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Modeling of Temperature Rise in Concrete Using Fly Ash

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Summary

This paper proposes models for thermal conductivity and specific heat of hardening concrete and the material parameters of different types of fly ashes to determine the temperature rise in concrete. Thermal conductivity of hardening concrete is computed based on the volumetric ratio and the respective thermal conductivity values of the ingredients. Similarly, the specific heat model is based on the weight fractions and respective specific heat values of the ingredients. In the fly ash model, the reference heat rate and thermal activity of different types of fly ashes are expressed as functions of their CaO content. Temperature rise values in concrete specimens and a mat footing are computed using the proposed models and compared with the measured results. Good correlation among the analytical and test results is obtained.

1. Introduction

When water is added to cement, an exothermic reaction takes place causing a temperature rise in concrete after mixing. As the thermal conductivity of concrete is comparatively low, it acts like an insulator and heat produced inside mass concrete can not dissipate easily. At the same time, the exterior surface looses some heat. As a result, a temperature difference is developed between the exterior surface and the interior of the mass. This temperature difference causes internal tensile stress in mass concrete. When the tensile stress exceeds the tensile strength of concrete at that age, concrete structures, especially with external restrains, experience cracks. These cracks in the early age of concrete affect the durability and shorten the life span. So some means are required to control the temperature rise in concrete. Among other means, one effective method is to reduce the cement content of concrete by replacing it with fly ash [1]. Kishi and Maekawa [2] proposed a multi-component hydration model for blended cement with blast furnace slag and fly ash. This paper proposes a modification of the fly ash component of their model considering the difference of hydration heat produced by different fly ashes for their chemical compositions [1]. As the temperature rise in concrete is also a function of its thermal conductivity and specific heat, models are proposed here to predict these thermal coefficients at different stages of hydration [3].

2. Assumptions of the models

The following assumptions are made in proposing the models for thermal coefficients and material parameters of fly ash:

1. Linear combination rule is used in computing the thermal coefficients of concrete.
2. The changes of total volume and unit weight of concrete during hydration are assumed to have negligible effect on thermal properties of concrete.
3. For non air-entrained concrete, as the thermal conductivity of air is very small as compared to those of other ingredients, it is neglected in computing the heat conductivity of concrete.
4. As the weight fraction of air is very small as compared to those of the other ingredients, it is neglected in computing the specific heat of concrete.
5. Volume of air remains unchanged during the hydration.
6. Volume decrease of the hydration product during hydration is neglected.
7. The material parameters of fly ash are expressed as functions of its CaO content.

3. Thermal coefficients of concrete

3.1 Thermal Conductivity

As the hydration reaction proceeds, the amount of free water in concrete reduces with an increase in the amount of hydrated product and concrete converts gradually from a fresh state to plastic and hardened states. So the thermal conductivity of concrete increases with time, especially in early age. The thermal conductivity of concretes with different mix proportions and containing different types of materials are also different. Here a model is proposed to compute the heat conductivity of concrete at different ages based on the volumetric ratio and thermal conductivity of the individual components of concrete, namely coarse aggregate, fine aggregate, cement and water. The volumetric ratio of fly ash as a cement replacing material is also considered. As coarse aggregate, fine aggregate and air are inert, their volumetric ratio and heat conductivity remain constant throughout the hydration. But the volume of unhydrated cementitious material (eg. cement and fly ash) and free water reduces and the amount of hydrated product increases with time. Considering these factors, the following equations are proposed to determine the heat conductivity of concrete during the hydration process.

$$Z(t) = n_g z_g + n_s z_s + n_{fw}(t) z_w + n_{uc}(t) z_c + n_{ufa}(t) z_{fa} + n_{hp}(t) z_{hp} \quad (1)$$

$$n_{uc}(t) = \left(1 - dh_c(t)\right) n_{c0} \quad (2)$$

$$dh_c(t) = \frac{Q_{3A}(t)}{Q_{3A\max}} \rho_{3A} + \frac{Q_{AF}(t)}{Q_{AF\max}} \rho_{AF} + \frac{Q_{3S}(t)}{Q_{3S\max}} \rho_{3S} + \frac{Q_{2S}(t)}{Q_{2S\max}} \rho_{2S} \quad (3)$$

$$n_{ufa}(t) = \left(1 - dh_{fa}(t)\right) n_{fa0} \quad (4)$$

$$dh_{fa}(t) = \frac{Q_{FA}(t)}{Q_{FA\max}} \quad (5)$$

$$n_g + n_s + n_{w0} + n_{c0} + n_{fa0} + n_a = 1.0 \quad (6)$$

$$n_{hp}(t) = 1 - \left(n_g + n_s + n_{fw}(t) + n_{uc}(t) + n_{ufa}(t) + n_a\right) \tag{7}$$

where, Z(t) : conductivity of concrete at any time

n_g, n_s, n_a : volumetric ratio of gravel, sand and air

n_{w0}, n_{c0}, n_{fa0} : initial volumetric ratio of free water, cement and fly ash at the time of mixing (at t=0)

$n_{fw}(t)$, $n_{uc}(t)$, $n_{ufa}(t)$, $n_{hp}(t)$: volumetric ratio of free water, unhydrated cement, unhydrated fly ash and the hydrated product, respectively, at the time considered.

z_g, z_s, z_w, z_c, z_{fa}, z_{hp} : thermal conductivity of gravel, sand, cement, fly ash and the hydrated product, respectively.

$dh_c(t)$, $dh_{fa}(t)$: degree of hydration of cement and degree of reaction of fly ash at the time considered

V_c, V_{fa} : unit volume of cement and fly ash at the time of mixing (t=0)

Q_{3A}, Q_{AF}, Q_{3S}, Q_{2S}, Q_{FA} : heat generated by C_3A, C_4AF, C_3S , C_2S and fly ash, respectively.

Q_{3Amax}, Q_{AFmax}, Q_{3Smax}, Q_{2Smax}, Q_{FAmax} : maximum heat generated by C_3A, C_4AF, C_3S , C_2S and fly ash, respectively.

ρ_{3A}, ρ_{AF}, ρ_{3S}, ρ_{2S} : weight percentage of C_3A, C_4AF, C_3S and C_2S, respectively, in cement (%).

3.2 Specific Heat

Specific heat of concrete is expected to change with the moisture content as the hydration reaction proceeds. In the proposed model, specific heat of concrete at any time is calculated based on the weight fraction of the components and their individual specific heat values. As specific heat of a body is related to its mass, the weight fractions of the components are used in computing the specific heat of concrete. The proposed equations are as follows:

$$S(t) = w_g s_g + w_s s_s + w_{fw}(t) s_w + w_{uc}(t) s_c + w_{ufa}(t) s_{fa} + w_{hp}(t) s_{hp} \tag{8}$$

$$w_{uc}(t) = \left(1 - dh_c(t)\right) w_{c0} \tag{9}$$

$$w_{ufa}(t) = \left(1 - dh_{fa}(t)\right) w_{fa0} \tag{10}$$

$$w_g + w_s + w_{w0} + w_{c0} + w_{fa0} = 1.0 \tag{11}$$

$$w_{hp}(t) = 1.0 - \left(w_g + w_s + w_{fw}(t) + w_{uc}(t) + w_{ufa}(t)\right) \tag{12}$$

where, S(t) = specific heat per unit weight of concrete at the time considered.

w_g, w_s = weight ratio of gravel and sand per unit weight of concrete.

$w_{fw}(t)$, $w_{uc}(t)$, $w_{ufa}(t)$, $w_{hp}(t)$ = weight ratio of free water, unhydrated cement, unhydrated fly ash and the hydrated product, respectively, at the time considered.

s_g, s_s, s_w, s_c, s_{fa}, s_{hp} = specific heat of gravel, sand, water, cement, fly ash and the hydrated product, respectively.

w_{c0}, w_{fa0}, and w_{w0} = weight of cement, fly ash and water per unit weight of concrete at the time of mixing (at t=0).

4. Material parameters of fly ash

As fly ash can not continue the reaction independently without an activator, it is difficult to determine the heat of its reaction based on experiments. On the other hand, heat rate measured with the addition of a reagent affects the reactivity of admixtures. So reference heat rates for different types of fly ash are set comparing the analytical results with the experimental ones. The reference heat rate of a particular type of fly ash at a constant temperature is expressed as a function of the accumulated heat generated by the fly ash and the heat generation is again considered to be a function of the CaO content. It is assumed here that the total heat generation as well as heat generation rate is higher for a high calcium fly ash. The relationship proposed for a constant temperature of 20 ^{0}C is shown in Fig 1. The thermal activity of a fly ash is expressed as a function of its CaO content and a constant value is assumed for the whole hydration period. The proposed relationship is shown in Fig. 2

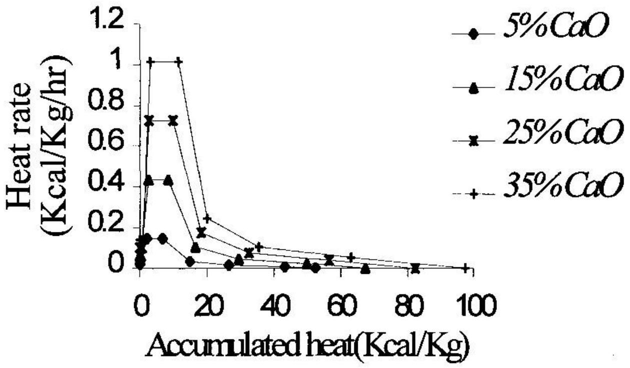

Fig. 1 Reference heat rate of fly ash

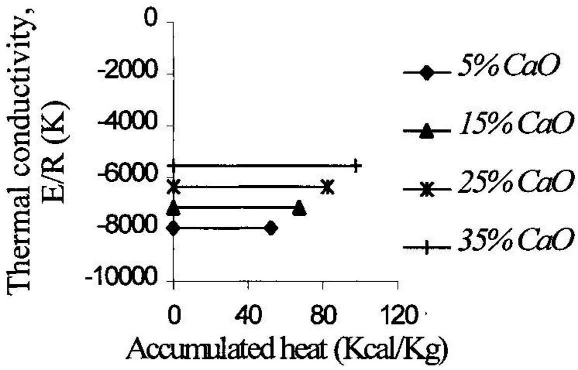

Fig. 2 Thermal activity of fly ash

5. Ca $(OH)_2$ consumption ratio for the reaction of fly ash

In the proposed models for material parameters of fly ashes, it is assumed that the supply of water and $Ca(OH)_2$ are enough for the reaction of the fly ash. The $Ca(OH)_2$ produced by the reaction of cement with water acts as an activator for the reaction of the fly ash to produce C-S-H. If there is an insufficient supply of $Ca(OH)_2$ in liquid state, the reaction of fly ash is retarded. This retardation of reaction is taken into consideration by introducing a term called consumption ratio of $Ca(OH)_2$. The consumption ratio of $Ca(OH)_2$ by fly ash is considered to depend on two factors, the ratio of CaO to SiO_2 (C/S) content of the fly ash and the percentage replacement of fly ash. It is assumed here that as the C/S ratio of the fly ash is increased, it consumes less amount of $Ca(OH)_2$ to produce the C-S-H. On the other hand, a higher cement replacement by fly ash causes a lower production and hence a lower consumption of $Ca(OH)_2$ at the later stages of hydration. So the average consumption ratio all over the reaction is decreased with the increase in percentage replacement of cement. Two different functions of the $Ca(OH)_2$ consumption ratio based on C/S ratio and percentage replacement of fly ash are proposed as shown in Fig.3 and Fig.4. Using these coefficients, the consumption ratio of $Ca(OH)_2$ for any type of fly ash and for any percentage replacement can be calculated by the following relationship:

$$R_{FACA} = R_{FACS} \times R_{FAPR} \tag{13}$$

where, R_{FACA} : Consumption ratio of $Ca(OH)_2$ by the fly ash used as cement replacement.
R_{FACS} : Consumption ratio based on the C/S ratio of the fly ash.
R_{FAPR} : Consumption ratio based on the percentage replacement of fly ash.

6. Comparison between test and computed results

The proposed models are incorporated into the multi-component hydration heat model of Kishi and Maekawa [2]. The multi-component heat model takes into account the heat produced by each oxide compound during the hydration including those generated in the process of ettringite formation, by proposing referential heat rate and thermal activity for each compound. Then, the total hydration heat can be summed from the heat generated by each component at any level of degree of hydration. For pozzolans, the referential heat rates and thermal activities of slag and fly ash were also proposed. The analytical results from the modified multi-component model are compared with experimental ones. In the experiment, cubic concrete specimens were cast in laboratory using cement only and cement with fly ash as binding material. Ordinary Portland cement Type 1 was used. Two samples of fly ash from Mae Moh generating plant were selected. Fine aggregate was river sand and coarse aggregate was crushed limestone. The chemical composition of cement and fly ashes used in the experiment are shown in Table 1. Table 2 shows the physical properties of the binders and aggregates. Mix proportions of the tested concrete were shown in Table 3. Figs 6 and Fig.7 show the temperature rise in specimens with 40%, 50%and 60% cement replacement by fly ash type A and B, respectively. The control concrete mixture for comparing with these fly ash concrete specimens is CC1. Fly ashes A and B contain CaO contents of 8.36% and 16.84%, respectively. It is shown in Fig.5 that for the cement mixtures, higher cement content results in higher temperature rise. Fig.6 and Fig.7 illustrate that replacing more cement with fly ash lowers the temperature rise in the concrete. By comparing Fig.6 and Fig.7, the fly ash with larger CaO content results in higher temperature rise of the fly ash concrete. Fig.8 shows the temperature history in a concrete footing with dimension

Table 1 Chemical composition of cement and fly ashes

Binder	Chemical composition (% by weight)								
Type	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	Free lime
Cement	64.60	20.30	6.41	2.87	1.50	2.29	0.29	0.34	1.00
Fly ash FAA	8.36	46.02	26.79	10.09	2.47	1.20	0.74	2.68	0.11
Fly ash FAB	16.84	40.14	19.84	11.50	2.68	3.18	0.94	2.10	0.42
Fly ash FAC	13.30	41.00	20.90	13.20	2.70	4.00	0.91	2.35	0.20

Table 2 Physical properties of cement, fly ashes, fine aggregate and coarse aggregate

Physical properties	Cement	Fly ash FAA	Fly ash FAB	Fine aggregate	Coarse aggregate
Specific gravity (g/cm^3)	3.13	1.92	2.22	2.58	2.72
Blaine fineness (cm^2/g)	3350	1900	1990	-	-
Absorption (%)	-	-	-	0.89	0.31
Fineness Modulus	-	-	-	3.11	-
Maximum size (mm)	-	-	-	4	20

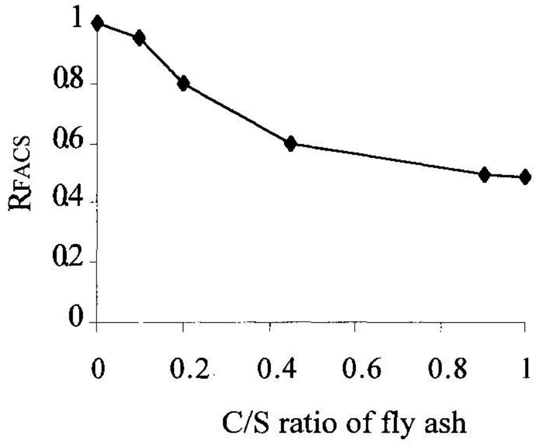

Fig.3 Relationship of R_{FACS} and C/S

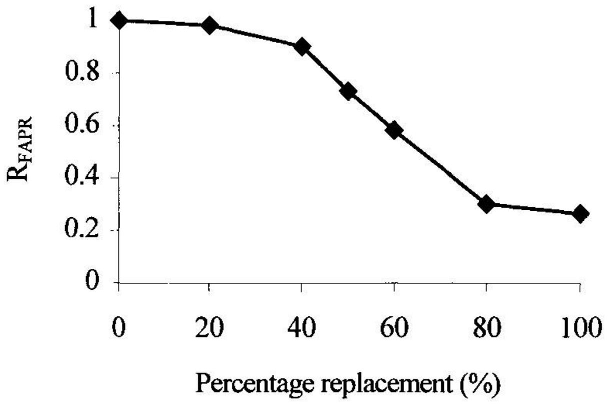

Fig.4 Relationship of R_{FAPR} and % replacement

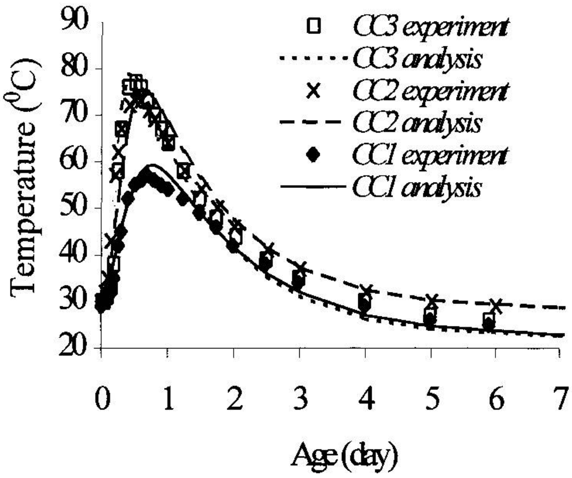

Fig.5 Temperature in plain concrete specimens

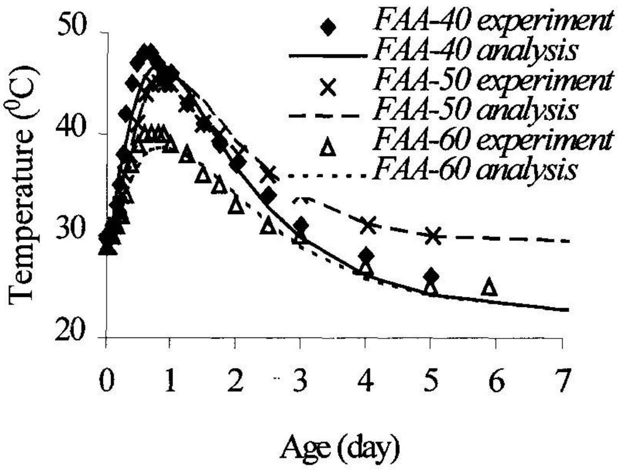

Fig.6 Temperature in concrete with fly ash FAA

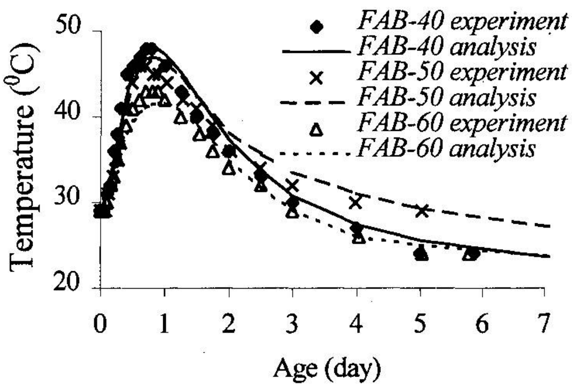

Fig.7 Temperature in concrete with fly ash FAB

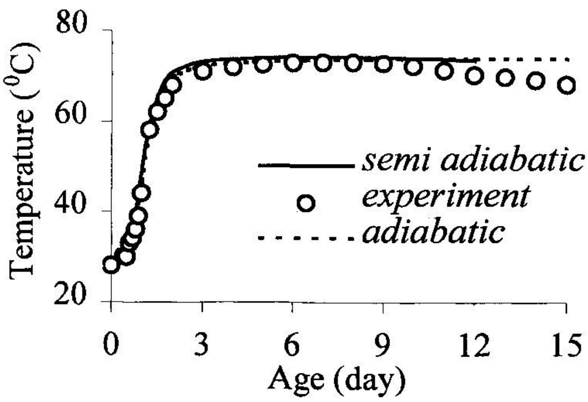

Fig.8 Temperature in a footing with fly ash FAC

Table 3 Mix proportion of the tested concrete

Mix	Component (kg/m^3)							Initial concrete temperature (°C)
	w/b (%)	f/b (%)	C	f	w	S	G	
CC1	50.0	0	350	0	175	818	1057	30.0
CC2	47.5	0	454	0	215	723	943	28.0
CC3	30.3	0	558	0	163	810	904	30.0
FAA-40	47.5	40	205	137	162	801	1035	30.0
FAA-50	47.5	50	174	174	165	781	1018	29.0
FAA-60	47.5	60	135	202	160	790	1021	29.0
FAB-40	50.0	40	210	140	175	786	1017	29.0
FAB-50	47.5	50	176	176	167	792	1032	29.0
FAB-60	47.5	60	141	211	167	793	1025	29.0
Footing*	40.0	47.5	210	190	160	810	1010	30.0

Remarks : w : water, b : total binder (c+f), f : fly ash, S : fine aggregate, G : coarse aggregate
* uses fly ash FAC.

of 38.4m×8.4m×4.75m using a fly ash replacement of 47.5%. Temperatures at the centers of all specimens were measured using thermocouples. Analytical results were obtained after incorporating the proposed models into the multi-component hydration heat model of Kishi and Maekawa [2]. Thermal coefficients of the concrete ingredients were assumed according to the recommendations of American Society of Heat and Refrigerating Engineers [4] and those for the hydrated products were obtained by data back analysis. Since the mat footing in Fig.8 was big enough to consider the condition of adiabatic at the center, the footing was analyzed in adiabatic condition.

7. Concluding remarks

Comparing the analytical results with the experimental ones for the test specimens and the practical structure as shown in Figs 5 to 8, it can be concluded that the models can be applied to concrete structures using a cement replacement by any type of fly ash and of any percentage. However, future studies still have to be carried out for a better prediction and also for other types of powder materials.

8. References

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