Pergamon

Cement and Concrete Research 32 (2002) 751–756

CEMENT AND CONCRETE RESEARCH

Heat evolution of high-volume fly ash concrete

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Received 1 December 1999; accepted 6 December 2001

Abstract

In this paper, the results of a laboratory investigation conducted with heat evolution of high-volume fly ash (HVFA) concrete are presented. Heat evolution of concrete was studied by measuring the temperature increase in concrete under adiabatic curing condition. Characteristic of heat evolution of fly ash concrete was found to be strongly dependent on the replacement level of fly ash and dosage of superplasticizer used to maintain workability. It was also found that using fly ash as cement replacement resulted in a reduction on the maximum temperature rise. Increasing the replacement level of fly ash caused lower temperature rise in concrete. Superplasticizer caused a delay in peak temperature rise time; this is taken as an indicator that high-dosage superplasticizer used in concrete caused retardation in hydration of cement. Concretes having similar ingredients showed similar peak temperature rise whether they are superplasticized or not.

Keywords: Heat evolution; High-volume fly ash; Superplasticizer

1. Introduction

The hydration of Portland cement paste is accompanied by heat evolution, which causes a temperature rise in concrete. Heat evolution of concrete is particularly important with regard to mass concrete where cooling can lead to cracking after a large temperature rise. Mass concrete is defined by the ACI Committee 116 [1] as ‘any volume of concrete with dimensions large enough to require the measures be taken to cope with generation of heat of hydration from the cement and attendant volume change to minimise cracking’. Currently, mass concrete is no longer considered only for dam construction; it is also used for foundation and members of structures for many classes as multistorey and nuclear reactor building [2].

It is known that using fly ash as cement replacement in concrete reduces the temperature rise by reducing the amount of cement used for a unit volume. One of the earlier reports on the influence of fly ash on heat of hydration was made by Davis et al. [3] who reported that the heat of hydration of fly ash cement is less than that of the corresponding Portland cement.

Philleo [4] reported the first major use of fly ash in concrete in the construction of a gravity dam to control temperature rise in mass concrete.

Bamforth [5] reported from an extensive study of mass concrete that the larger the amount of cement replaced by fly ash or slag, the slower rate is the temperature rise and the higher the reduction in temperature rise.

Wolley [6] studied the characteristic of heat of hydration of pulverised fly ash concrete in thin structures. His extensive laboratory and in situ investigation with different mix proportions showed that introduction of pulverised fly ash as partial replacement reduced noticeably the peak temperature in concrete.

There is an agreement in recently published materials on the reduction in temperature rise when fly ash was used as partial replacement of cement [7–9].

There were numerous studies on the temperature rise in concrete containing fly ash. However, there are few studies in the literature regarding temperature rise of very high-volume fly ash (HVFA) concrete (i.e., 70% replacement) with very low and optimal W/C ratio (i.e., 0.28–0.29). Thus, the aim of this work is to provide more data for the

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0008-8846/02/$ – see front matter
PII: S0008-8846(01)00755-4

Table 1
Particle size distribution of fine and coarse aggregate, and fly ash

Sieve size (mm)	Sand (%) passed	Specification for sand [14]
10	100	100
5	95.95	89–100
2.36	86.7	60–100
1.18	81.11	30–100
0.6	34.99	15–100
0.3	9.36	5–70
0.15	1	0–15

Sieve size (mm)	Gravel (%) passed	Specification for gravel [14]
14	100	100
10	85.15	85–100
5	2	0–25
2.36	0.5	0–5

Particle size (μm)	Fly ash (%) passed
100	99.80
80	97.10
60	96.50
50	95.30
40	89.20
30	84.70
25	76.80
20	66.30
15	51.20
10	43.10
8	31.90
6	25.40
5	19.50
4	12.30
3	7.10
2	6.20
1.5	0.02

heat evolution of very HVFA concrete. Another aim of this work is to prove that a high-performance concrete with moderate and high strength and low temperature rise could be produced using high volumes of fly ash as cement replacement.

In this paper, only temperature rise results are presented. Other properties of the concrete produced including abrasion, shrinkage, strength, porosity, and permeability were published elsewhere [10–12].

2. Mix proportions and properties of materials

A new mix design is used to produce high-performance and HVFA concrete. In the mix design, Cabrera vibrating slump [13] is used to determine the optimum water–cementitious material ratio.

Optimum water–cementitious material ratio was used to produce zero-slump concrete. This value was modified for superplasticized concrete to have flowing concrete. Ordinary Portland cement (OPC) and a low-calcium, Class F fly ash from Drax power station located in York County of England were used as a binder to produce concrete. Particle size distribution of fly ash is given in Table 1. Aggregate used was a well graded and quartzitic natural aggregate with a maximum size of 10 mm. Grading of fine and coarse aggregate satisfying the criteria [14] for use in concrete is also given in Table 1. Specific gravity of aggregate in saturated surface dry (SSD) condition is 2.65. Water absorption determined using BS 812 [15] is 0.1% and 0.6% for sand and gravel, respectively.

A specially selected superplasticizer was also used to maintain the workability of concrete. The superplasticizer used is a high-range water-reducing agent called Sikament 10 produced by Sika [16], which is a new generation formaldehyde-free, low-alkali, water-soluble polymer. It is in liquid form with nearly nil chloride content and can be used with all Portland cements. It can increase setting time with the dosage used. Concrete mixture proportions and properties of materials used are given in Tables 2 and 3. The workability of M0, M1, and M3 mixtures, ranging from 570 to 600 mm, were measured using a flow table. M2 and M4 are the concrete mixtures having zero slump called roller compacted concrete (RCC).

3. Adiabatic curing system and experimental procedure for heat evolution

Many researchers [17–19] developed their own adiabatic curing systems, however, they differ from each other regarding shape and size of system, sample shape and size, insulation and heat provision. The details of current adiabatic curing system used are given in Figs. 1–3. The system was designed to measure the temperature rise in concrete and to provide accurate control of temperature and versatile

Table 2
Properties of cement and fly ash

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI	Specific gravity (kg/m^3)	Fineness (retain in 45 μm sieve) (%)	Specific surface area (m^2/g)
C	20.77	4.93	3.06	63.28	2.42	3.02	0.70	0.28	0.81	3150	–	0.35
FA	50.20	28.59	13.17	2.55	1.28	0.57	2.39	0.98	2.85	2400	8.5	0.31

Table 3
Mix proportions for a cubic meter of concrete

Mix no.	Cement (kg/m^3)	Fly ash (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water (kg/m^3)	Optimum W/C	Actual W/(FA + C)	SP (l/m^3)
M0	400	–	600	1200	220	–	0.55	–
M1	120	280	600	1200	112	0.29	0.28	5.6
M2	120	280	600	1200	116	0.29	0.29	–
M3	200	200	600	1200	132	0.30	0.33	5.6
M4	200	200	600	1200	120	0.30	0.30	–

data logging. The thermocouple is used in the measurement of temperature change in the system.

The microcomputer IBM-compatible 386 type is used to control the system and recording the data acquired. The computer transfers the data between input and output devices, and determines the temperature difference between water and concrete, then sends the pulse to the heaters to adjust the temperatures. It also stores the data in a file. A software called IoCalc is used to provide the link between the curing system and the computer. Detailed information for the IoCalc program can be found in its manual [20].

The fresh concrete sample was cast in an insulated control box by means of a vibrating table. The height of the sample was 400 mm. Its top and bottom were square-shaped with a side of 400 and 300 mm, respectively. The control box was sealed using a plastic tape after casting. A copper pipe with 250-mm length was inserted into the fresh concrete at about middle point of sample, therefore, thermocouples can be placed in it. The control box was placed in the curing tank of the temperature-matched curing apparatus. The copper pipe was filled with oil to provide heat transmission and then thermocouples were inserted in it. Then the computer-aided adiabatic curing system was run. When the peak temperature rise was registered, the system was allowed to cool down. The procedure was repeated for each concrete mixture.

4. Results and discussion

The results of heat evolution measurement are given in Figs. 4–6. It can be seen from Fig. 4 that OPC control concrete (M0) reached the highest peak temperature of about 55 °C. M1 and M2 concretes in which fly ash replaced 70% OPC by mass showed the lowest peak temperature of about 30 °C (Fig. 5a). M3 and M4 concretes in which fly ash replaced 50% OPC by mass showed lower peak temperature (about 42 °C) than OPC concrete (Fig. 5b), however, they showed higher temperature rise than M1 and M2 concretes (Fig. 4). From these results, it is clear that the replacement of OPC with fly ash results in a reduction of the temperature rise in concrete. This influence is attributed to the dilution of the OPC and the slower hydration of the fly ash with the $Ca(OH)_2$ of the hydrating cement. From the above discussion, it can also be concluded that the higher the replacement level of fly ash in concrete, the higher the reduction in temperature rise. These results are found to be in line with published material [3,6–9,21].

M1 and M2 concretes showed similar heat evolution in terms of peak temperature (Fig. 5a). However, there was a difference between M1 and M2 concretes regarding the rate of heat evolution. M1 concrete reached the peak temperature later than M2 concrete. It should be noted that M1 was

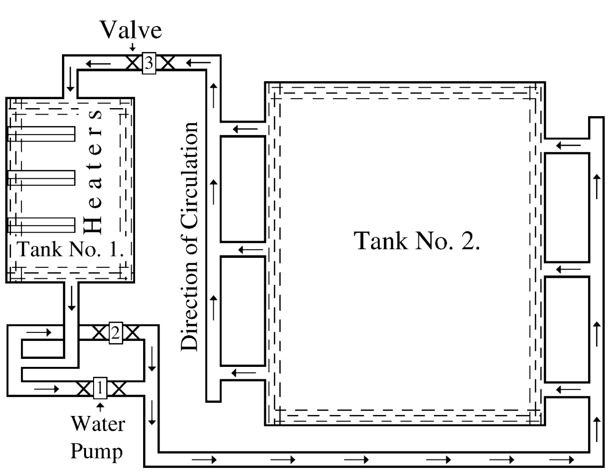

Fig. 1. Details of the curing tanks (top view).

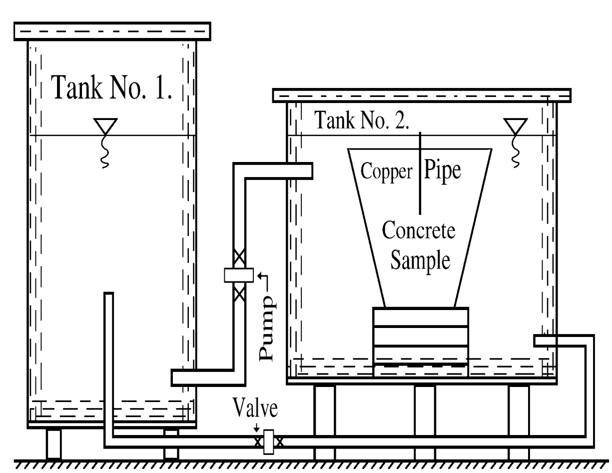

Fig. 2. Details of the curing tanks (side view).

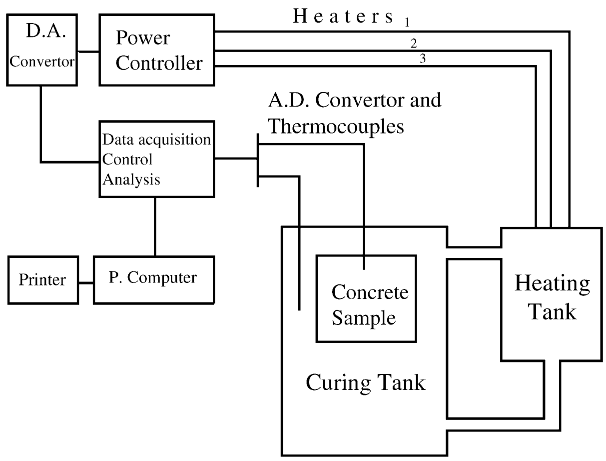

Fig. 3. Data acquisition and control of curing system.

a workable concrete in which high dosage of superplasticizer was used. Similar observation can be made for M3 and M4 concretes (Fig. 5b). The delay of temperature rise for M1 and M3 concrete (Figs. 5–6) is attributed to the retarding effect of the high dosage superplasticizer used [22–24]. This conclusion also supports the lower hydration rate at early age as well as lower compressive and tensile strength at early age for the same concretes [13,25]. In addition, more or less every concrete reached peak temperature within 3 days.

The results show that 50% fly ash reduced the peak temperature from 55 °C to about 42 °C; that is, 50% fly ash caused a reduction in the peak temperature of 23%. This indicates that moderate levels of fly ash (20–30%) may not cause a significant reduction in the heat evolution of concrete (a reduction in the peak temperature of 10–15% may be anticipated).

Furthermore, the results of a current research work carried out at Cukurova University [26] showed that the changes in W/C ratio influence the temperature rise in concrete. For

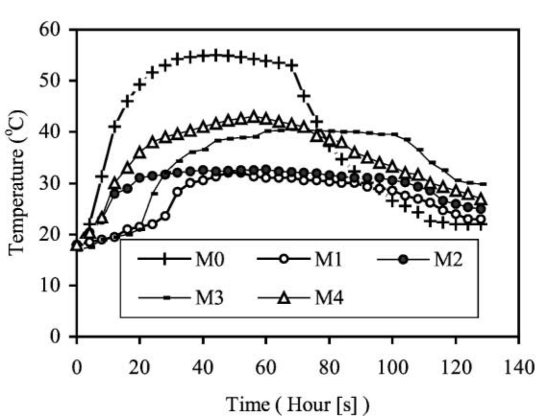

Fig. 4. Temperature rise in HVFA and OPC concrete.

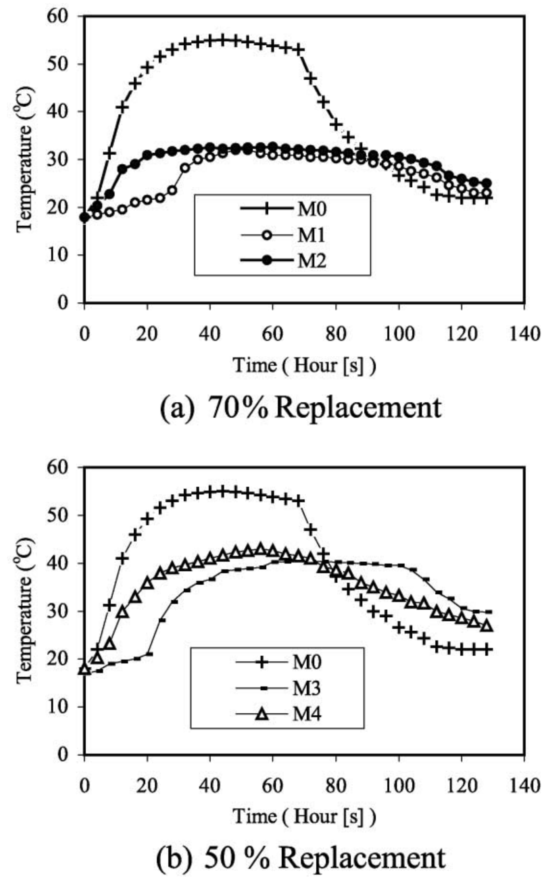

Fig. 5. Temperature rise in HVFA and OPC concrete. (a) 70% replacement. (b) 50% replacement.

instance, concretes made with 0.35, 0.45, 0.55 W/C ratio and about 400 kg/m^3 OPC developed 40.2, 42.4, 44.4 °C peak temperature in the laboratory environment with no insulation and nonadiabatic curing condition.

In this study, the reference concrete was made with W/C ratio of 0.55, and fly ash concretes were made with W/C ratio from 0.28 to 0.33. The author, taking into consideration the results given in the above paragraph, expects that if reference concrete had been made with a W/C ratio of about 0.3, then the peak temperature rise in reference concrete would have been a few degrees lower than 55 °C of peak temperature of the current reference concrete due to the fact that a lower W/C ratio results in a lower degree of hydration [24,27].

Although detailed strength, porosity, and permeability properties of the concrete produced are given elsewhere [12,13,25], the average 28-day compressive strength of moist-cured 100-mm side cube specimens is 50 MPa for the M0 mixture, 40 MPa for the M1 and M2 mixtures, and 65 MPa for the M3 and M4 mixtures. The concrete produced proved that HVFA concrete has very low porosity and permeability as compared to OPC concrete [13]. It also showed better resistance to abrasion than that of OPC concrete [10]. Therefore, this work proved that a high-

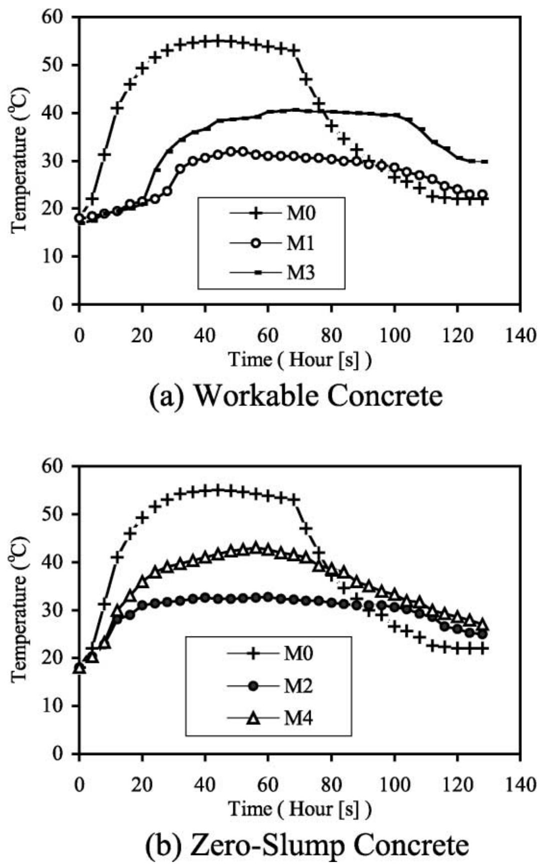

Fig. 6. Temperature rise in HVFA and OPC concrete. (a) Workable concrete. (b) Zero-slump concrete.

performance concrete with moderate and high strength and low temperature rise could be produced using high volumes of fly ash as cement replacement.

Although similar findings were found with the published literature, this work provided data for concrete made with very HVFA and very low W/C ratio.

5. Conclusions

From the laboratory results and the discussion made above, the following conclusions are made:

1. Using fly ash as cement replacement resulted in a reduction on the maximum temperature rise under adiabatic curing condition.
2. The higher the replacement level of fly ash, the lower the temperature rise.
3. Superplasticizer caused a delay in maximum temperature rise time; this is taken as an indication that high dosage of the superplasticizer caused retardation in hydration.
4. Concretes, which have similar proportions, showed similar peak temperature rise regardless of whether they are superplasticized or not.
5. Concrete containing large amounts of fly ash can be used in the field where thermal cracking due to heat of hydration should be avoided such as dam construction, large foundation, and particularly nuclear reactor building.
6. The results presented in this paper are applicable to concrete with fly ash within the levels examined (50–70%).
7. A high-performance concrete with moderate and high strength and low temperature rise could be produced using high volumes of fly ash as cement replacement.

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