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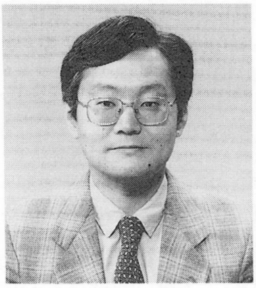
EVALUATION OF ADIABATIC TEMPERATURE RISE OF CONCRETE MEASURED WITH THE NEW TESTING APPARATUS

(Translation from Proceedings of JSCE, No396, August 1988)



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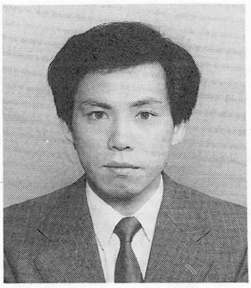

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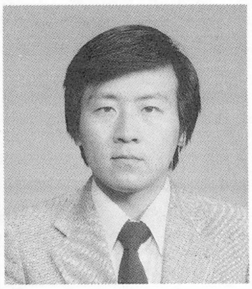

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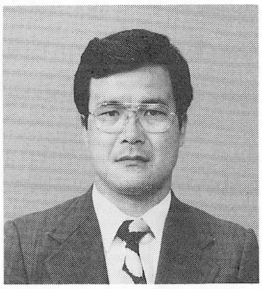

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SYNOPSIS

The influence of different types of cement, cement content per unit volume of concrete, and concreting temperature on adiabatic temperature rise were evaluated during this study. The adiabatic temperature rise was measured with a new testing apparatus, with high reliability that has been confirmed through comparison with time-dependent temperature changes in mass concrete structures. Before evaluation, the most suitable equation for approximating the adiabatic temperature rise as a functional formula of time was selected based on the experimental results. Further, comparison of the above approximate values with standard values proposed by JSCE or JCI was done, and problems involved in these standard values were pointed out.

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1. INTRODUCTION

Thermal cracks in mass concrete structures caused by heat of hydration in cement are matters of concern because they reduce utility and durability of mass concrete structures. In response, temperature of mass concrete and thermal stress must be evaluated in advance to predict the likelihood of thermal cracks and, consequently, plan effective measures to cope with the problems. Numerical calculation method, such as the finite element method, are already recognized as means of analyzing temperature. Therefore, if the values for thermal properties of concrete are adequate, precise analysis can be made[1],[2]. Although there are several thermal property values, calorific values of concrete, attributable to heat of hydration of cement, are thought to have the most significant impact on results of analysis of temperature.

Caloric values of concrete may be determined through (1) calculations in which the heat of hydration of cement is measured by the heat dissolution method or conductive microassessment of heat, and (2) direct measurement of the adiabatic temperature rise in concrete. If the first method is chosen, measured values cannot be applied to thermal analysis of mass concrete without additional procedures in that heat of hydration of cement is measured at constant temperatures[3]. In contrast, if the second method is selected, measured values may be applied to thermal analysis as is[4].

There are a number of factors that affect adiabatic temperature rise. However, cement type, cement content per unit volume of concrete (referred to hereafter as "unit cement content"), and concreting temperatures are thought to be the three most important aspects to consider. In addition, the effects of the testing apparatus on the evaluation process and results have been deemed significant in the past few years[4],[5]. Sharper awareness of the effects of the testing apparatus in the processes has made it crucial to evaluate performance capabilities of the testing apparatus. This study includes evaluation to determine if testing apparatus permits the test specimen to approach a state of total heating insulation. Additionally, there are several schools of thought on equations for approximating adiabatic temperature rise. There must be further research on such equations, however, to determine the accuracy of correlation[4].

In this study, the new testing apparatus used enabled us to confirm that the test specimen had approached a state of total heating insulation. After that observation, we calculated the effect that cement type, unit cement content, and concreting temperature had on adiabatic temperature rise. Thereafter, we took into consideration optimum approximations for showing adiabatic temperature rise, based upon the data obtained in experiments. Finally, we compared the approximate values with standard values found in the standard specification for design and construction of concrete structures by JSCE (referred to hereafter as "RC specification")[6] and JCI guideline[7].

2. RESEARCH IN RETROSPECT

Approximately thirty years ago, Japan began reporting the results of research on adiabatic temperature rise in concrete. Since then, there has been a wealth of data provided from numerous researchers and scientists in this field of study. Nevertheless, researchers and scientists have been using different testing apparatus to evaluate adiabatic temperature rise in concrete because of an absence of standardized testing methods[4],[5]. This has created the necessity to verify methods for confirming the accuracy and capabilities of testing apparatus.

R.Tsukayama has been studying ways to make valid approximations of adiabatic temperature rise in concrete[8]. In his research, he reports the following:

(1) Eq.(1), shown below, produces a reliable approximation of adiabatic temperature for ordinary portland cement(OPC).

(2) Eq.(2), shown below, produces a reliable approximation of adiabatic temperature rise (a) for ultra high early strength portland cement; (b) when escalating temperatures are low; and (c) when retarding agents are used.

E.Miyaji, however, indicates that Eq.(1) produces a poor approximation of adiabatic temperature rise even for OPC in the initial stages after concreting[9]. Similarly, H.Yamakawa reports approximations made using Eq.(1) are poor for OPC when rich mixture is used in hot-weather concreting[10].

T.Hiraga adds Eq.(3) and Eq.(4), below, as methods for approximating adiabatic temperature in concrete. He has studied the validity of approximations for general concrete and when retarding agents are used, including those approximations based on Eq.(3). These evaluations are based upon standard deviation of error in experimental values and approximations. He reports the following:

(1) Eq.(2) is preferable to Eq.(1) for approximation when study is done on general concrete.

(2) Eq.(3) is preferable to Eq.(1) and Eq.(2) when retarding agents are used.

$$Q(t)=Q_\infty(1-\exp(-rt)) \tag{1}$$
$$Q(t)=Q_\infty(1-\exp(-rt^s)) \tag{2}$$
$$Q(t)=Q_\infty(1-\exp(-r(t-t_0)^s) \tag{3}$$
$$Q(t)=Q_\infty(1-(1+rt)\exp(-rt)) \tag{4}$$

where $Q(t)$ is adiabatic temperature rise at t days, and Q_∞, r, s and t_0 are experimental constants.

In current RC specification and JCI guidelines, adiabatic temperature rise in concrete is generally determined based upon testing when needed. Yet, when not based upon testing, such indicators suggest that standard values for adiabatic temperature rise in concrete obtained from Eq.(1) may be used, primarily because of the simplicity of that formula[6],[7]. However, in terms of correlation with experimental values, it would appear that there is room for additional research.

In calculating each coefficient for Eq.(1) as the approximation of adiabatic temperature rise, R.Tsukayama determined the effect of concreting temperature and unit cement content, which are reflected in Q_∞ and r. Q_∞ and r are shown in the linear equation for unit cement content for each type of cement. The effect that concreting temperature had upon each coefficient differed slightly by coefficient. Q_∞ decreased in accordance with concreting temperature. In contrast, r was seen to increase proportionately with concreting temperature. Moreover, upon determination of the relationship between the coefficient r and the reciprocals, when concreting temperature was indicated in absolute temperatures, the Arrhenius law on rate of chemical reactions was proven.

For RC specification, coefficients for Eq.(1) are shown in a linear for unit cement content at concreting temperature of 10℃, 20℃, and 30℃ for all types of cements. JCI guidelines show basic values for coefficients in Eq.(1) in linear equations for unit cement content for concreting temperatures at 20℃ for all cements. For more careful evaluation of the effect of concreting temperature, there has been some thought given to providing supplemental coefficients corresponding to basic values in the linear equation for concreting temperature for every unit cement content of 200 kg/m^3, 250 kg/m^3, 300 kg/m^3, 350 kg/m^3,and 400 kg/m^3. However, calculation of intermediate coefficients for unit cement content and concreting temperatures entails time-consuming procedures. Therefore, without sacrificing reliability of approximations, methods that facilitate the calculation of coefficients are deemed necessary.

3. TESTING APPARATUS FOR EVALUATING ADIABATIC TEMPERATURE RISE

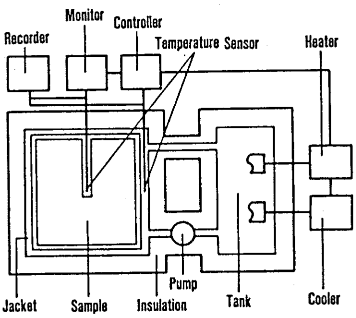


Fig. 1 Adiabatic temperature rise testing apparatus.

As shown in Fig.1, the testing apparatus used in these experiments are designed to measure adiabatic temperature rise by causing the test specimen to come into close contact with a heat conduction jacket with a circulatory path in a partition structure. The testing apparatus does not include heat insulating materials between the test specimen and the heat conduction jacket.

The testing apparatus does not merely evaluate heat insulation. The testing apparatus enables evaluation of concrete tendencies through comparison of adiabatic temperature rise and temperature history of an actual concrete structure (or a large-sized test specimen that is similar to an actual concrete structure) in conditions identical to those to which concrete to be laid will be exposed.

The test specimen was a cylinder of 60 cm in diameter and 60 cm high. Immediately after concreting, measurements were taken every 30 minutes. In general, measurements were discontinued at seven days. However, if heat generates slowly, even after a lapse of seven days, measurements were continued 10 to 14 days if noticeable adiabatic temperature rise was detected.

4.CONCRETE USED IN TESTING OF ADIABATIC TEMPERATURE RISE

For evaluation of adiabatic temperature rise in concrete using the new testing apparatus, cement type, unit cement content, and concreting temperature were varied. In total, testing of adiabatic temperature rise was carried out on 72 experimental variations. Four types of cement were studied: ordinary portland cement(OPC); moderate heat portland cement(MHPC); portland blast-furnace slag cement type B(BCB); and fly-ash cement type B(FCB). Unit cement contents were 200 kg/m^3, 250kg/m^3, 300kg/m^3, 350kg/m^3, and 400 kg/m^3. Concreting temperature were 10°c, 20 °c, and 30 °c. For detailed analysis of the effect of concreting temperature on adiabatic temperature rise, concreting temperatures of 5°c,15 °c, and 25°c for unit cement content at 300kg/m^3 were added.

Table 1 shows the chemical composition and heat of hydration of cement under study. Slag in BCB was 40%; fly-ash in FCB was 20%. Mix proportion of concrete was set at the following : (a)the maximum coarse aggregate was 40 mm of crushed

Table 1 Chemical composition and heat of hydration of cement.

Type of cement	Chemical composition (%)									Heat of hydration (cal/g)		
	ig. loss	insol	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total	3 days	7 days	28 days
OPC	0.5	0.3	21.8	5.9	3.1	64.4	1.2	1.8	99.0	61.2	73.8	92.0
MHPC	0.5	0.2	23.4	4.0	4.1	63.9	1.4	1.8	99.3	50.4	68.5	81.0
BCB	0.4	0.5	26.4	8.8	1.9	56.0	3.1	2.0	99.1	58.0	75.6	90.1
FCB	1.0	11.8	19.5	4.8	2.7	56.4	1.2	1.8	99.2	53.4	69.6	83.0

stone; (b)slump was 8cm; and (c)air content was 4%. Unit cement contents were 200kg/m^3, 250kg/m^3, 300kg/m^3, 350kg/m^3, and 400kg/m^3. The cement-water ratio varied from 81% to 37.5%. AE water reducing agent in the amount of 0.25% of unit cement content was used. To obtain allotted air volume content, an air volume regulating agent was also used.

5.RELIABILITY OF APPROXIMATIONS OF ADIABATIC TEMPERATURE RISE

Eq.(3) was correlated with Eq.(2), both equations being included in the four equation outlined in part 2 above. This equation accounts for comparatively mild adiabatic temperature rise in the initial stages after concreting, similar to adiabatic temperature rise of concrete in which a water-reducing retarder is used, but is considered reliable for approximating adiabatic temperature of concrete in the event that temperature rise is rapid in later stages. However, in this research study, approximations of adiabatic temperature by Eq.(3) were nearly the same as approximations made by Eq.(2).

Therefore, for more accurate assessment of reliability of approximations, Eq.(1), Eq.(2), and Eq.(4) were taken into study. By the method of least squares, coefficients for approximations were found by using data obtained every other 30 minutes starting with readings taken directly after concreting to the time at which measurement readings were discontinued.

Fig.2 indicates the reliability of approximations. Approximations made by Eq.(1) show that experimental values are low for the period covering the stage immediately following concreting to one day. In contrast, experimental values increase through day 4. In the final period of readings, however, experimental values again decrease. In particular, correlation with experimental values through day 1 are poor; experimental values are smaller than values obtained by approximation by as much as 7 °c. In contrast, approximations obtained through from Eq.(2) and Eq.(4), all covering the time from concreting through day 7 correlated well. The margin of error between those approximations and experimental values is at most 2 °c.

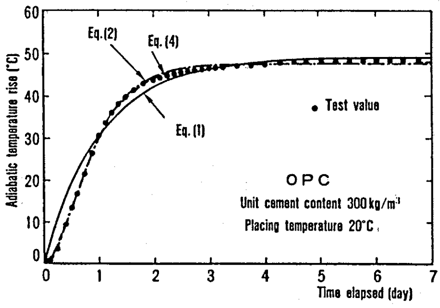
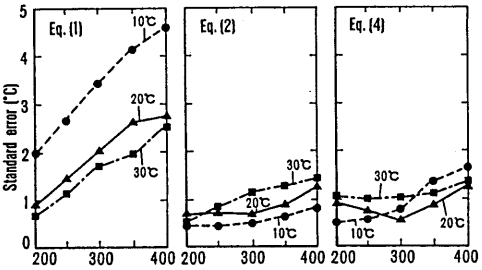


Fig. 2 Adaptabilities of approximation equations.

Fig.3-6 show standard deviation between approximations and experimental values. From these Figures, Eq.(1) is found to be generally inferior to Eq.(2) and Eq.(4). In addition, notwithstanding cement type, margin of error significant -- the greater the unit cement content and the lower concreting temperatures becomes, the greater the margin of error. The effect of unit cement content and concreting temperatures is not as apparent in approximations based on Eq.(2) and Eq.(4) as it is in approximations based on Eq.(1). In addition, both Eq.(2) and Eq.(4) have significantly better reliability than Eq.(1).

In general, there is little difference in accuracy between Eq.(2) and Eq.(4). However for blended cements, such as BCB or FCB, the reliability of Eq.(2) is slightly better because of a lower margin error with experimental values and the effect of unit cement content and concreting temperature is small.

When analyzing temperature of mass concrete structure, produced from FEM or other methods, the rate of temperature rise per unit of time has a significant



Values in figure indicate placing temperatures

Fig.3 Errors of approximation equations (Case of OPC).

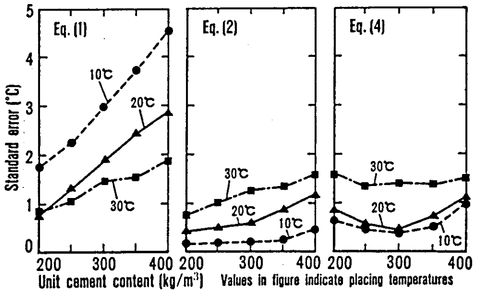


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Fig.4 Errors of approximation equations (Case of MHPC).

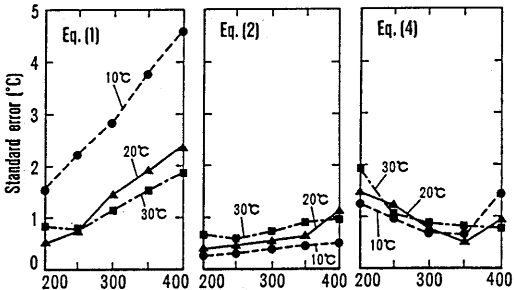

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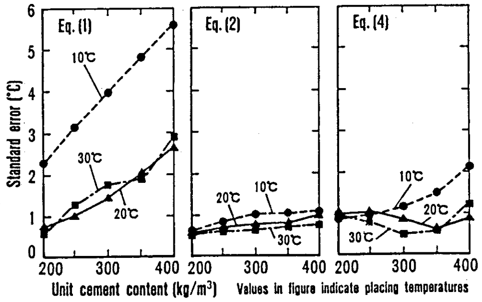
Fig.5 Errors of approximation equations (Case of BCB).



Values in figure indicate placing temperatures

Fig.6 Errors of approximation equations (Case of FCB).

impact of the results of analysis. Fig.7 maps the comparison of rate of temperature rise from the approximations, made by the above three equations, and experimental values. The rate of temperature rise in experimental values is displayed at values that differentiate by time the curve of data obtained from readings taken every other 30 minutes, linking the adjacent three points in a quadratic parabola.

The rate of temperature rise in experimental values does in fact decrease following a peak. This appears to be due to occurrence of heating in early stages after concreting. After that, there are a second rise in temperature and two peaks at 7 hours and at 1 day. Thereafter, there is a gradual decrease in the rate of temperature rise. The size and time of peaks vary considerably by cement type, unit cement content , and concreting temperature. Moreover, if concreting temperature is low, unit cement content is small or heat occurrence is mild, it was deduced that there would only be one peak following initial heat occurrence.

As shown in Fig.7, if adiabatic temperature rise in concrete is approximated by Eq.(1), there will be considerable variations in experimental values when there is a peak in rate of adiabatic temperature rise because of the curve that steadily decreases from the stage directly following concreting. Therefore, reliability of approximations made by Eq.(1) are markedly poor during the time following concreting where there is a peak in experimental values through 1 day. Rates of adiabatic temperature rise, obtained from Eq.(2) and Eq.(4), do not go as far as approximation of the peak directly following concreting in experimental values or the two peaks later. Nevertheless, the tendency for time-dependent temperature change in the rate of adiabatic temperature rise is comparatively well accounted for in both equations. Thus, we can say that the two equations provide adequate practical reliability. Fig.8 shows the accuracy

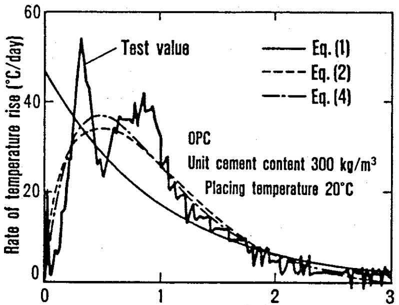


Fig.7 Adaptability of approximation equation to rate of temperature rise.

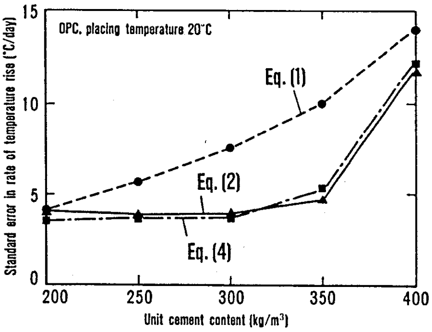


Fig.8 Errors of approximation equations for rate of temperature rise.

and reliability of both Eq.(2) and Eq.(4) in correlation to rate of adiabatic temperature rise. Even noting margin of error with experimental values for OPC, there is hardly any variation between the two equations.

Study of reliability of approximations of adiabatic temperature rise resulted in judgment that approximations based on Eq.(2) and Eq.(4) were superior to approximations obtained by Eq.(1). This deduction was made from margin of error in correlation to adiabatic temperature rise and rate of temperature rise. In addition, although the reliability of approximations made by Eq.(2) differed little from reliability of approximations made by Eq.(4), Eq.(2) was slightly better when blended cements were the subject matter. Therefore, in the research that followed on adiabatic temperature rise in concrete using the new testing apparatus, approximations of adiabatic temperature rise were made in accordance with Eq.(2) and coefficients obtained therefrom were used to make calculations.

6.EVALUATION OF COEFFICIENTS IN APPROXIMATIONS

Table 2 shows each coefficient, approximated by Eq.(2), for each variation in concreting temperature, unit cement content and cement type. Fig.9 shows the relationship of each coefficient and unit cement content for each cement type. Fig.9 also shows the relationship of Q_∞ and unit cement content, which is clarified in linear equation of unit cement content for concreting temperatures at 20°c. Coefficients that show Q_∞ in a linear equation of unit cement content are compiled in Table 3. Fig.10 indicates the effect that concreting temperature has on Q_∞ by a percentage in comparison to Q_∞ when concreting

Table 2 Coefficients of approximation equations for adiabatic temperature rise of various cements.

Placing temperature °C	Type of cement	Unit cement content (kg/m³)	Q_∞	r	S
5	OPC	300	51.5	0.264	1.642
	MHPC		42.5	0.119	1.563
	BCB		51.7	0.211	1.407
	FCB		46.7	0.101	1.629
10	OPC	200	35.1	0.296	1.367
		250	44.3	0.333	1.478
		300	51.0	0.386	1.634
		350	56.0	0.443	1.806
		400	60.0	0.484	1.959
	MHPC	200	32.4	0.226	1.269
		250	36.9	0.245	1.404
		300	43.7	0.228	1.487
		350	48.9	0.225	1.617
		400	53.4	0.212	1.729
	BCB	200	40.3	0.278	1.116
		250	45.6	0.303	1.291
		300	51.0	0.340	1.409
		350	56.7	0.370	1.598
		400	60.1	0.445	1.832
	FCB	200	32.2	0.153	1.328
		250	37.5	0.143	1.501
		300	45.7	0.158	1.638
		350	51.9	0.177	1.794
		400	56.9	0.200	1.970
15	OPC	300	50.2	0.494	1.538
	MHPC		43.0	0.383	1.372
	BCB		51.1	0.495	1.378
	FCB		45.1	0.253	1.508
20	OPC	200	35.1	0.782	1.181
		250	42.6	0.916	1.309
		300	48.9	1.043	1.429
		350	54.0	1.411	1.618
		400	58.1	2.228	1.734
	MHPC	200	30.6	0.604	1.070
		250	36.4	0.659	1.151
		300	41.0	0.644	1.259
		350	46.7	0.768	1.321
		400	51.7	0.940	1.407
	BCB	200	36.6	0.770	0.949
		250	43.0	0.760	1.090
		300	47.4	0.938	1.285
		350	52.5	1.153	1.429
		400	57.5	1.392	1.540
	FCB	200	30.4	0.483	1.195
		250	37.9	0.475	1.313
		300	44.2	0.621	1.537
		350	50.7	0.771	1.606
		400	55.2	1.103	1.765
25	OPC	300	48.7	1.316	1.402
	MHPC		41.2	0.818	1.185
	BCB		48.2	1.012	1.199
	FCB		44.8	0.752	1.322
30	OPC	200	34.3	1.249	1.083
		250	42.7	1.300	1.204
		300	49.4	1.812	1.381
		350	53.4	2.833	1.554
		400	58.3	3.108	1.729
	MHPC	200	32.0	0.761	0.921
		250	36.5	0.853	1.080
		300	42.6	0.881	1.182
		350	47.6	1.151	1.204
		400	52.6	1.273	1.266
	BCB	200	37.3	1.005	0.866
		250	40.3	1.232	1.106
		300	46.6	1.410	1.223
		350	50.9	1.987	1.351
		400	56.0	2.079	1.440
	FCB	200	31.7	0.718	1.125
		250	38.6	0.725	1.291
		300	44.6	0.955	1.453
		350	49.0	1.446	1.522
		400	54.0	1.509	1.700

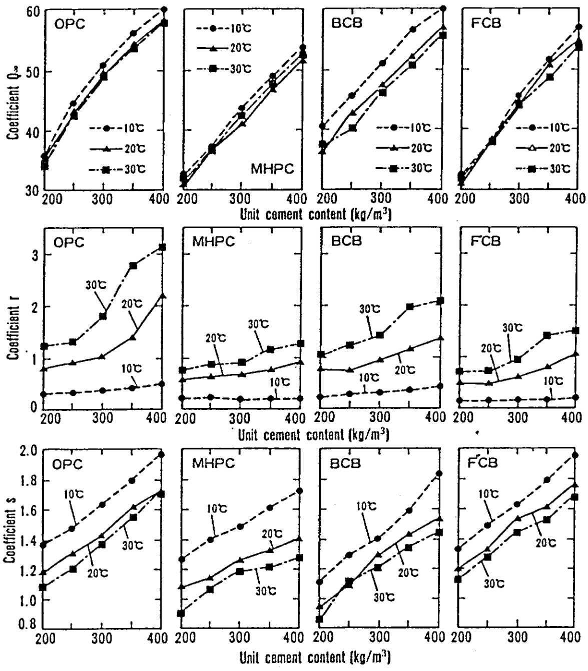


Fig. 9 Relationships of coefficients of approximation equations and unit cement contents.

Table 3 Relationship between Q∞ and unit cement content C* (kg/m³) in case of placing temperature 20°C.

Type of cement*	Ultimate value Q∞ of adiabatic temperature rise Q∞=A0+AI+C*	
	A 0	A 1
O P C	13.16	0.115
M H P C	9.78	0.105
B C B	16.62	0.103
F C B	6.24	0.125

Table 4 Coefficient of correction curve of Q∞ according to placing temperature T* (°C).

Type of cement	Correction value p for Q∞ p=A0+AI x T*+A2 x T*²		
	A 0	A 1	A 2
O P C	1.083	−0.0063	0.00011
M H P C	1.118	−0.0109	0.00026
B C B	1.168	−0.0120	0.00019
F C B	1.088	−0.0075	0.00016

temperature is 20°c. From this figure, the effect of concreting temperature on Q∞ is deemed proper for consideration in a quadratic equation for concreting temperature indicated in the figure. Coefficients of supplemental curves for Q∞ for concreting temperature for each type of cement are complied in Table 4. In this research, the effect of concreting temperature on Q∞ , which is indicated as the final value of adiabatic temperature rise, was not as significant

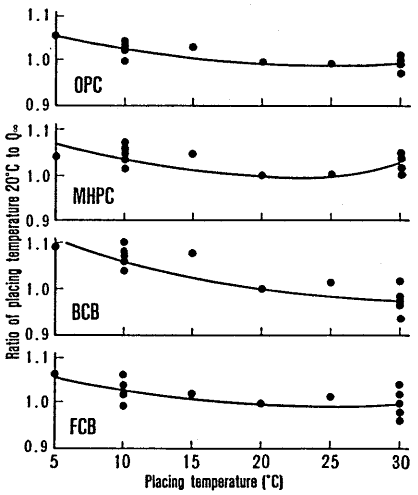


Fig. 10 Correction curve for Q∞ according to placing temperature.

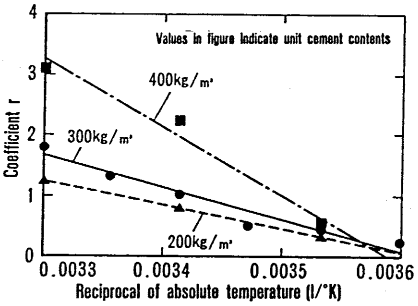


Fig. 11 Arrhenius plot of coefficient r

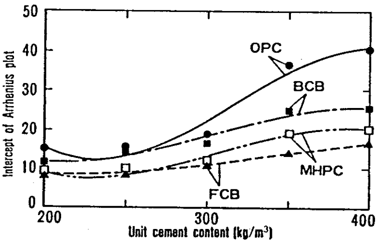


Fig. 12 Relationship between intercept of Arrhenius plot of coefficient r and unit cement content.

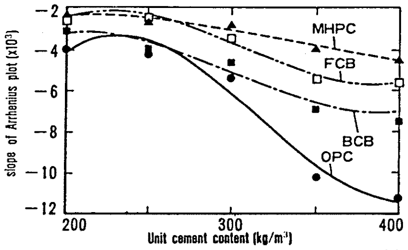


Fig. 13 Relationship between slope of Arrhenius plot of coefficient r and unit cement content.

as the effect indicated in previous reported studies.

R is a coefficient closely related to rate of temperature rise, in short, rate of chemical reactions. For OPC, Fig.11 indicates the relationship between r and reciprocals of findings on concreting temperatures in absolute temperatures. The Arrhenius law is proven in regard to chemical reactions for both. However, the Arrhenius plot varies by unit cement content. Findings of the intercept and slope of the Arrhenius plot were made for each unit cement content. These values were then indicated in a cubic equation for unit cement content --see Fig.12 and Fig.13. The above-mentioned coefficients have been compiled in Table 5 for each cement type. Therefore, r for random temperatures can be found from concreting temperature and the intercept and slope the Arrhenius plot show in a cubic equation for unit cement content.

Table 5 Relationship between intercept and slope of Arrhenius plot of r and unit cement content C^* (kg/m^3).

Kind		Coefficient of cubic equation $V=A0+A1\times C^*+A3\times C^{*2}+A3\times C^{*3}$			
		A 0	A 1	A 2	A 3
Intercept	OPC	310.20	−3.189	0.01085	-1.140×10^{-5}
	MHPC	37.62	−0.320	0.00108	-0.103×10^{-5}
	BCB	112.51	−1.167	0.00425	-0.469×10^{-5}
	FCB	157.81	−1.642	0.00573	-0.621×10^{-5}
slope	OPC	-8.910×10^{4}	9.175×10^{2}	−3.123	3.288×10^{-3}
	MHPC	-1.090×10^{4}	0.942×10^{2}	−0.318	0.305×10^{-3}
	BCB	-3.186×10^{4}	3.316×10^{2}	−1.209	1.337×10^{-3}
	FCB	-4.496×10^{4}	4.688×10^{2}	−1.637	1.776×10^{-3}

Table 6 Relationship between intercept and slope of Arrhenius plot of s and unit cement content C^* (kg/m^3).

Kind	Type of cement	Coefficient of quadratic aquation $U=A0+A1\times C^*+A2\times C^{*2}$		
		A 0	A 1	A 2
Intercept	OPC	−5.861	1809×10^{-2}	-1.891×10^{-5}
	MHPC	−11.833	6.263×10^{-2}	-11.699×10^{-5}
	BCB	−17.575	11.495×10^{-2}	-20.344×10^{-5}
	FCB	−4.463	2.170×10^{-2}	-4.091×10^{-5}
slope	OPC	1.979×10^{3}	−5.061	0.663×10^{-2}
	MHPC	3.605×10^{3}	−17.272	3.339×10^{-2}
	BCB	5.204×10^{3}	−32.287	5.894×10^{-2}
	FCB	1.466×10^{3}	−5.303	1.165×10^{-2}

S is a coefficient that regulates rate of adiabatic temperature rise. For OPC, Fig.14 shows the relationship between s and reciprocals of findings on concreting temperature in absolute temperatures. Here, the Arrhenius law pertaining to chemical reactions was proven for both. The line of the Arrhenius plot varied by unit cement content. As was done for r, the intercept and the slope of the line of the Arrhenius plot was found for each unit cement content. Moreover, these values were indicated as a quadratic equation of unit cement content. Table 6 provides the coefficient in the aforementioned quadratic equations for each type of cement. Therefore, s, for random temperatures, can be found from concreting temperature and the intercept and slope of the Arrhenius plot, shown in the quadratic equations for unit cement content.

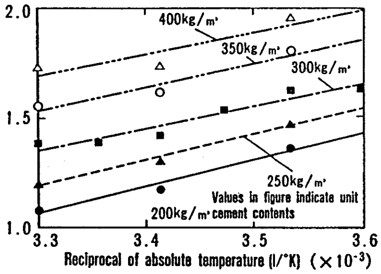


Fig.14 Arrhenius plot of coefficient S.

Coefficients for approximations of adiabatic temperature rise, for random conditions, made by Eq.(2), may be calculated by the procedure above. Fig.15 gives an example which indicates the reliability of Eq.(2), which uses the coefficients calculated by the aforementioned procedures, by standard deviation of error with experimental values. From this figure, it was deduced that these procedures enabled evaluations to be made at minimal sacrifice of accuracy between approximations and experimental values.

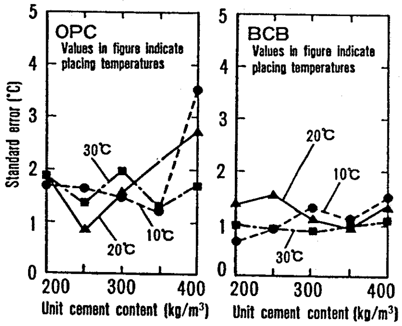


Fig.15 Errors in quantification.

7. Comparison with RC Specification and JCI Guidelines

Fig. 16 compares standard values provided by RC specification and JCI guidelines with Q_∞ (referred to hereafter as "approximate values") calculated using Eq.(2) when calculations were made in accordance with part 6. With the exception of BCB at concreting temperatures of 10°C and 30°C and MHPC at a concreting temperature of 30 °C, there are no significant differences between standard values of RC specification and those of JCI guidelines. For this reason, comparisons were made using RC specification. However, JCI values were used when standard values of RC specification were lacking.

Regardless of cement type, approximate values were larger than standard values for all concreting temperatures. For example, between approximate values and standard values for OPC, there was a difference of 4-6 °C when concreting temperature was 10°C; a difference of 5-9 °C when concreting temperature was 20°C; and a difference of 5-12°C when concreting temperature was 30°C. When concreting temperatures were high and unit cement content were large, differences between approximate values and standard values widened. Approximate values increased slightly in accordance with a decrease in concreting temperature. However, these differences were negligible. In contrast, for OPC standard values provided low estimates of the rates at which Q_∞ increased in accordance with increase in unit cement content at high concreting temperatures. It was concluded that the difference arose as a result of those factors. In addition, when percentages corresponding to standard values of approximate values were found, differences varied by both concreting temperature and unit cement content. Overall differences were as large as 20%.

Values in figure indicate placing temperatures

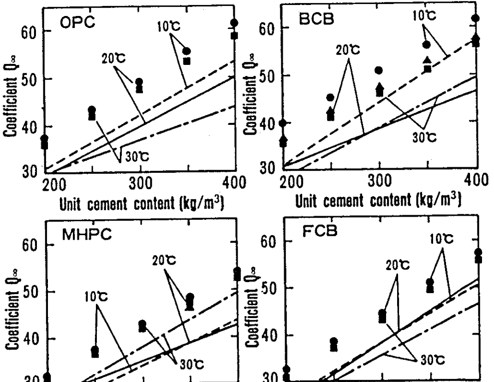


Fig.16 Comparison of approximate and standard values of coefficient Q_∞.

(Plots indicate approximate values and curves of standard values)

Fig.17 indicates time-dependent change in difference of adiabatic temperature rise for standard values and approximate values on OPC. Here, concreting temperatures were set at 20 °C and unit cement content was varied. As mentioned on reliability of approximation in part 5, standard values approximated by Eq.(1) indicate that standard values are larger than approximate values measured over half a day following concreting. This is due to the existence of rate of temperature rise beginning from time of concreting. However, after that stage, approximate values exceed standard values. Moreover, the larger the unit cement content becomes, the greater the difference for both tends to become. For unit cement content at 300 kg/m^3, the maximum difference is about 13 °C. For unit cement content at 400 kg/m^3, the difference is approximately 20 °C. When unit cement content is small, time-dependent change in differences between approximate values and standard

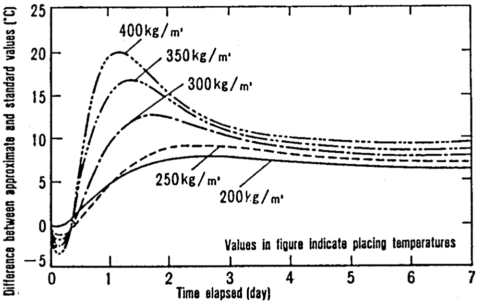


Fig.17 Example of difference in approximate and standard values in case of variation in unit cement content.

values will less than around $Q\infty$ because rate of temperature rise is small in comparison with standard values. In contrast, when unit cement content is large, there are many instances in which approximate values exceed rate of adiabatic temperature rise in comparison to standard values. Therefore, in the study of time-dependent change in differences between approximations and standard values, all tendencies to surpass $Q\infty$ were noted. For this reason, when section measurements are comparatively large and when structures have a high propensity to cracking, important discrepancies may well arise in research on thermal stress for analytic temperature values based on approximate values and analytic values based on standard values.

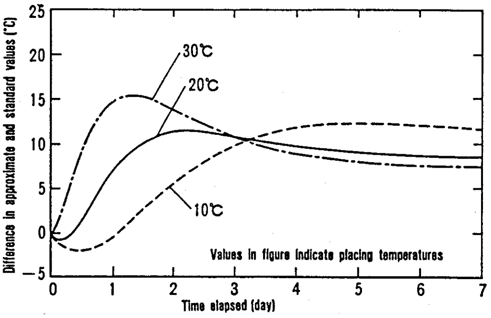


Fig.18 Example of difference in approximate and standard values in case of variation in placing temperature.

Fig.18 shows time-dependent changes in differences of adiabatic temperature rise for approximate values and standard values. The cement type is BCB, unit cement content is 300 kg/m^3 and concreting temperature varies. As soon as concreting temperature rises, approximate values significantly exceed standard values from the time following concreting because rate of temperature rise also increase from the time immediately following concreting for approximate values. If the effect of difference in rate of temperature rise is taken into account, differences of both will be greater. However, in the end, there will be convergence into the difference of $Q\infty$ for both. When concreting temperatures are 10°C and 20°C, the difference is a maximum of 12°C. When concreting temperature is at 30°C, the difference is 15°C. A combination of factors of cement type, unit cement content, and concreting temperature will cause time-dependent changes in differences between approximate values and standard values to be much larger than the differences of $Q\infty$.

8. Conclusion

By using the testing apparatus which confirmed that the test piece did approach a state of total heating insulation, adiabatic temperature rise in concrete was measured in instances in which various factors of cement type, unit cement content , and concreting temperature were varied. Evaluations were made accordingly. The following conclusions were drawn from this research study.

(1) There are several proposed methods for approximating adiabatic temperature rise. However, in terms of correlations of adiabatic temperature rise and rate of temperature rise the following formula is deemed best:

$$Q(t)=Q\infty(1-\exp(-rt^{s}))$$

$Q(t)$ is adiabatic temperature rise at t days.

$Q\infty$, r, s are experimental constants.

(2) Evaluations of effect of cement type, unit cement content, and temperature on each coefficient of this formula were as follows:
$Q\infty$ is shown in a linear equation for unit cement content for each type of cement. In addition, consideration should be given to the effect of concreting temperature by supplementing with a quadratic equation in correlation to $Q\infty$ at concreting temperature of 20°C. R is a coefficient closely related to the rate

of chemical reactions. Thus, the Arrhenius law is proven between r and reciprocals when concreting temperature is expressed in absolute temperatures. The intercept and slope of the Arrhenius plot for r can be expressed in a cubic equation of unit cement content.

s is a coefficient that regulates rate of adiabatic temperature rise. As with r, the Arrhenius law was proven between s and reciprocals when concreting temperature was expressed in absolute temperature. The intercept and slope of the Arrhenius plot for s can be expressed in a quadratic equation of unit cement content. Therefore, approximations of adiabatic temperature rise, for random condition, can be obtained for unit cement contents and concreting temperatures.

(3) Approximations made of adiabatic temperature rise obtained in this research study were compared with standard values of RC specification and JCI guidelines. Differences in final temperature rise was generally 20%. Time-dependent change in differences for both was determined to be larger than that figure.

ACKNOWLEDGEMENTS

Special thanks is given to Professor Hajime Okamura of the University of Tokyo for his help and guidance in this research study. Special mention is also made of Mr.Norio Yokota and Mr.Toshiyuki Sato of Sumitomo Cement,Co.,Ltd. for their assistance in carrying out experiments and drafting theses on research.

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