Properties of concrete containing fly ash and temperature control measures used during construction

Xinkai Yu, Jinyang Li
Chengdu Engineering Corporation Limited, Power Construction Corporation of China, Chengdu, Sichuan, 610072, China
*Corresponding author’s e-mail: feiyu.1122@163.com

Abstract. In recent years, fly ash cement has been applied in engineering with the continuous application of concrete admixtures. Although we have been using fly ash concrete and have done a lot of experimental research, but the understanding of its thermophysical properties was not complete, and further research was needed. This paper presented results of a study into important fundamental thermal and physical properties of both fly ash mortar and fly ash concrete. Different replacement percentage of OPC by FA ranging from 0 to 60% by mass were devised. Increasing fly ash content was found to delay the initial setting time and final setting times, decrease both compressive and flexural strengths and reduce hydration heat. It also can effectively reduce the hydration heat evolution of cement-fly ash binder. The adiabatic temperature rise of cement fly ash material in engineering can be estimated by reduction coefficient $k$. In fly ash concrete tests, thermal properties, including thermal diffusivity, conductivity, specific heat, ultimate tensile strain and static elasticity modulus were also measured and reported. There also appeared the relationship between compressive strength and flexural strength showed similar linear change with the replacement rate of fly ash rising from 30% to 60%. Most importantly, pipe cooling tests of fly ash concrete were carried out and from the perspective of temperature control of mass concrete, dynamic pipe cooling measures were investigated.

1. Introduction
A hydropower station was situated in southeast China, which was one of the biggest hydropower stations under construction. The barrage of the hydropower station was expected to be a gravity dam made up of roller-compacted concrete. Before the construction began, concrete materials used in the dam were investigated, and finally, fly ash concrete was selected. Fly ash, has been widely used as an admixture in cement production process [1 ~2]. The workability and durability of concrete can be improved remarkably by adding Portland cement with part of fly ash. [3~4].

The properties and applicability of cement-based materials with 80% replacement rate of fly ash has been studied [5 ~6]. The effect of different fly ash mixing ratio on the basic properties of concrete has been studied extensively, consist of physical properties [7 ~10], hydration properties [11~14] and self-compacting properties [15~16]. Fly ash is widely used in large-scale structures such as roller compacted concrete [17~18].

Although a lot of research has been done on fly ash and some achievements have been achieved, there are still some problems that need to be carefully studied, such as the influence of fly ash on the heat of hydration and on thermal properties [19~20]. Besides, the influence of fly ash on thermal properties has been studied by only few researchers [21]. Due to the increasing amount of fly ash, people...
pay more and more attention to the thermal performance of concrete with large amount of fly ash. In this paper, the comprehensive thermomechanical properties of fly ash cement-based materials has been studied in order to provide more comprehensive knowledge for the research of fly ash cement-based materials. According to the measured hydration heat of mortar, the reduction coefficient of fly ash in the process of hydration heat evolution can be calculated, and the adiabatic temperature rise of concrete containing fly ash can be effectively predicted. In addition to thermo-mechanical properties of concrete mixtures, pipe cooling tests of fly ash concrete were reported, and dynamic temperature control measures used in the hydropower station was investigated, which aimed at ensuring the quality of fly ash concrete constructed in the dam.

2. Materials

The fly ash (FA) used in this study meets the National Standards of China. (GB/T50146-2014) [22]:

- a) Loss on ignition (LOI) is controlled within 8.0% by mass;
- b) Content of SO₃ is less than 3.0% by mass;
- c) Fineness modulus is less than 20%.

Also, the ordinary Portland cement (OPC) meets the National Standards of China. (GB/T200-2017) [23]:

- a) LOI is controlled within 3.0% by mass;
- b) Content of MgO is less than 5.0% by mass;
- c) Content of SO₃ is less than 3.5% by mass;
- d) Alkali content is less than 0.60% by mass.

Main chemical constituents and density of FA and OPC were as followed in Table 1.

| Materials | SiO₂ | K₂O | Al₂O₃ | CaO | MgO | Fe₂O₃ | Na₂O |  SO₃ | LOI | Density (kg/m³) |
|-----------|------|------|-------|-----|-----|-------|------|------|-----|----------------|
| FA        | 58.23| 0.82 | 24.81 | 2.66| 1.96| 8.62  | 0.15 | 0.31 | 0.78| 2510           |
| OPC       | 21.67| 0.50 | 4.79  | 58.75| 4.01| 5.03  | 0.16 | 2.55 | 1.66| 3160           |

3. Cement-fly ash mortar tests

In order to study the effect of FA on hydration and physical properties of cement-fly ash (CFA) mortar, four groups of different replacement percentage of OPC by FA ranging from 0 to 60% by mass were devised (see Table 2) [5]. The other composition of all CFA mortar mixtures were listed in the Table 2.

| Mix    | Percentage of FA (by mass, %) | w/b | OPC | FA | Sand | Materials (g) |
|--------|-------------------------------|-----|-----|----|------|---------------|
| CFA-1  | 0                             | 0.5 | 450 | 0  | 1350 | 225           |
| CFA-2  | 30                            | 0.5 | 315 | 135| 1350 | 225           |
| CFA-3  | 50                            | 0.5 | 225 | 225| 1350 | 225           |
| CFA-4  | 60                            | 0.5 | 180 | 270| 1350 | 225           |

3.1 Physical properties of cement-fly ash mortar

The initial setting time, final setting time and fluidity of CFA mortar were tested according to GB/T50146-2014[24]. The test results were followed in Table 3. It was clear shown from Table 3 that the higher the percentage of FA, the longer both the initial and final setting times. This was mainly due to the ash properties of FA, which required calcium hydroxide from hydration of OPC for its hydration [25]. However, the results of fluidity do not seem to be affected by FA content.
Table 3. Setting times and fluidity

| Mix   | Setting Time (hour: min) | Fluidity (mm) |
|-------|--------------------------|----------------|
|       | Initial Setting          | Final Setting  |
| CFA-1 | 3:03                     | 4:30           | 135.3          |
| CFA-2 | 4:44                     | 5:39           | 135.2          |
| CFA-3 | 4:55                     | 7:31           | 135.5          |

At the same time, the compressive and flexural strength tests of CFA mortar were carried, the results were shown in Table 4. The variation of the compressive and flexural strength with the replacement percentage of FA for OPC of different time were plotted in Figure 1. From Table 4 we know, with the increasing of time, the compressive strength and flexural strength increased. In addition, the strength of cement-based materials were reduced by increasing the percentage of FA, which indicated that replacing OPC with FA decreased the strength of cement-based materials, especially in 90 days.

Table 4. Compressive and flexural strengths

| Mix   | Compressive Strength (MPa) | Flexural Strength (MPa) |
|-------|-----------------------------|-------------------------|
|       | 7d  | 28d | 90d | 7d  | 28d | 90d |
| CFA-1 | 30.6 | 48.1 | 61.5 | 6.3 | 8.3 | 9.9 |
| CFA-2 | 18.0 | 30.5 | 49.5 | 4.6 | 6.4 | 9.1 |
| CFA-3 | 10.7 | 17.7 | 30.9 | 2.9 | 4.3 | 6.3 |
| CFA-4 | 7.0  | 11.3 | 18.9 | 1.9 | 3.2 | 4.4 |

Figure 1. Variation of strengths with fly ash content of different time: (a) Compressive strength and (b) Flexural strength.

The results showed that the compressive strength and flexural strength usually increased with the passage of time, but both of them decreased with the increase of FA replacement rate. The relation between the compressive strength and the flexural strength was plotted in Figure 2. The experimental results were compared with the society model given by American Concrete Institute (ACI) (shown as Equation(1)) [26]. The results showed that ACI curve could not be used to reflect the relationship between compressive strength and flexural strength. However, it was clear that this relationship also satisfied linear variations and could be expressed as a linear formula: $f_t = 0.62(f_c)^{1.61}$ (the square error: 0.978).

$$f_t = 0.62(f_c)^{1.61}$$

where, $f_t$ is the flexural strength and $f_c$ is the compressive strength.
3.2 Effect of fly ash on hydration heat evolution

In order to study the influence of fly ash on the evolution of hydration heat, hydration heat at different ages (from 0 to 7 days) was measured in a 20 ml ampere bottle with the initial hydration temperature of 20°C. The measured data of hydration heat of CFA-1, 2, 3 and 4 was shown in Figure 3. The results showed that the hydration heat of CFA-1 was the highest, that of CFA-2 was higher than that of CFA-3, and that of CFA-4 was the lowest. This indicated that the thermal evolution of CFA binder decreased significantly with the increased of FA replacement rate.

Figure 3. Hydration heat.

In order to analyze the influence of FA on hydration heat evolution, a calculation equation of adiabatic temperature rose by Bofang Zhu [27] was used. The equation could be expressed as

\[ \theta(t) = \frac{Q(t)(W + kF)}{c\rho} = \frac{Q_b(t)W_b}{c\rho} \]

where: \( Q(t) \) is the hydration heat of OPC, \( W \) is the content of OPC, \( k \) is a reduction coefficient, \( F \) is the content of FA, \( c \) is the average specific heat, \( Q_b(t) \) is the hydration heat of CFA binder, \( W_b \) is the content of CFA binder and \( \rho \) is the density of mortar.

Based on Equation (2), the reduction coefficient \( k \) of FA on hydration heat could be expressed as

\[ k = \frac{Q_b(t)W_b}{Q(t)F} \]

Combined Equation (3) and test results of hydration heat was shown in Figure 3, the reduction coefficient \( k \) was calculated, and the results of \( k \) were drawn in Figure 4. For the same FA content, the reduction coefficient increases with time, peaked at about 2 days, and then decreased. The reduction coefficient \( k \) reached the maximum value of 0.27 at CFA-3 and the minimum value of 0.12 at CFA-4. In addition, there was no obvious relationship between the reduction coefficient and FA percentage.
4. Fly ash concrete tests

According to above CFA mortar test results, and referring to other dams’ construction experiences, concrete mixes used in the hydropower station were finally designed with different replacement level of FA for OPC (30%, 50% and 60%, by mass, see Table 5). C-1 was designed as ordinary concrete, while C-2 and C-3 were used as roller-compacted concrete. Corresponding with CFA mortar tests, the ratio of water-to-binder (w/b) was 0.50. In the concrete mix of C-1, the contents of total binder, water and sand were 190 kg/m$^3$, 95 kg/m$^3$ and 670.4 kg/m$^3$ respectively. The contents of total binder in C-2 and C-3 was 150 kg/m$^3$, and water, sand and aggregate were 75 kg/m$^3$, 808.5 kg/m$^3$ and 1458.2 kg/m$^3$, respectively.

| Mix  | Percentage of FA (by mass, %) | w/b | OPC | FA | Materials (kg/m$^3$) | Density (kg/m$^3$) |
|------|-------------------------------|-----|-----|----|----------------------|-------------------|
| C-1  | 30                            | 0.5 | 133 | 57 | 670.4 1516.1         | 2471.5            |
| C-2  | 50                            | 0.5 | 75  | 75 | 808.5 1458.2         | 2416.7            |
| C-3  | 60                            | 0.5 | 90  | 60 | 808.5 1458.2         | 2416.7            |

4.1 Thermal properties of fly ash concrete

Relevant thermal parameters of fly ash concrete were tested based on (DL/T5150-2017)[28], the test results were shown in Table 6. We could see in Table 6, the increase of FA percentage led to a slight decrease in thermal conductivity and linear expansion coefficient, and a slight increase in Poisson's ratio, but the increase was relatively small. In general, the increase of FA replacement rate would not affect these thermal parameters. The experimental data of adiabatic temperature rise of concrete were shown in Figure 5. As can be seen from the Figure 5, the adiabatic temperature rise of C-1 increased fastest, while that of C-3 was the lowest.

| Properties                      | C-1   | C-2   | C-3   |
|---------------------------------|-------|-------|-------|
| Poisson's ratio                 | 0.179 | 0.184 | 0.185 |
| Thermal diffusivity (m$^2$/h)   | 0.0037| 0.0041| 0.0041|
| Thermal conductivity (kJ/(mh$^\circ$C)) | 9.694 | 9.667 | 9.619 |
| Average specific heat (kJ/(kg$^\circ$C)) | 1.012 | 0.954 | 0.951 |
| Linear expansion coefficient (10$^4$/$^\circ$C) | 7.31  | 7.01  | 6.76  |
Figure 5. Adiabatic temperature rise of concrete.

4.2 Mechanical properties of fly ash concrete

Test results of compressive strength and flexural strength of concrete mixes at the age of 7, 28 and 90 days were shown in Figure 6. The results showed that the compressive strength and flexural strength usually increased with the passage of time, but both of them decreased with the increase of FA replacement rate. Also, it was observed that the strength difference between C2 and C3 was far smaller than the difference between C1 and C2, indicated that once the percentage of FA was over 50%, both compressive and flexural strengths were little affected. The relation between the compressive strength and the flexural strength was plotted in Figure 6(c). It was clearly noted that the relationship similarly met a linear variation, which could be expressed by a linear formula as: $f_t = 0.076f_c - 0.065$ (the square error: 0.975).

Figure 6 Strength results of fly ash concrete (a) Compressive strength; (b) Flexural strength; (c) Relationship between compressive and flexural strengths.
Table 7 reported the effect of FA on ultimate tensile strain and static elasticity modulus. As listed in the table, the increase of FA percentage results in a significant decrease in the average ultimate tensile strain and also resulted in a relatively small decrease in the static modulus of elasticity. Generally, the ultimate tensile stress could be expressed as Equation (4)[27]. This denoted that using FA to replace OPC significantly reduced the ultimate bearing capacity of concrete.

Table 7. Mechanical properties of concrete

| Mix  | Ultimate Tensile Strain ($\times 10^{-6}$) | Static Elasticity Modulus ($\times 10^4$MPa) |
|------|------------------------------------------|-----------------------------------------|
|      | 7d            | 28d            | 90d            | 7d            | 28d            | 90d            |
| C-1  | 55.7          | 71.8           | 87.0           | 3.08          | 3.79           | 4.44           |
| C-2  | 45.8          | 63.0           | 68.7           | 2.73          | 3.50           | 4.28           |
| C-3  | 36.7          | 47.5           | 73.2           | 2.65          | 3.46           | 4.21           |

\[ \delta = \frac{\epsilon_p E_c}{K_f} \]  

where: \( \epsilon_p \) is the ultimate tensile strain, \( E_c \) is the static elasticity modulus and \( K_f \) is a safety coefficient.

5. Pipe cooling tests

In the construction of the hydropower station, one of the most important things was to ensure the quality of mass concrete constructed in the dam. In order to prevent the appearance of thermal cracks in mass concrete, pipe cooling system was commonly used. At the beginning period of the construction of the hydropower station, many concrete replacement blocks were casted, and a few of them were selected and used to carry out pipe cooling tests. The purpose of concrete replacement blocks was to replace rushed and unsafe rock in the base of the dam to ensure the safety. Concrete replacement blocks used to perform pipe cooling tests were shown in Figure 7. Concrete block A was composed by C-1 concrete, while concrete block B and C were made of C-2 concrete and C-3 concrete, respectively. The depth of concrete block A was about 3.0 meters, and a fiber optic temperature sensor (No. TL-7) was embedded in the middle. In concrete block B, two fiber optic temperature sensors (No. TL-1 and TL-2) were embedded, and their exact locations were shown in the figure. The depth of concrete block C was about 2.0 meters, and there were two fiber optic temperature sensors (No. TL-4 and TL-5) embedded.

![Figure 7. Distribution of fiber optic temperature sensors in concrete blocks.](image)

5.1 No pipe cooling

Concrete block A, B and C were casted without pipe cooling system, and the measured temperature curves are shown in Figure 8. Figure 8(a) showed temperature curve of the concrete block A measured by temperature sensor TL-7, which presented that the highest temperature was about 35.11°C at the age of concrete approximate 1.5 days. Because there was no pipe cooling process, after peaking at the highest value, the temperature dropped quite slowly Figure 8(b) plotted temperature history of concrete
block B and C. It could be noted that because the locations of temperature sensors embedded in concrete block were different (see Figure 7), the obtained temperature curves were little different. Overall, the temperature of C-2 concrete was higher than the temperature of C-3 concrete. The highest temperature of concrete C-2 and C-3 peaked at about 27.25°C and 25.43°C, respectively. According to the construction technical specification established for the hydropower station, the allowed highest temperature of concrete C-1 was about 30°C, while the temperature in concrete C-2 and C-3 was 26°C. Obviously, without pipe cooling process, the temperature of concrete C-1 and C-2 cannot meet the technical specification.

![Figure 8](image)

**Figure 8.** Temperature history of concrete without pipe cooling: (a) C-1; (b) C-2/C-3.

### 5.2 Pipe cooling process

Figure 10 presented the distribution of water pipes in a concrete block. The outer radius and inner radius of high density polyethylene plastic pipe for dam were 0.016 meters and 0.014 meters respectively. Temperature sensor TL-24 was embedded in a concrete block made up of C-1 concrete, whereas temperature sensor TL-31 was embedded in a C-2 concrete block. The locations of the two temperature sensors were similar, which both were in the middle of the block (as shown in Figure 9).

![Figure 9](image)

**Figure 9.** Distribution of water pipes.

During pipe cooling, except temperature of concrete, water temperature and water flow used in pipe cooling process were also measured. Figure 10(a) showed the pipe cooling process occurred in a C-1 concrete block, whereas Figure 10(b) plotted the pipe cooling process in a C-2 concrete block. As shown in the figure, water temperature used in pipe cooling tests was similar in the two cases, and the average water temperature both was about 10°C. The fluctuation of water temperature was mainly caused by air temperature, water pumps and cooling machine. In fact, it was impractical to keep the temperature of cooling water constant. During the first two days of pipe cooling, the average water flow used in the two cases was about 2.0m³/h, which controlled the highest temperature quite well. In Figure 10(a), the highest temperature of C-1 concrete was about 29.11°C on April 13, 2015, as the highest temperature in Figure 10(b) was approximate 24.93°C on April 1, 2015. The measured highest temperature both met the requirement of the construction technical specification. Figure 10(a) showed that the temperature measured by TL-24 began declining stably after April 13, 2015, so water flow was adjusted to about 1.0m³/h on April 15, 2015 to avoid the temperature of concrete reducing too fast. After April 17, 2015, the water flow was reduced to about 0~0.5m³/h, and the measured temperature of concrete kept declining steadily. In Figure 10(b), after April 2, 2015, water flow became about 0~0.3m³/h, resulting in a
significant rise trend of concrete temperature which started on April 6, 2015. In order to stop the rise trend, the water flow was increased to 1.2 m$^3$/h on April 8, 2016. After that, the temperature started dropping steadily again, and on April 12, 2015, the water flow was adjusted back to a relatively low level (about 0–0.4 m$^3$/h).

Figure 10. Temperature history of concrete under pipe cooling process: (a) C-1; (b) C-2.

6. Conclusions
Based on the above analysis, the following conclusions can be summarized:

[1] Fly ash as a replacement material for Portland cement can delay the initial setting time and final setting time, and can decrease the compressive strength and flexural strength. When the fly ash content was more than 30%, the effect was particularly obvious. With the replacement rate of fly ash rising from 30% to 60%, the relationship between compressive strength and flexural strength showed similar linear change.

[2] In terms of hydration properties, fly ash can effectively reduce the hydration heat evolution of cement-fly ash binder. The coefficient of reduction of hydration heat evolution of fly ash varies from 0.12 to 0.27, but the relationship with fly ash percentage was not obvious. Combined with Equation 2 and reduction coefficient $k$, the adiabatic temperature rise of cement-fly ash material in engineering can be estimated.

[3] In concrete engineering, replacing Portland cement with fly ash has a significant effect on the adiabatic temperature rise of concrete, while other thermal properties (thermal diffusivity, thermal conductivity and average specific heat) have little effect. Also, the relationship between compressive strength and flexural strength similarly showed a linear variation. Besides, ultimate tensile strain and static elasticity modulus both experience various degrees’ reduction as the replacement percentage of fly ash for Portland cement rises.

[4] In pipe cooling tests, it is found that the ordinary concrete (C-1) and the roller compacted concrete (C-2) must use pipe cooling system to control temperature, while another roller compacted concrete mix (C-3) can be free from pipe cooling measures. Generally, the highest temperature of concrete occurs at the age of approximately 1.5 days. During the first two days of pipe cooling, the average water flow should remain at about 2.0 m$^3$/h to restrain temperature rise. After that, the value of water flow should be flexibly adjusted according to the measured temperature curve. Also, it’s noted that keeping the temperature of cooling water constant is impractical, and the most efficient way to achieve dynamic control of concrete temperature is the adjustment of water flow.

Notation

| Symbol | Description |
|--------|-------------|
| $f_c$  | Compressive strength |
| $f_t$  | Flexural strength |
| $\theta$ | Adiabatic temperature rise of concrete |
| $Q$    | Hydration heat of Portland cement |
| $k$    | Reduction coefficient |
| $c$    | Specific heat |
| $\rho$ | Density |
| $F$    | Content of fly ash |
\( Q_b \) Hydration heat of cement-fly ash binder  
\( \tau \) Age of concrete or mortar  
\( W \) Content of cement

\( E_c \) Static elasticity modulus  
\( \varepsilon_p \) Ultimate tensile strain  
\( K_f \) Safety coefficient

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