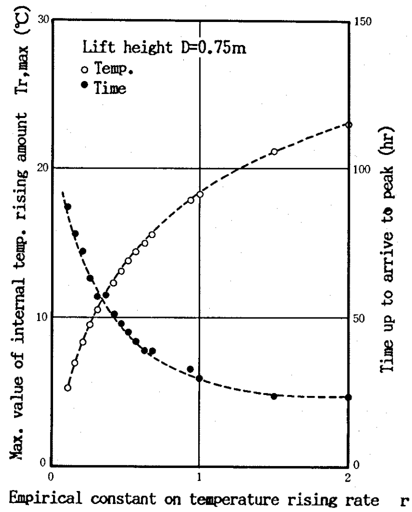


Fig.8 Relation between Tr,max, DAYmax and r (Calculated value)

γ and Tγ,max for the case of the member dimension of 0.75m. From this result, it is recognized that Tγ,max increases hyperbolically with the increase in γ and DAYmax decreases hyperbolically. The smaller the γ, the larger the effect on Tr,max. The results for the member dimensions of 1.5m and 3.0m are shown in Fig. 9, 10.

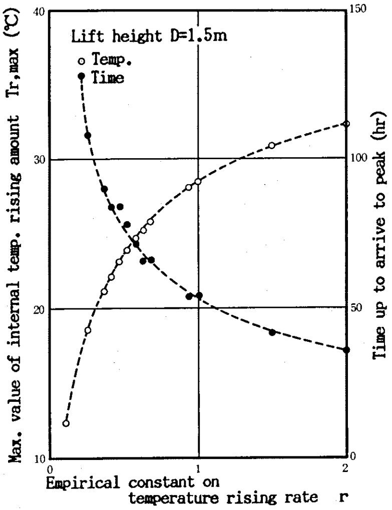


Fig.9 Relation between Tr,max, DAYmax and r (D=1.5m)

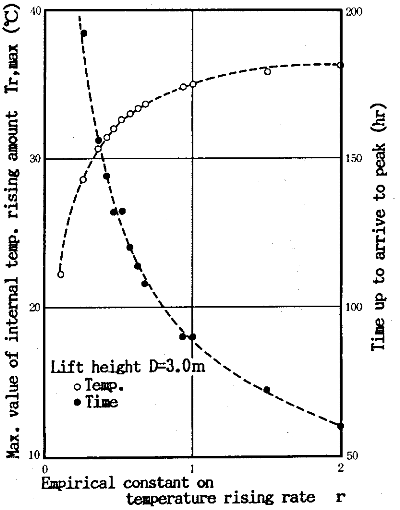


Fig.10 Relation between Tr,max, DAYmax and r (D=3.0m)

The similar tendency to the case of 0.75m was also recognized in these member dimensions. A relation between γ and the maximum value Ts,γ,max of the surface temperature rise is shown in Fig. 11. This indicates the same tendency as the case of the internal temperature rise.

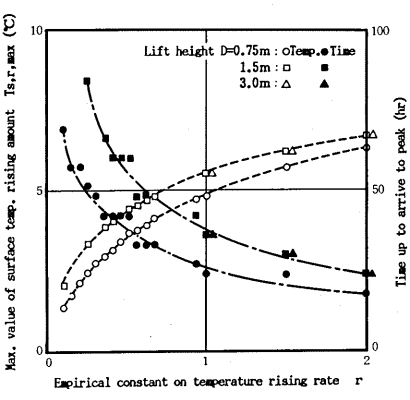


Fig.11 Relation between Ts,r,max and r

Table.4 Effect of Q∞, r affecting to concrete temperature

Factor	Lift height (m)	Max. of reference internal temp. rising amount Tr,max(℃)	Fluctuation wide of Tr,max(℃) when factor fluctuates.		
			±10%	±20%	±30%
Final adiabatic temperature rising amount (Q∞)	0.75	13.8	(10) ±1.4	(20) ±2.8	(30) ±4.2
	1.50	23.9	(10) ±2.4	(20) ±4.8	(30) ±7.2
	3.00	32.9	(10) ±3.3	(20) ±6.6	(30) ±9.8
Empirical constant r relative to temp. rising rate	0.75	13.8	(5) ±0.7	(10) ±1.4	(15) ±2.1
	1.50	23.9	(3) ±0.8	(7) ±1.6	(10) ±2.4
	3.00	32.9	(2) ±0.5	(3) ±1.0	(5) ±1.5

Note) • Reference of Q∞, r : Q=36.8, r=0.523
• The values of parenthesis are the rates (%) of the fluctuation of Tr,max to the reference of Tr,max

Table 4 shows the fluctuation of $T_{\gamma,max}$ corresponding to changes in Q_∞ and r by the amount $\pm$10%, $\pm$20% and $\pm$30% respectively. The fluctuation $T_{\gamma,max}$ agrees with that of Q_∞. The effect of γ on $T_{\gamma,max}$ with the increase in the member dimension is small: that is, for D=3.0m, although γ fluctuates by $\pm$30%, $T_{\gamma,max}$ fluctuation is approximately $\pm$1.5°C.

Thus, the effects of Q_∞ and r on the concrete temperature were revealed such that the former affected $T_{\gamma,max}$ and the latter affected both $T_{\gamma,max}$ and DAYmax. Next, a quantitative tendency of these effects was considered.

Table.5 Examination for the additivity of effects of Q_∞ and r

Lift height (m)	Fluctuation of constant Q_∞, r	Fluctuation of Tr,max in fluctuation of individual constant		③	④	⑤	Tr,max considered simultaneously with the fluctuation of Q_∞, r	⑦ Error	⑧
		① Q_∞	② r	①+②	Based Tr,max (℃)	③+④		⑥−⑤	|⑦/⑥| (%)
0.75	±10%	±1.4	±0.7	±2.1	13.8	15.9 11.7	15.8 11.7	−0.1 0.0	0.6 0.0
	±30%	±4.2	±2.1	±6.3	13.8	20.1 7.5	20.2 8.0	0.1 0.5	0.5 6.3
3.0	±10%	±3.3	±0.5	±3.8	32.9	36.7 29.1	36.3 28.8	−0.4 −0.3	1.1 1.0
	±30%	±9.8	±1.5	±11.3	32.9	44.2 21.6	43.8 21.5	−0.4 −0.1	0.9 0.5

Note) • Reference of Q_∞, r : Q_∞=36.8, r=0.523
• Tr,max : Maximum of internal temp. rising amount

Table 5 shows the values of $T_{\gamma,max}$ for the member thickness of 0.75m and 3.0m when Q_∞ and r are fluctuated by +10 % and $\pm$30%, respectively. In case of D=0.75m, $T_{\gamma,max}$ with the reference value being 13.8°C fluctuates 11.7°C when the two factors fluctuate by −10%. As already stated, when Q_∞ and r fluctuate by −10% respectively, $T_{\gamma,max}$ fluctuates by 1.4°C and 0.7°C. When the sum of the both values, 2.1°C, is added to 11.7°C, $T_{\gamma,max}$ results in 13.8°C. This value corresponds to the reference value of $T_{\gamma,max}$. When γ decreases by 10%, which causes DAYmax increases by 6 hours from the reference value as be seen from Fig. 8. The DAYmax, 48 hours, at the value of γ decreased by the amount 10% is adjusted by the 6 hours, which results in 42 hours. This result agrees with the reference value of DAYmax. For the member dimension of 3.0m, the similar relationship holds. From the above result, it is proved that γ affecting the concrete temperature can be evaluated separately and furthermore respective effect can be estimated by superimposing. The calculation of mass concrete temperature rise proposed in this study stands on the basis of this relationship.

2.2 Thermal Characteristics of Concrete

According to Tokuda's study[6], the range of the specific heat C of concrete is from 0.2 to 0.8 kcal/kg°C (537 - 3349J/kg°C) and the range of the thermal conductivity λ is from 0.5 to 3.0kcal/mh°C (0.582 - 3.489W/m²°C). And the range of the thermal diffusivity is from 0.0003 to 0.0088m²/h. This study examined the effect of the thermal characteristic affecting concrete temperature.

Fig. 12 shows the relation between h^2 and $T_{\gamma,max}$ for the 1.5m thick member. $T_{\gamma,max}$ decreases hyperbolically with increase of h^2, but the smaller the h^2, greater the effect on $T_{\gamma,max}$. If h^2 is in the range of 50 x 10^{-4} to 60 x 10^{-4}m²/h, its effect is only about 1°C.

Table.6 Factor and level

Factor	Level
Specific heat kcal/kg℃ (J/kg℃)	0.2, 0.3, 0.4, 0.5, 0.8 (0.838, 1.257, 1.676, 2.095, 3.352)
Thermal conductivity kcal/mhr℃ (W/m℃)	0.5, 1.0, 2.0, 3.0, 4.0 (0.582, 1.163, 2.326, 3.489, 4.652)
Member dimension (m)	0.75, 1.5, 3.0

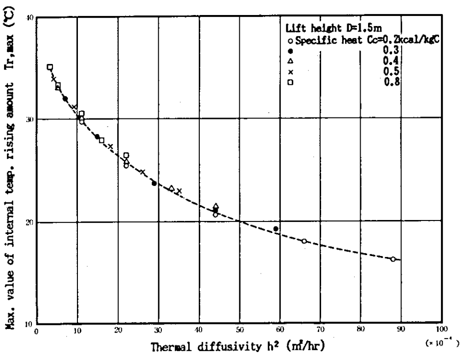


Fig.12 Relation between h^2 and Tr,max

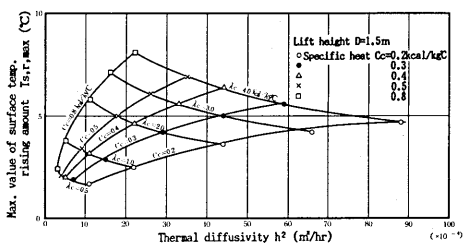


Fig.13 Relation between h^2 and Ts,r,max

Fig. 13 shows the relation between h^2 and $T_{s,\gamma,max}$ for 1.5m thick member. The relation between $T_{s,\gamma,max}$ and the thermal characteristics of concrete cannot be correlated solely by h^2 as the case of $T_{\gamma,max}$. In Fig. 13, if h^2 is constant, $T_{s,\gamma,max}$ increases with the increases of C and λ. And $T_{s,\gamma,max}$ increases in parabolily with the increase in h^2. In the range of h^2 of ordinary mass concrete, 20×10^{-4} - 40×10^{-4} m^2/h, the effect of h^2 on $T_{s,\gamma,max}$ is considered to be within 5°C approximately.

2.3 Placing Temperature

The effect of the placing temperature Tp on concrete can be considered in the adiabatic temperature rising characteristics. When T_ρ goes up, Q_∞ decreases and γ increases. Accordingly, since Q^∞ decreases for a higher Tp, $T_{\gamma,max}$ also decreases. But since γ increases, $T_{\gamma,max}$ increases.

Table 7 is the result from the statistical analysis of a concrete temperature measured in slabs. The appropriateness of the regression formula shown in Table 7 was examined. In the case of T_ρ=20°C and D=0.75m, the regression formula shown in Table 7 gives $T_{\gamma,max}$=14.4°C, $T_{s,\gamma,max}$=8.2°C and DAYmax=1.4days. While the values calculated by a finite difference method resulted in $T_{\gamma,max}$=13.8°C, $T_{s,\gamma,max}$=3.6°C and DAYmax=1.9days as shown in Fig. 3 and Fig. 6. $T_{\gamma,max}$ agrees well with these calculations. But deviations are recongnized in both $T_{s,\gamma,max}$ and DAYmax. In consideration of the fact that the heat transfer rate β=20Kcal/

$m^2h°C$ ($23.26W/m^{2}°C$) calculated by the finite difference method is larger than the measured value, the difference between the both calculated values is considered to be small. Thus, although the precision in the regression formula needs further examination, it is considered that the effect of the placing temperature can be evaluated qualitatively by this formula.

Table.7 Relation between Tp and the characteristic value on concrete temperature

Characteristic value	Subject lift height (m)	Number of data	Coefficient of correlation	Regression equation
Tr, max	D=0.75	64	0.44	Tr, max=0.188Tp+10.6
Ts, r, max		50	0.35	Ts, r, max = 0.125Tp+5.7
DAY max		64	−0.58	DAYmax = −0.032Tp+2.02
Ts, r, max	0.75≦D≦5.5	73	0.30	Ts, r, max=0.314Tp+8.7
DAY max	1.0≦D≦1.5	71	−0.82	DAYmax=−0.023Tp+1.81

From the result in Table 7, a positive correlation is recognized between Tρ and $T_{\gamma,max}$. $T_{\gamma,max}$ increases as Tρ increases. $T_{s,\gamma,max}$ is also the same as $T_{\gamma,max}$. These facts indicate that the effect of the increase in γ is more significant than the effect of the decrease in Q_∞ due to the increase in Tρ. DAYmax results in a small value with the increase in Tρ. The effect of γ is recognized.

2.4 Ambient Temperature

The effect of ambient temperature was examined by a numerical analysis as well as by measured values. Table 8 shows the various factors in the numerical analysis.

Fig. 14 shows the relation between the member dimension and $T_{\gamma,max}$ with the ambient temperature Ta and Tp as input parameters. $T_{\gamma,max}$ increases as the ambient temperature increases, but the rate is reduced as the member dimension increases. When the member dimension is about 4.0m, the effect to $T_{\gamma,max}$ is hardly recognized.

Table.8 Factor and level

Factor	Level
Ambient temp. (℃)	−10, 0, 10, 20, 30
Member dimension (m)	0.75, 1.0, 2.0, 3.0, 4.0
Placing temp. (℃)	10, 20, 30
Final adiabatic temp. rising amount Q_∞(℃)	35.1, 31.3, 29.9
Empirical constant r	0.446, 0.892, 1.338

* Ambient temp. is absolute value.

Fig. 15 shows the relation between Ta and $T_{s,\gamma,max}$. A positive linear correlation is recognized between Ta and $T_{s,\gamma,max}$. The fact that $T_{s,\gamma,max}$ increases with the decrease in Tp is due to a large inflow of heat through the boundary into the member as the ambient temperature rises. From the result in Fig. 15, it is considered that the effect of the member dimension on $T_{s,\gamma,max}$ is almost nothing.

Next the author examined the effect of Ta on the concrete temperature through the

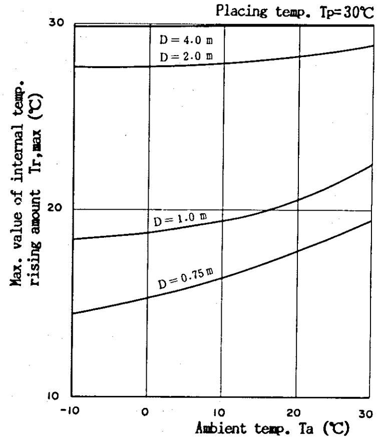
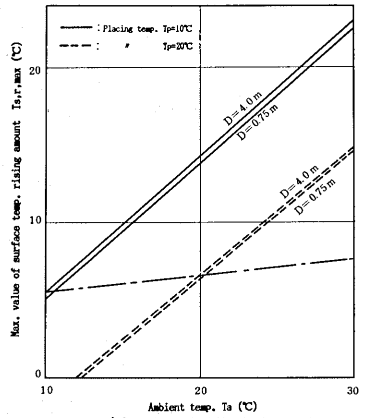


Fig.14 Relation between Ta and Tr,max



Note) One point chained line is the case that the ambient temperature is equal to the placing temperature.

Fig.15 Relation between Ta and Ts,r,max

measured values. Table 9 shows the result of statistical analysis. The tendency of Tγ,max to increase as Ta, increases as shown by the result of the numerical analysis is also recognized in the measured values. Furthermore, the same result holds for Ts,γ,max.

Table.9 Relation between Ta and characteristic value on the concrete temperature

Characteristic value	Number of data	Coefficient of correlation	Regression equation
Tr, max (℃)	64	0.52	Tr, max = 0.199Ta + 11.10
Ts, r, max (℃)	58	0.40	Ts, r, max = 0.340Ta + 9.53
Tm, max (℃)	35	0.97	Tm, max = 1.067 Ta + 13.79
DAY max (日)	64	−0.50	DAYmax = −0.025Ta + 1.81

2.5 Member Dimension

From the result of the numerical analysis shown in Fig. 14, the tendency that Tγ,max increases parabolically with increasing in the member dimension is recognized. It is proved that Ts,γ,max dependents on the member dimension as in Fig. 15.

Table 10 shows the result of statistical analysis on the measured values. The result of the numerical analysis showed a positive correlation between member dimension and Tγ,max. It is confirmed from the measured value analysis that the correlation between member dimension and Ts,γ,max is small and the effect of the member dimension on Ts,γ,max is very small.

Table.10 Relation between member dimension and characteristic value on the concrete temperature

(Tr,max : ℃, D : m, DAYmax : days)

Characteristic value	Cement type, Unit cement content	Number of data	Coefficient of correlation	Regression equation (Tr,max=AD+B) A	B
Max. value of internal temperature rising amount (Tr,max)	Result of investingation into the actual conditins	97	0.83	17.65	1.13
	NP, 240<C≦250kg/m³	10	0.77	9.50	12.60
	NP, 290<C≦300kg/m³	8	0.76	4.65	26.65
	NP, 290<C≦300kg/m³	6	0.80	7.73	15.32
	NP, 320<C≦330kg/m³	15	0.41	6.07	25.40
	NP, 270<C≦280kg/m³	11	0.93	29.33	−2.09
	FB	14	0.81	18.60	5.06
	MBF C=280 kg/m³	33	0.85	16.51	4.80
Max. value of surface temperature rising amount (Ts,r,max)		50	0.17	2.12	6.26
Time up to arrive to peak of internal temperature rising amount (DAYmax)	15<Tp≦25 ℃	32	0.72	1.27	0.43
	25<Tp≦35 ℃	19	0.62	1.78	−0.22
(DAYmax = AD + B)	5<Tp≦15 ℃	39	0.49	1.24	0.92

Note) NP : Normal portland cement
FB : B Type of fly ash cement
MBF : B Type of moderate heat blast-furnace cement

2.6 Heat Transfer Rate

Table 11 shows the various factors in the numerical analysis.

Table.11 Factor and level

Factor	Level
Coefficient of heat transfer β kcal/m²hr ℃ (W/m²℃)	0.001, 1, 10, 20, 30, 40, 50, 100, 1000 (0.001, 1.163, 11.63, 23.26, 34.89, 46.52, 58.15, 116.3, 1163)
Member dimension D (m)	0.75, 1.5

Fig. 16 shows the relation between heat transfer rate β and Tγ,max. Tγ,max decreases hyperbolically with increase in β. For β of about 10 Kcal/m²h°C (11.63W/m²°C) or more, the rate decrease in Tγ,max is small and, although β changes from 10(11.63W/m²h) to 1000Kcal/m²h°C (1163W/m²°C),Tγ,max changes only by about 2°C. From this fact, the effect of β on Tγ,max can be regarded negligible. In the range of β =5 to 30Kcal/m²h°C (5.815 to 34.89W/m²°C), a common range for mass concrete, Tγ,max fluctuates by 2 to 3°C.

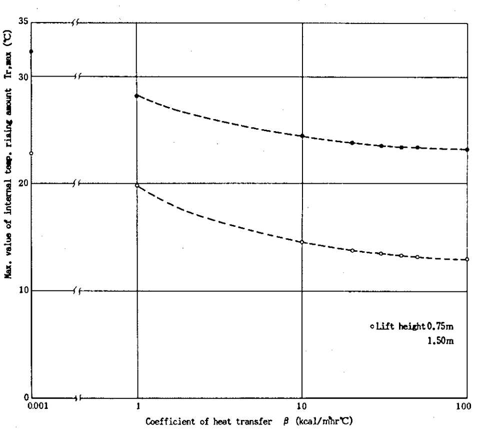


Fig.16 Relation between β and Tr,max

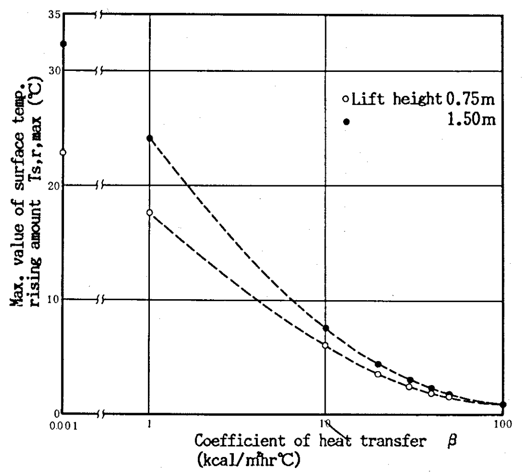


Fig.17 Relation between β and Ts,r,max

Fig. 17 shows the relation between β and Ts,γ,max. With an increase in β, Ts,γ,max approaches to 0°C and when β=1000Kcal/m^2h°C (1163W/m^2°C), Ts,γ,max becomes approximately 0°C. The effect of β on Ts,γ,max is larger and in a common range of β of 5 to 30Kcal/m^2h°C (5.815 to 34.89W/m^2°C), Ts,γ,max fluctuates by about 10°C.

2.7 Curing

The effect of curing on the concrete temperature was examined by a numerical analysis by evaluating the heat transmission coefficient on the member surface. Table 12 shows the various factors in the numerical analysis.

Table.12 Factor and level

Factor	Level
Coefficient of heat transfer U kcal/m²hr ℃ (W/m℃)	0.20, 0.38, 0.94, 1.67 2.04, 3.45, 8.33, 10.0 (0.233, 0.442, 1.093, 1.942 2.373, 4.012, 9.688, 11.63)
Member dimension D (m)	0.75, 1.5, 3.0
Ambient temp. Ta (℃)	0, 10, 20
Placing temp. Tp (℃)	20

Fig. 18 shows the relation between U and Tγ,max for 1.5m thick member. Tγ,max decreases hyperbolically with increase in U and its rate of decrease increases as the ambient temperature drops. Furthermore, the rate of decrease in Tγ,max reduces as the member dimension increases. When the member dimension is about 3m, the effect of U on Tγ,max is almost negligible.

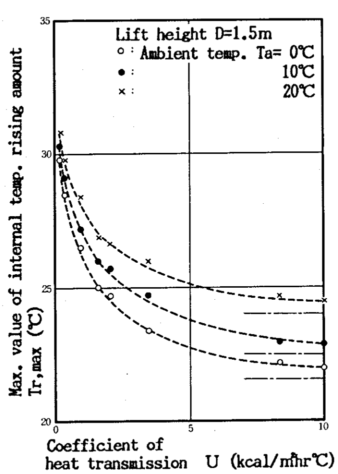


Fig.18 Relation between U and Tr,max

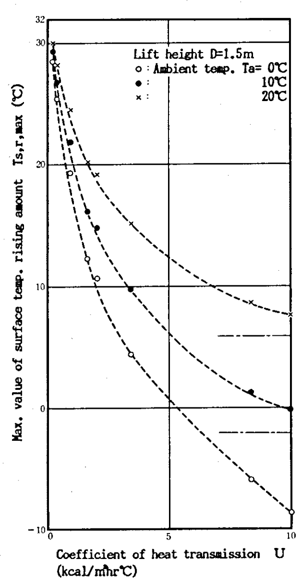


Fig.19 Relation between U and Ts,r,max (℃)

Fig. 19 shows the relationship between U and $T_{s,\gamma,max}$. $T_{s,\gamma,max}$ decreases hyperbolically with increase in U. When U is constant, a tendency is recognized that $T_{s,\gamma,max}$ increases proportionally with increase in Ta. This increasing rate reduces with decrease in U. Since the member surface approaches an adiabatic condition with decrease in U, it is recognized to be independent of Ta.

3. PROPOSAL OF A MASS CONCRETE TEMPERATURE CALCULATION

3.1 Calculation Procedure

For an examination of the mass concrete thermal crack control, the following characteristic values on the concrete temperature must be evaluated. These characteristic values are the maximum value $T_{\gamma,max}$ of internal temperature rise, the material age DAYmax that cause $T_{\gamma,max}$, the maximum value $T_{s,\gamma,max}$ of surface temperature rise, the age DAYs,max that cause $T_{s,\gamma,max}$ and $T_{\gamma,max}$ and $T_{s,\gamma,max}$ in 7 days and 14 days. These characteristic values may be analyzed by a finite element method. However, if a highly accurate result can be obtained by a simple calculation, it is considered to be significant in the practical use. The methods proposed by Yanagida, ACI and Nojiri are in line with this procedure.

The author clarified the effect of various factors affecting the concrete temperature by the numerical analysis and the measured value analysis as stated above. And the author clarified also that the relation of an additivity hold for between the concrete temperature and the adiabatic temperature rising characteristics. From these results, author proposes the following simple calculation for the concrete temperature.

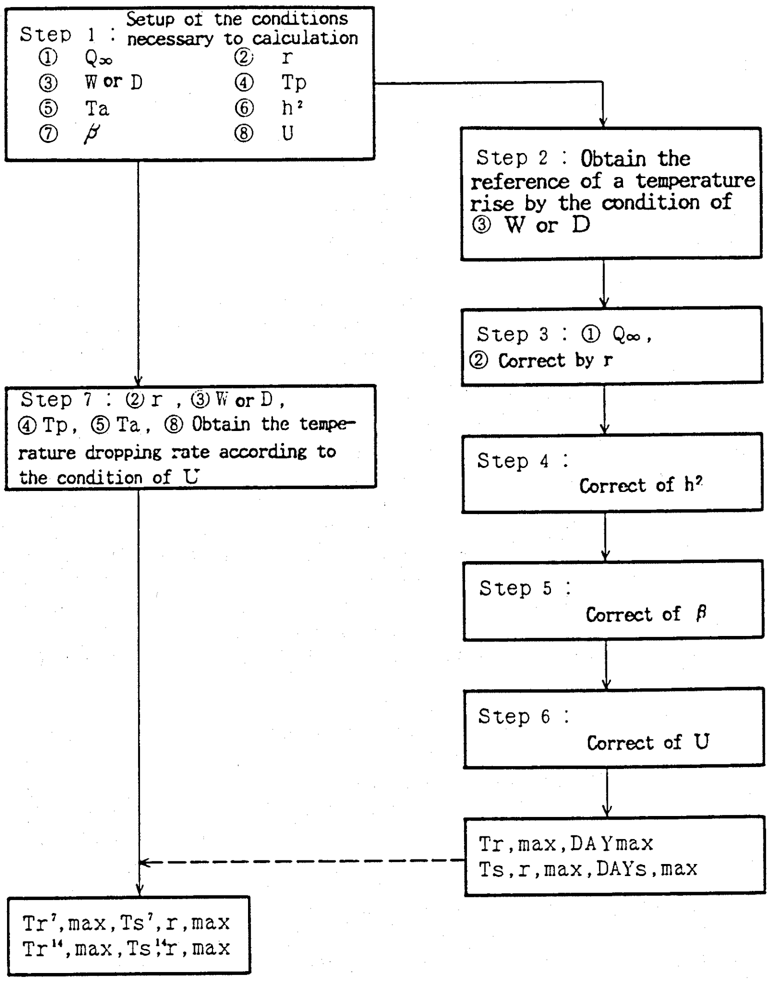
Fig. 20 shows the flow of calculation. The standard curves calculated by the reference condition (C=0.318Kcal/kg°C), λ=2.094Kcal/mh°C (2.435W/m^2°C), h^2= 0.0029m^2/h, Q_∞=36.8°C, γ=0.523, Tp=Ta=°C, β=20Kcal/m^2h°C (23.26W/m^2°C) as shown in Fig. 21 are corrected in order by the calculated conditions to obtain the required results. The effects on the concrete temperature due to each factor are evaluated separately, and each effective amount is superimposed to the results of the reference conditions. Although the reference conditions of Tp and Ta are taken as 0°C, these absolute values are 20°C. The correction, when there is a difference between T_ρ and Ta, is carried out by Step 6, but a strict correction shouldbe carried out by Fig. 14 and 15. The concrete temperatures after 7 days and 14 days should be calculated using the temperature dropping rate defined by the following formula.

Internal temperature dropping rate=($T_{\gamma,max}$ − $T^t_{\gamma,max}$)/$T_{\gamma,max}$

Surface temperature dropping rate =($T_{s,\gamma,max}$ − $T^t_{s,\gamma,max}$)/$T_{s,\gamma,max}$

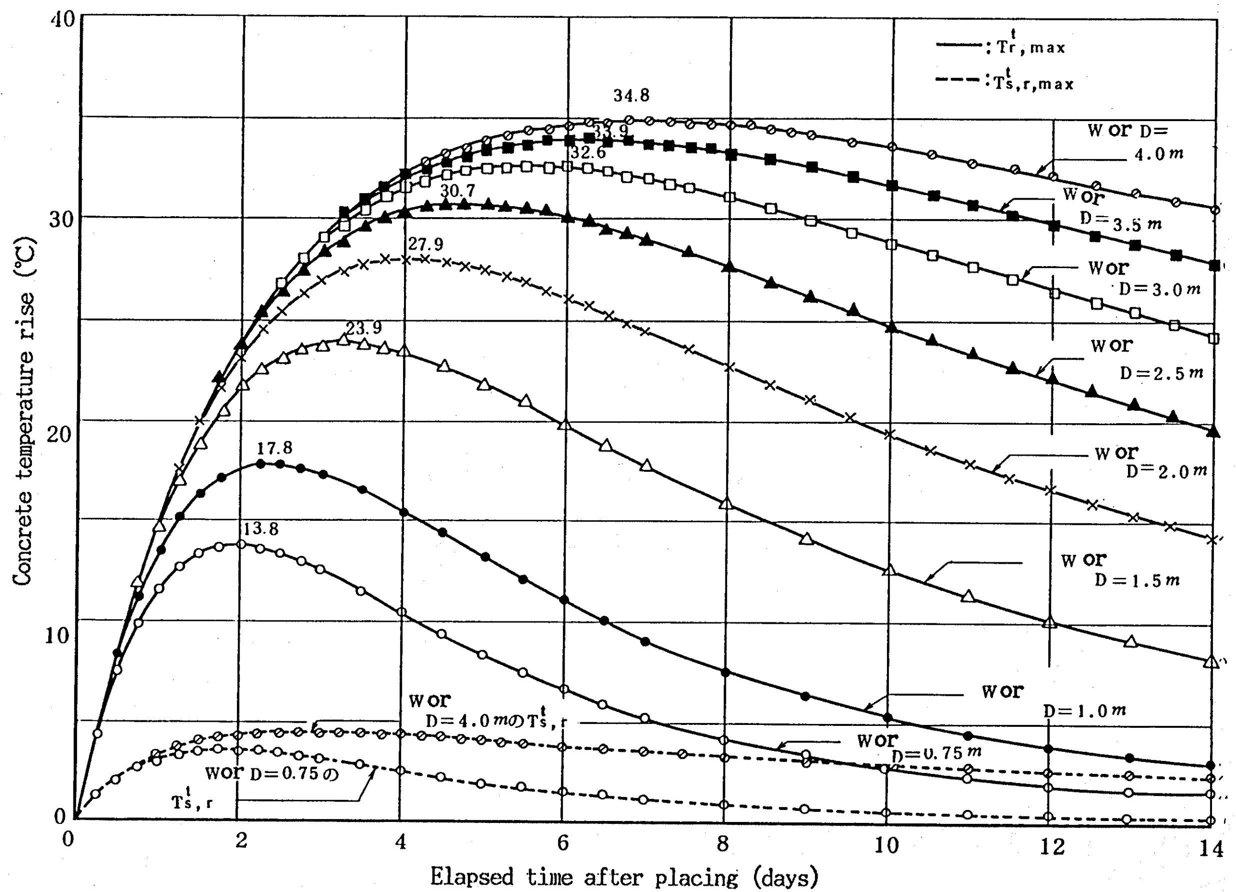
Where, $T^t_{\gamma,max}$ is $T_{\gamma,max}$ in t days and $T^t_{s,\gamma max}$ is $T_{s,\gamma,max}$ in t days. Since the effects of γ, h^2 and U were recognized to be larger in the result examined on the effect of the factors affecting the temperature dropping rate, these effects were decided to be calculated by the three factors. The effect to Ta should be considered on U. Fig. 22 and 23 show the figure for determination of the dropping rate to .

The analyses of the reference conditions are carried out for a slab model. However, for walls with doubled heat radiation it was recognized to have a tendency almost agreed with that of the slab as shown in Fig. 24. Accordingly, even



Q_∞ : Final adiabatic temperature rising amount (℃)
r : Empirical constant on the temperature rising rate
W,D : Wall thick, Lift height (m)
Tp : Placing temperature (℃)
Ta : Ambient temperature (℃)
h^2 : Thermal diffusivity (m²/hr)
β : Coefficient of heat transfer (kcal/m²hr℃)
U : Coefficient of heat transmission
Tr,max : Maximum value of internal temperature rising amount (℃)
Ts,r,max : Maximum value of surface temperature rising amount (℃)
DAYmax : Age that indicate Tr,max (hr)
DAYs,max : Age that indicate Ts,r,max (hr)
Tr^7,max : Maximum value of internal temperature rising amount for 7 days of the age (℃)
Tr^{14},max : Maximum value of internal temperature rising amount for 14 days of the age (℃)
Ts^7,r,max : Maximum value of surface temperature rising amount for 7 days of the age (℃)
Ts^{14},r,max : Maximum value of surface temperature rising amount for 14 days of the age (℃)

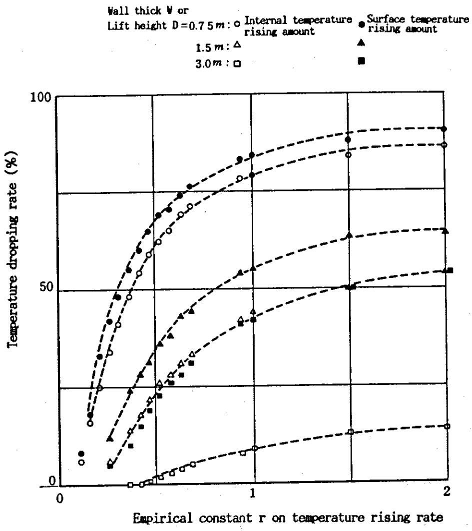
Fig.20 Flow of simple calculation



Reference conditions **Unit**

Cc =0.318 Kal/kg℃
(=1.312 J/kg℃)
λc =2.094 Kal/mhr℃
(=2.435 W/m℃)
h^2 =0.0029 m^2/hr
Q∞=36.8℃
r =0.523
Tp = 0℃
Ta = 0℃
β = 20 Kal/m^2hr℃
(=23.26 W/m^2℃)

Fig.21 Standard Curve for calculation of concrete temperature



Note) The internal temperature means the temperature at the center section of member

Fig.22 Temperature dropping rate (7 days age)

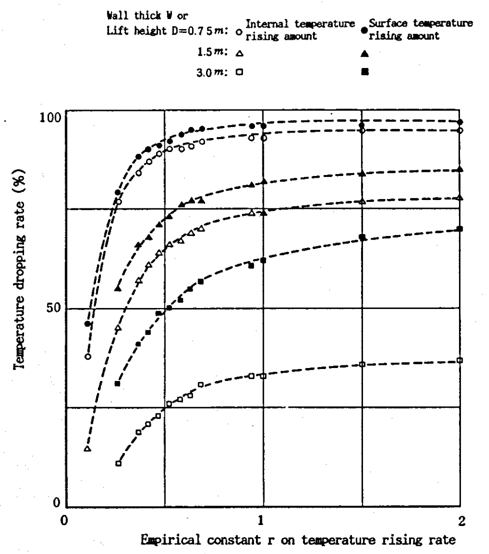


Fig.23 Temperature dropping rate (14 days age)

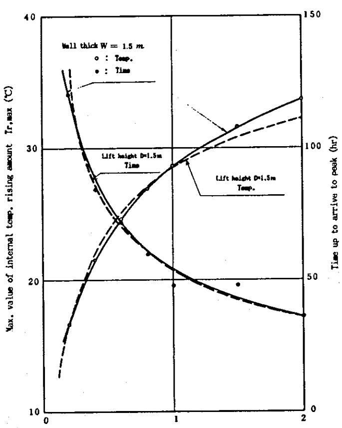


Fig.24 Comparison between Tr,max of slab shape and Tr,max of wall shape

for a wall shape mass concrete, the proposed method is considered to be applicable though the accuracy somewhat decreases.

The corrections for h^2, β and U are shown in the cases of D=1.5m, Ta=10°C and Tp=20°C. Where, these are taken as h^2=0.0033m²/h, β=12Kcal/m²h°C (13.956W/m²°C) and U=5.2 Kcal/m²h°C (6.048W/m²C). Since h^2 from Fig. 12 is larger by 0.0004m²/h than the reference value of h^2=0.0029m²/h, $T\gamma$,max -1.0°C corresponded to its difference is added to it. Subsequently, from Fig. 16, since β is smaller by 8Kcal/m²h°C (9.304W/m²°C) than the reference value of 12Kcal/m²h°C (13.956W/m²°C), the difference +0.8°C of $T\gamma$,max corresponds to it is added to the reference value of $T\gamma$,max. The correction of U should be carried out by ...... line in Fig. 18 because the difference between Ta and Tp is 10°C. Since U=5.2Kcal/m²h°C (6.048W/m²°C) is smaller by 14.8Kcal/m²h°C (17.212W/m²°C) than the reference value, the difference 1.3°C corresponds to it sould be added to the reference value of $T\gamma$,max. Thus, the differences from the reference values are superimposed for correction and $T\gamma$,max for the given condition can be calculated.

3.2 Examination of Adaptation Due to the Measured Value

The author examined the adaptation of the proposed simple calculation procedure for the measured values in an actual structure. Table 13 shows the measured values and the calculation condition.

Table.13 Measured value to actual structure used to the examination of adaptation

Name of the measured field	Calculating condition									Measured value							
	Used cement, Unit cement content (kg/m³)	Placing temp. Tp (°C)	Thermal diffusivity h^2 (m²/hr)	Q_∞ (°C)	r	Member dimension D (m)	Ambient temp. Ta (°C)	Coefficient of heat transfer β kcal/m²hr°C (w/m²°C)	Coefficient of heat transmission U kcal/m²hr°C (w/m²°C)	Tr,max (°C)	DAY max (hr)	$T_{s,r}$, max (°C)	DAY_s,max (hr)	Tr^7, max (°C)	Ts^7_r, max (°C)	Tr^{14}, max (°C)	Ts^{14}_r, max (°C)
A	NP 250	11.3	0.0025	35.0	0.631	2.0	6.5	10.0 (11.63)	9.12 (10.607)	30.0	50	3.5	48	22.9	−2.0	11.8	−3.1
B	NP 298	12.9	0.0027	43.0	0.797	1.8	10.0	20.0 (23.26)	15.2 (17.678)	34.1	36	15.1	24	22.1	3.9	16.1	2.1
C	NP 260	17.7	0.0025	37.0	0.690	4.0	14.6	20.0 (23.26)	25.2 (29.31)	37.5	120	13.2	86	37.2	8.5	33.2	3.4
D	NP 240	29.4	0.0027	34.0	1.161	3.9	29.3	20.0 (23.26)	18.6 (21.632)	34.6	72	10.6	120	32.6	4.6	26.6	2.6
E	MBB 280	29.5	0.0027	40.1	0.892	0.75	30.5	20.0 (23.26)	6.82 (7.932)	21.0	34	13.0	22	10.7	/	/	/

Table.14 Concrete temperature calculated results according to the proposed method

Name of the measured field	Author,s method															
	$T_{r,max}$ (℃)		DAY_{max}(hr)		$T_{s,r,max}$ (℃)		$DAY_{s,max}$(hr)		$T_{r,}^{7}max$ (℃)		$T_{s,r}^{7}$, max (℃)		T_r^{14}, max (℃)		$T_{s,r}^{14}$, max (℃)	
	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value
A	30.0	1.00	84	1.68	7.3	2.09	38	0.79	23.4	1.02	8.9	5.45	13.5	1.14	4.3	2.39
B	34.8	1.02	73	2.03	7.3	0.48	29	1.21	23.7	1.07	3.9	1.00	12.5	0.78	1.8	0.86
C	38.0	1.01	158	1.32	23.0	1.74	100	1.16	35.7	0.96	15.9	1.87	27.0	0.81	10.1	2.97
D	36.2	1.05	121	1.68	5.8	0.55	48	0.40	32.2	0.99	3.3	0.72	23.2	0.87	2.0	0.77
E	20.4	0.97	39	1.15	11.2	0.86	37	1.68	4.9	0.46						
Average value of Calculated value/ Measured value $\bar{x}$		1.01		1.57		1.14		1.05		0.90		2.26		0.90		1.75
Square root of unbiased variance		0.03		0.34		0.73		0.48		0.25		2.18		0.16		1.10
Coefficient of fluctuation		0.03		0.22		0.64		0.46		0.28		0.96		0.18		0.63

Table 14 shows the calculated results of the mass concrete temperature according to the proposed method. The results are recognized to be in a good agreement in the calculated values and the measured values of $T_{\gamma,max}$, $T^{7}_{\gamma,max}$ and $T^{14}_{\gamma,max}$. The average values of the ratios of the calculated values to the measured values are 1.01, 0.90 and 0.90, respectively.

3.3 Comparison of Various Calculations

The proposed method was examined in comparison with various calculations. The compared calculations are the finite defference method , the finite element method, Yanagida's method and ACI method.

Table.15 Concrete temperature calculated results according to various calculations

Name of the measured field	Finite Difference Method																Yanagida		A C I			
	Tr, max (℃)		DAYmax (hr)		Ts,r,max (℃)		DAYs,max(hr)		Tr^{7}, max (℃)		Ts^{7},r,max (℃)		Tr^{14},max (℃)		Ts^{14},r,max (℃)		Tr,max (℃)		Tr,max (℃)		DAYmax (hr)	
	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value
A	28.9	0.96	90	1.80	8.7	2.49	48	1.00	25.7	1.12	3.2	2.60	16.0	1.36	−2.5	0.81	36.4	1.21	17.5	0.58	86	1.72
B	34.3	1.01	66	1.83	5.2	0.34	42	1.75	24.4	1.10	1.7	0.44	11.4	0.71	−1.2	1.57	40.1	1.18	20.6	0.60	76	2.11
C	36.2	0.97	156	1.30	18.2	1.38	138	1.60	36.1	0.97	17.0	2.00	32.9	0.99	0.8	0.24	49.3	1.31	28.1	0.75	134	1.12
D	38.4	1.11	84	1.17	9.0	0.85	69	0.58	35.4	1.09	1.5	0.33	30.0	1.13	−1.3	1.50	45.3	1.31	31.0	0.90	86	1.19
E	21.0	1.00	36	1.06	14.4	1.11	30	1.36	14.6	1.36							19.2	0.91	15.6	0.74	24	0.71
Average value of Calculated value/ Measured value $\bar{x}$		1.01		1.43		1.23		1.26		1.13		1.34		1.05		1.03		1.18		0.71		1.37
Square root of unbiased variance		0.06		0.36		0.80		0.47		0.14		1.13		0.27		0.63		0.16		0.13		0.55
Coefficient of fluctuation		0.06		0.25		0.65		0.37		0.12		0.84		0.25		0.61		0.14		0.18		0.40

Name of the measured field	Finite Element Method															
	Tr, max (℃)		DAYmax (hr)		Ts,r,max (℃)		DAYs,max(hr)		Tr^{7},max (℃)		Ts^{7},r,max (℃)		Tr^{14},max (℃)		Ts^{14},r,max (℃)	
	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value	Calculated value	Calculated value / Measured value
A	27.4	0.91	96	1.92	7.8	2.23	48	1.00	24.3	1.06	3.9	2.95	16.1	1.36	−1.0	0.32
B	33.6	0.99	72	2.00	8.8	0.58	24	1.00	25.1	1.14	3.0	0.77	14.3	0.89	0.9	0.43
C	35.0	0.93	144	1.20	24.2	1.83	84	0.98	34.8	0.94	21.9	2.58	31.8	0.96	16.3	4.79
D	31.2	0.90	72	1.00	5.5	0.52	24	0.20	28.3	0.87	−4.1	1.89	22.9	0.86	−4.7	2.81
E	22.2	1.06	48	1.41	14.4	1.11	24	1.09	6.1	0.57						
Average value of Calculated value/ Measured value $\bar{x}$		0.96		1.51		1.25		0.85		0.92		2.05		1.02		2.09
Square root of unbiased variance		0.07		0.44		0.76		0.37		0.22		0.96		0.23		2.14
Coefficient of fluctuation		0.07		0.29		0.61		0.44		0.24		0.47		0.23		1.02

Table 15 shows the result of comparison. Each calculated value/measured value of $T_{\gamma,max}$, $T^{7}_{\gamma,max}$ and $T^{14}_{\gamma,max}$ according to the finite difference method is 1.01, 1.13 and 1.05, respectively. In the finite element method, it is 0.96, 0.92 and 1.02, respectively. And the coefficient of fluctuation of the calculated value/measured value is 5 to 25%, which is almost similar to that of the proposed method. Especially, $T_{\gamma,max}$ results were consistent approximately from each method of the proposed, the finite difference method and the finite element method, but the coefficient of fluctuation calculated by the proposed method is smaller than that of other two methods. Accordingly, the proposed method was adjusted according to the results from more involved analysis methods of the finite difference and the finite element.

Next, the simple methods of Yanagida and ACI are examined for comparison. The calculated results using these methods are shown in Table 15. The result shows that the Yanagida's method gave a higher result and the ACI method gave a lower result. The coefficients of fluctuation of the calculated value/measured value of $T\gamma$,max are 14% and 18%, respectively, which are 4 to 6 times of those of the proposed method. Thus, the proposed method was proved to give a highly accurate mass concrete temperature compared with the conventional methods. The verification on the average value $\bar{x}$ was conducted by a statistical method. The result was recognized without a significant difference between the proposed method and the finite difference method and the finite element method. While a significant difference was recognized between the proposed method and the Yanagida's and ACI methods by 1% of the significant level.

From the above, the proposed method by the author was shown to be applicable for calculating a mass concrete temperature with the similar accuracy to the finite difference method and the finite element method.

4. SUMMARY

This study examinated the effect of various factors affecting a mass concrete temperature by the numerical analysis and the measured value analysis. Proposal of a simple calculation of the mass concrete temperature on the basis of these results was given. The results are as follows

(1) A highly possitive correlation exists between the final adiabatic temperature rising amount Q_∞ and the maximum value $T\gamma$,max of the temperature rise with relation to placing temperature. The $T\gamma$,max increases linearly with increase in Q_∞. Q_∞ affects little to the time DAYmax to reach $T\gamma$,max.

(2) $T\gamma$,max increases hyperbolically with increase in the empirical constant γ for temperature rising rate and DAYmax decreases hyperbolically.

(3) The effects of Q_∞ and γ affecting the concrete temperature can be evaluated separately and the both effects can also be evaluated through superimpose of the individual effect.

(4) In the range of the thermal diffusivity h^2 for a common concrete, the effect of h^2 affecting $T\gamma$,max is within approximately 3°C. And the effect to the maximum value Ts,γ,max of the surface temperature rise due to the placing temperature is within approximately 5°C.

(5) T_γ,max increases as the ambient temperature goes to higher, but the increasing rate reduces with increase in the member dimension.

(6) The ambient temperature and Ts,γ,max approach follows a linear relationship and Ts,γ,max increases as the ambient temperature goes to higher.

(7) $T\gamma$,max increases parabolically as the member dimension increases, but effect of the member dimension affecting Ts,r,max is small.

(8) In the range of a common heat transfer rate, Tr,max fluctuates by 2 to 3°C and Ts,r,max fluctuates by about 10°C.

(9) $T\gamma$,max and Ts,γ,max decrease hyperbolically with increase in the heat transmission coefficient.

(10) The simple calculation procedure for a mass concrete temperature proposed by the author on the basis of the additivity can estimate the mass concrete temperature in a similar accuracy to the finite element method.

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