Strength and Hydration Heat of Concrete using Fly Ash as a Partial Replacement of Cement

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Synopsis: The benefits of using fly ash as a partial replacement for cement in concrete are well documented. This paper presents the strength development and hydration heat properties of concrete using Class F fly ash sourced from Western Australia. Compressive strengths at different ages were determined and semi-adiabatic temperature rise during the initial stage of hydration was measured by thermocouples. The 28-day compressive strengths of two control concrete mixtures were 62 and 68 MPa. It was found from the experimental results that the average 28-day compressive strengths of concretes with 30% and 40% cement replacements by fly ash were 84% and 63% of the strengths of the respective control mixtures. However, the 90-day strength of concrete with 30% cement replacement was equal to the strength of the control concrete. A 20% reduction in the maximum temperature was observed in the concrete with 40% cement replacement by the fly ash. It is found from the test data that the percentage reduction in the maximum temperature of fly ash concrete can be estimated as one-half of the percentage replacement of cement by fly ash.

Keywords: concrete, fly ash, hydration heat, strength.

1. Introduction

Fly ash is a by-product of the burning of coal in electric power generation plants. It is often used in concrete as a partial replacement for cement in mass concrete. The replacement of cement by fly ash reduces the heat of hydration in concrete structures. This reduces the thermal gradient, and therefore the chance of thermal cracking is reduced (1). Fly ash has been used as a cement replacement since 1935, where it was used in mass concrete gravity dam applications in the United States of America (2). Its use has been widespread since then, in structures such as dams, bridge piers and abutments, and mass concrete footings (3).

According to the Ash Development Association of Australia, only about 14% of the fly ash produced in Australia is currently used for some beneficial purpose (4). Currently, the annual amount of unused fly ash in Australia is about 11 million tons. Unused fly ash may cause environmental pollution if not properly stored. As the production of concrete is very energy intensive in terms of greenhouse gas emissions, utilisation of fly ash as a partial replacement of cement in concrete is beneficial to the environment because it reduces the use of cement and also reduces the waste and environmental pollution of unused fly ash. The partial replacement of cement by fly ash makes concrete a more environmentally friendly material and enhances the sustainability of the construction industry.

The fly ash locally available in Western Australia is mainly Class F (ASTM 618). Usually, fly ash concrete has lower early age strength than OPC concrete but gains more strength at a later age (5). Replacement of cement with a Class F fly ash results in lower strengths and slower strength gain than occurs with Class C fly ash. This is due to the greater cementitious properties of Class C fly ash (6).

Reduction of the heat of hydration to different extents by using fly ash has been documented in previous research (1, 7, 8). The heat of hydration in concrete using fly ash as a partial replacement of cement is influenced by many parameters, such as the ambient temperature in the curing climate, the amount of cement, the amount of fly ash, and the chemical composition and fineness of the cement and fly ash (9). A lower ambient temperature results in a lower heat of hydration. Heat is the result of the hydration reaction between the cement and water, so a higher content of cement results in a higher heat of hydration. The replacement of cement by fly ash typically decreases the heat evolution due to a slower hydration reaction. Cement with smaller average particle size results in a greater surface area, and hence increases the hydration reactions and promotes the evolution of heat. Cement with a greater percentage of C_3A and C_3S will produce more heat as these compounds are involved in the early stages of hydration reaction.

Experimental data on the strength and heat of hydration of concrete using West Australian fly ash is scarce in literature. Since the properties of fly ash vary depending on its source, and fly ash properties affect the strength and hydration heat of concrete, this paper studies the properties of concrete using fly ash sourced from Western Australia.

2. Experimental Work

Experimental work was carried out in the laboratory to quantify the compressive strength and hydration heat of concretes using 30% and 40% cement replacements by fly ash. Cement replacements at these percentages were used in the experiments because they were considered to be substantial to result in significant reductions of hydration heat with reasonable reductions of early-age strength.

2.1 Materials and mixture proportions

The concretes used to make the test specimens were mixed in the laboratory. The type of cement was general purpose Portland cement with a specific surface area of 412 m^2/kg. The fly ash used was a Class F (ASTM 618) and Fine Grade (AS 3582) fly ash sourced from Western Australia. The percentage of the fly ash passing through a 45 μ sieve was 75%. The chemical compositions of the cement and fly ash are shown in Table 1. Two different combinations of the aggregates were used, which were similar to those normally used for commercial concrete mixtures. Similar proportions of aggregates have been used in other experimental works (9). The coarse aggregates were 20mm nominal size and 10mm nominal size crushed stone. They were prepared to saturated surface dry (SSD) condition by soaking in water for 24 hours. The sand used was river sand. Tap water was used in mixing the concretes.

Two control mixes of concrete without fly ash, and 4 mixes with fly ash replacing 30% and 40% of Portland cement, were used to cast the test specimens. The mixture proportions of the two series of mixes (A and B) are given in Table 2. The control mixes are designated as OPCA and OPCB. The mixes with 30% and 40% cement replacement by the fly ash are designated as FA30A and FA40A respectively, corresponding to control mix OPCA. Similarly, FA30B and FA40B are the fly ash concrete mixes corresponding to the control mix OPCB. The total binder contents of the mix series A and B were 400 and 480 kg/m^3 respectively. The water to binder ratios of series A and B were 0.44 and 0.37 respectively.

Table 1. Chemical compositions and loss on ignition of cement and fly ash (mass %).

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	TiO_2	MgO	P_2O_5	SO_3	LOI*
Cement	20.4	4.8	2.9	64.2	0.29	-	-	2.0	-	2.4	2.3
Fly ash	50.8	26.9	13.5	2.05	0.33	0.57	1.57	1.33	1.46	0.31	1.42

** Loss on ignition*

2.2 Test specimens and procedure

The concretes were mixed using a pan type laboratory concrete mixer. Slump tests were carried out to determine the workability of the fresh concrete. The slump values of the mixes OPCA, FA30A and FA40A were 60, 75 and 100 mm respectively. The corresponding values for the mixes OPCB, FA30B and FB40B were 40, 55 and 70 mm respectively. Standard 100 mm × 200 mm cylinders were cast for compressive strength tests, and were then cured by immersion in water at 22 ^{0}C for up to 28 days. The cylinders were tested at the ages of 7, 28, 56 and 90 days.

The heat-of-hydration test specimens were cast in cube-shaped moulds with internal dimensions of 350 mm x 350 mm x 350 mm. The moulds were constructed using form-ply. Each mould was lined with 25 mm polystyrene to reduce the amount of heat escaping from the concrete. This was done to simulate the semi-adiabatic temperature rise in a mass concrete structure. Polystyrene has a much lower thermal conductivity than concrete. Using the thermal conductivities of polystyrene and concrete as 0.03 W/m.K and 2.0 W/m.K respectively, 25 mm polystyrene insulation effectively provides the same rate of heat transfer as a 1666 mm layer of concrete.

A photo of a heat-of-hydration mould is shown in Figure 1. A thermocouple was placed at the centre of the concrete specimen to measure the temperature during the hydration process. The thermocouple was connected to an electronic data logging system, which logged the temperature rise with respect to time after casting of the concrete. The heat of hydration of the concrete was logged for four and a half days. The placement and mean ambient temperatures of the specimens of series A were 20 ^{0}C and 18 ^{0}C respectively. The corresponding temperatures of the specimens of series B were 19 ^{0}C and 17 ^{0}C respectively.

Table 2. Mixture proportions of concrete.

Mix	Ingredients (kg/m^3)						Water / binder ratio
	Cement	Fly ash	Water	Sand	10 mm aggregate	20 mm aggregate	
OPCA	400	0	177	642	404	860	0.44
FA30A	280	120	177	642	404	860	
FA40A	240	160	177	642	404	860	
OPCB	480	0	177	642	1200	0	0.37
FA30B	336	144	177	642	1200	0	
FA40B	288	192	177	642	1200	0	

Figure 1. Formwork for heat of hydration specimens

3. Test Results and Discussion

The compressive strengths of the concrete specimens at different ages up to 90 days are given in Table 3. The strengths presented in this table are the mean values obtained from 3 cylinder specimens. It is seen that the 28-day compressive strengths of the concretes are in the range of 40 to 68 MPa. The maximum temperature at the centre of the hydration heat specimens and the corresponding duration of hydration after casting are also given in this table. The maximum temperatures ranged from 45 to 58 ^{0}C, and occurred between 12 and 18 hours after casting of the specimens.

3.1 Effect of fly ash on the compressive strength of concrete

The effects of fly ash on the strength of concrete mixes are presented in Figures 2 to 5. Figures 2 and 4 show the strengths of the fly ash concretes relative to the control concretes at the ages of 7, 28, 56 and 90 days. It can be seen that the fly ash concrete samples had a lower compressive strength than an identical control mix at an early age. As expected, a greater replacement of cement by fly ash resulted in a greater reduction of strength. In Figure 2, The strengths of the concrete with 30% cement replacement in series A are shown as 70%, 82%, 94% and 99% of the control concrete strengths at the ages of 7, 28, 56 and 90 days. The corresponding percentages of strengths for 30% cement replacement in series B are 80%, 87%, 91% and 98% (Figure 4). Therefore, with 30% cement replacement, the strength is about 75% of the strength of control concrete at the age of 7 days and is almost equal to that of the control concrete at the age of 90 days. Similarly, for 40% cement replacement, the strength is about 55% of the strength of the control concrete at the age of 7 days and about 80% of the strength of control concrete at the age of 90 days.

Table 3. Compressive strength and hydration heat results.

Mix	Compressive strength (MPa)				Heat of hydration at centre	
	7 days	28 days	56 days	90 days	Peak temperature (^{0}C)	Corresponding hydration duration (hr)
OPCA	52.4	62.8	69.8	72.0	50.7	15
FA30A	36.7	51.6	65.3	71.4	45.1	18
FA40A	29.8	41.0	50.9	60.1	41.5	20
OPCB	56.7	68.2	82.1	86.7	58.3	12
FA30B	45.6	59.0	74.7	84.9	51.2	13
FA40B	30.0	39.8	57.1	63.9	45.2	14

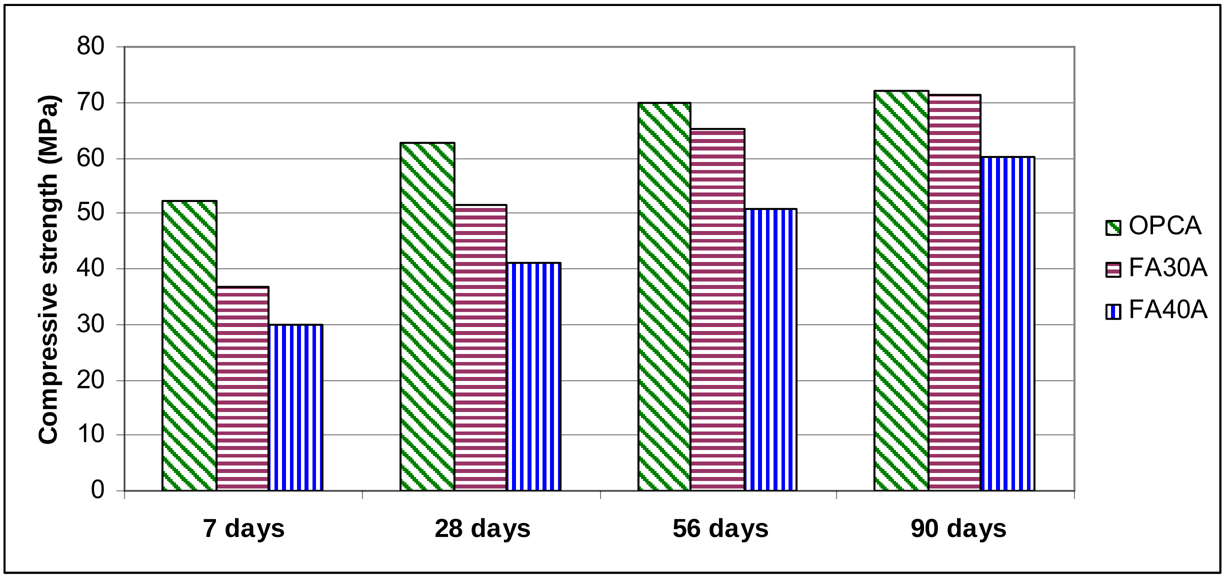

Figure 2. Compressive strength of concrete of series A at various ages.

The rates of strength gain of the concretes over time are shown in Figures 3 and 5. It is seen that the gradients of the curves for 30% cement replacement are generally greater than those of the control concretes at the ages of 7 and 90 days. The gradients of the curves for 40% cement replacement are generally slightly smaller than those for 30% cement replacement. Generally, the steeper gradients of the fly ash concrete at late ages compared to those of the control concretes indicate continual development of strength in the fly ash concretes. It can be observed from the trends of the curves that the compressive strength of mixtures with 30% fly ash will exceed the strength of the corresponding control mixes after 90 days. The difference between the strengths of mixtures with 40% fly ash and those of their corresponding control mixes are expected to decrease after 90 days.

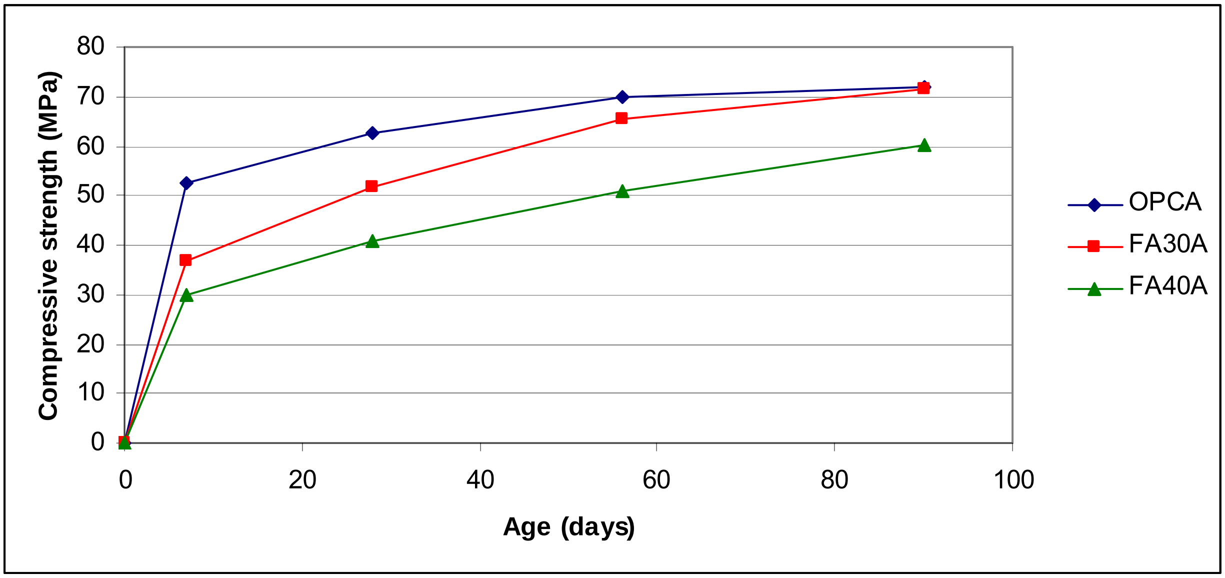

Figure 3. Rate of strength gain in concrete of series A.

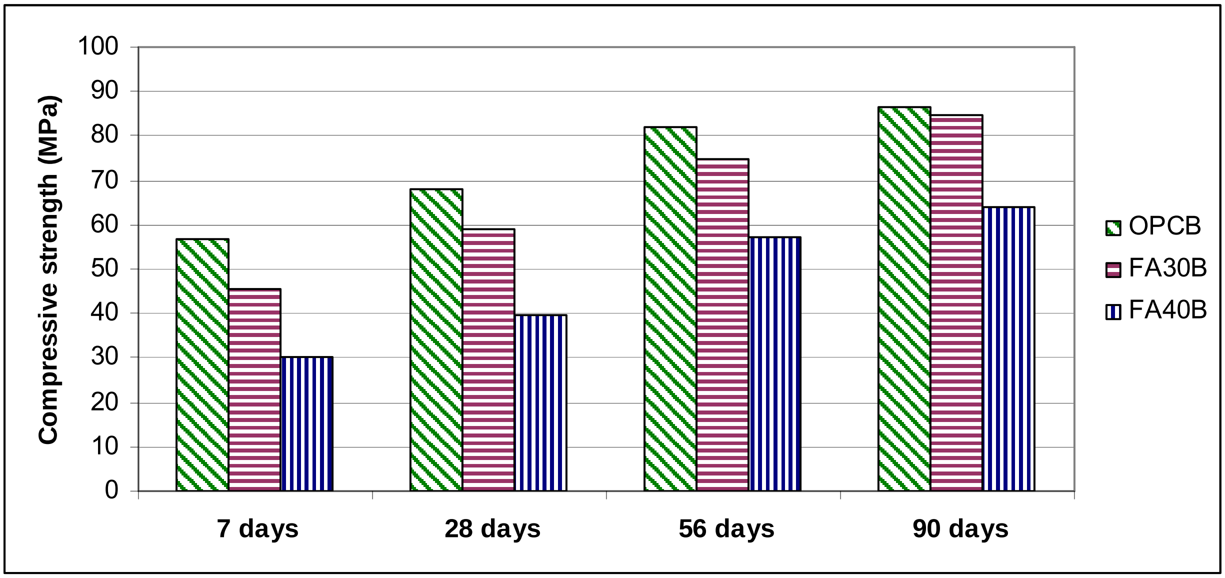

Figure 4. Compressive strength of concrete of series B at various ages.

3.2 Effect of fly ash on heat of hydration

The temperature rises at the centres of the concrete specimens are plotted against time in Figures 6 and 7. It is evident in these figures that the peak temperatures and the rates of temperature rise in the fly ash concrete specimens are smaller than those in the corresponding control concrete specimens. Generally, a larger cement replacement by fly ash resulted in a larger reduction of temperature and a delayed manifestation of the maximum temperature.

It can be seen in Table 2 and Figures 6 and 7 that the peak temperature in series A reduced from 55.7 ^{0}C in OPCA to 45.1 ^{0}C and 40.1 ^{0}C in FA30A and FA40A respectively. Therefore, the reductions in the peak temperatures in series A are 11% and 18% for 30% and 40% cement replacements respectively. Similarly, the reductions in the peak temperatures in series B are 12% and 22% for 30% and 40% cement replacements respectively. The percentage reductions in temperature rise are similar in both series of concretes.

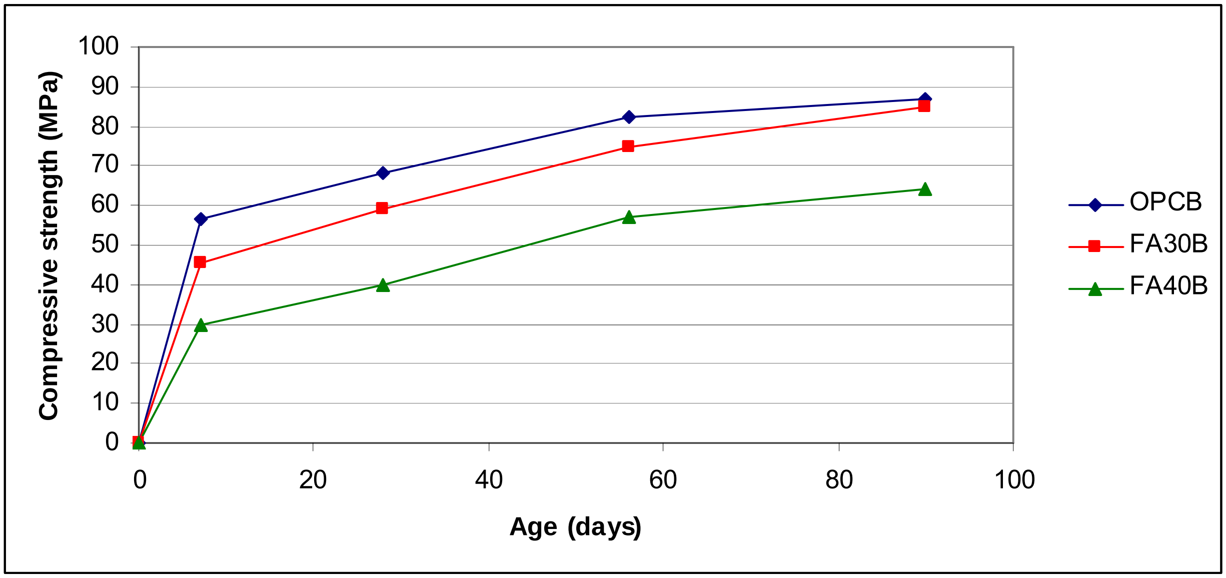

Figure 5. Rate of strength gain in concrete of series B.

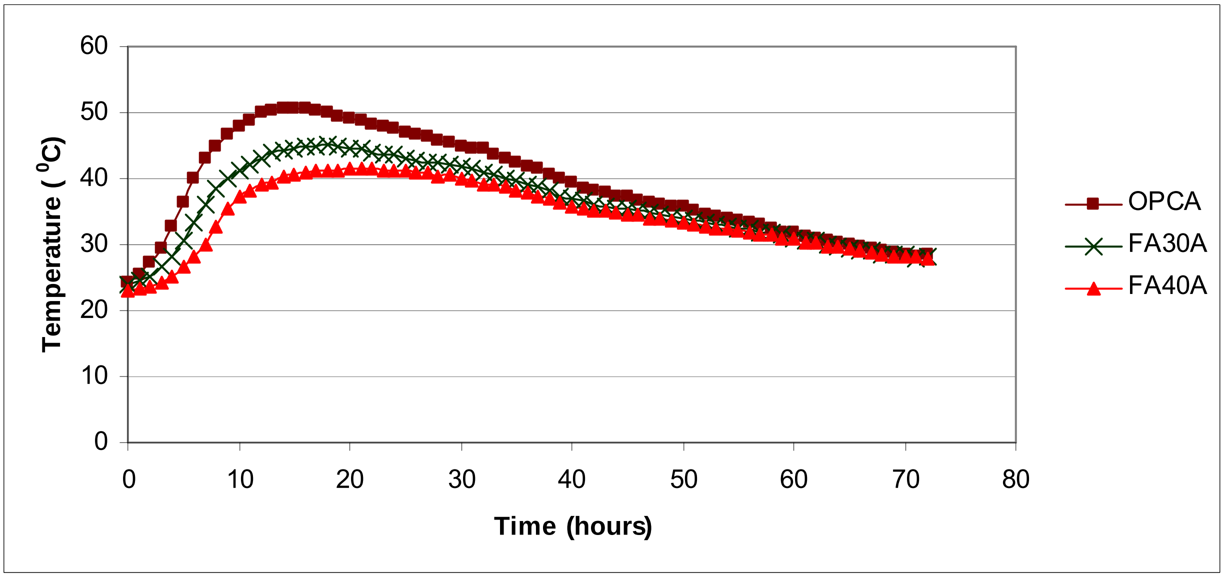

Figure 6. Temperature rise in concrete specimens of series A.

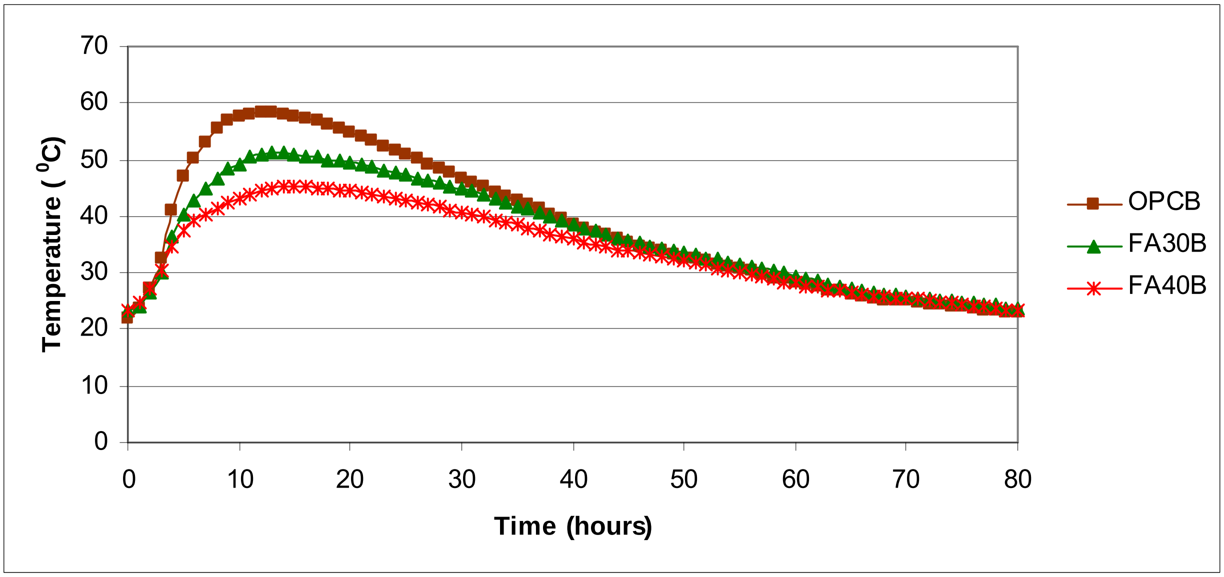

Figure 7. Temperature rise in concrete specimens of series B.

As a rule of thumb, caution is necessary to avoid thermal cracking in concrete when a temperature differential through the members exceeds 20 ^{0}C (10). It can be seen that the temperature differential between the core and surface (ambient) of the specimen FA40A is close to 20 ^{0}C. Therefore, it can be said that a 40% replacement of cement by fly ash has the potential to avoid thermal cracking in a mass concrete containing 400 kg/m^3 of general purpose Portland cement.

4. Estimation of the Maximum Temperature

Rigorous finite element analysis can be carried out to predict the temperature profile of concrete containing pozzolanic materials (11). However, a quick estimation of the maximum temperature can be useful to determine the approximate temperature differential between the core and surface of a concrete member. Two approximate methods were used to estimate the maximum temperatures of the fly ash concrete specimens. These approximate methods do not take into account the chemical composition of the fly ash.

The Portland Cement Association's (PCA) design and control of concrete mixtures gives a quick method for estimating the maximum temperature developed in mass concrete members (12). This method calculates the maximum temperature rise above the concrete placement temperature as 12 ^{0}C for every 100 kg of cement when the cement content is in the range of 300 to 600 kg/m^3 and the least dimension of the concrete member is 1.8 m. While the actual dimensions of the concrete in the heat of hydration specimens used in this study are only 350 mm, the effective heat transfer provided by the 25 mm thick polystyrene linings surrounding the concrete is considered to result in similar temperature development in the core of the specimens as in a member with a least dimension of 1.8 m. ACI committee 207 (13) suggests that modification to account for supplementary cementitious materials can be made by presuming that they liberate approximately half of the amount of heat of cement for a given mass. The PCA calculation for the maximum concrete temperature, taking into account this alteration for supplementary cementitious materials, is shown by Equation 1 (12).

$$T_{\max} = T_i + 12\frac{W_c}{100} + 6\frac{W_{scm}}{100} \qquad (1)$$

Where, T_{max} is the maximum concrete temperature during hydration (^{0}C), W_c is the cement content (kg/m^3), W_{scm} is the supplementary cementitious materials content (kg/m^3) and T_i is the concrete placement temperature (^{0}C).

Lea (14) suggests that as a first approximation, the percentage reduction in heat evolution may be taken as about one-half the percentage of cement substitution by the mineral admixture. It was found in a field test that a 30% substitution of Portland cement with fly ash in 2.5 m and 4.75 m deep concrete sections reduced the maximum temperature rise by about 15% (15, 16). However, using this method depends upon knowing the value of the maximum temperature of the corresponding control OPC concretes. This limits the application of this method. If the temperature rise in an OPC concrete element is known from previous experience or from similar projects, then the method can be used to estimate the maximum temperature rise in concrete elements containing fly ash. It can be used in preliminary design calculations to estimate the percentage replacement of cement with fly ash to achieve a certain temperature reduction. It can also be used to verify the temperature reductions calculated by using more rigorous techniques, such as finite element or spreadsheet-based solutions.

The approximate methods of PCA (Eq. 1) and Lea (14) were used to estimate the peak temperature rise in the test specimens. The predicted maximum temperatures are presented in Table 4. Comparisons between the test and predicted temperatures show that the PCA method overestimated the maximum temperatures in both control concretes, OPCA and OPCB. As a result, the predicted temperatures in the fly ash concrete specimens are higher than the measured temperatures. The predictions by the simple method of Lea are close to the measured values.

Table 4. Predicted and measured maximum temperatures.

Mix	Peak temperature (^{0}C)		
	Test	Predicted by PCA (Eq.1)	Predicted by Lea (14)
OPCA	50.7	68.0	-
FA30A	45.1	60.8	43.1
FA40A	41.5	58.4	40.6
OPCB	58.3	76.6	-
FA30B	51.2	68.0	49.6
FA40B	45.2	65.1	46.6

5. Conclusions

Experimental work was carried out in the laboratory to find out the effect of local fly ash sourced from Western Australia on the strength and hydration heat of concrete. Concrete mixes containing 400 and 480 kg/m^3 of cement and 30% and 40% cement replacements were used in the study. The following conclusions are drawn from the experimental results:

- Strengths of the fly ash concretes were generally lower than those of control concretes at early ages. The average 28-day compressive strengths of the concretes with 30% and 40% cement replacements by fly ash were 84% and 63% of the strengths of the respective control mixtures. The 90-day strengths of concretes with 30% cement replacement by fly ash were almost equal to the strengths of the corresponding control concretes.
- Cement replacement at 40% with fly ash reduced the core-surface differential temperature by about 20 ^{0}C in a concrete with 400 kg/m^3 of binder. Therefore, 40% cement replacement by fly ash has the potential to avoid risks of thermal cracking in concretes using a binder content of up to 400 kg/m^3.
- The percentage reduction in the maximum temperature of fly ash concrete can be estimated as one-half of the percentage replacement of cement by fly ash.

6. Acknowledgement

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7. References

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