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EXPERIMENTAL EVALUATION OF EARLY-AGE THERMAL BEHAVIOR OF FLY ASH CONCRETE USING SEMI-ADIABATIC CALORIMETRY

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Abstract. Early-age temperature development of concrete is governed by the balance between hydration heat generation and heat dissipation to the surrounding environment. Adiabatic calorimetry is commonly regarded as the most accurate experimental method for determining hydration-related thermal parameters of concrete; however, it requires complex equipment and is relatively costly. In contrast, semi-adiabatic calorimetry offers a simpler and more economical alternative. This study experimentally investigates the semi-adiabatic temperature development of concrete mixtures with different fly ash replacement levels. Four mixtures containing 0%, 10%, 20%, and 30% fly ash by mass of cementitious materials were tested using a laboratory calorimeter operated under semi-adiabatic mode. Concrete and chamber air temperatures were continuously monitored, and key thermal indicators were evaluated. The results show that increasing fly ash replacement reduces both the peak temperature and the overall temperature rise under consistent testing conditions. The temperature rise (ΔT) decreased from 23.9 °C to 17.5 °C as fly ash replacement increased from 0% to 30%. The reduction in temperature rise does not follow a strictly linear trend, and no clear monotonic relationship was observed for the time to peak temperature. Semi-adiabatic calorimetry is shown to provide reliable comparative indicators for preliminary assessment of early-age thermal behavior of concrete mixtures.

Keywords: semi-adiabatic calorimetry, early-age concrete, fly ash concrete, temperature development, hydration heat

1. INTRODUCTION

The temperature development of concrete at early ages is governed by the heat released during cement hydration and the ability of the material to dissipate this heat to the surrounding environment. In massive or moderately restrained concrete elements, the accumulation of hydration heat may lead to significant temperature rise and thermal gradients, which are among the primary causes of early-age cracking. Such cracking can adversely affect durability, serviceability, and long-term structural performance [1, 2, 3]. Therefore, understanding and characterizing the early-age thermal behavior of concrete remains an important task in both research and engineering practice.

Adiabatic calorimetry is commonly regarded as the most direct method for determining the intrinsic heat evolution and adiabatic temperature rise of concrete. Under ideal adiabatic conditions, heat exchange with the environment is minimized, allowing the temperature rise to reflect solely the hydration process [4, 5, 6]. However, adiabatic calorimeters are expensive, technically demanding, and rarely available outside specialized research laboratories. These limitations significantly restrict their application in routine laboratory testing and practical engineering projects.

As a more accessible alternative, semi-adiabatic calorimetry has been widely adopted to monitor the temperature evolution of concrete under partially insulated conditions. In semi-adiabatic tests, concrete specimens are allowed to lose heat to the surrounding environment, resulting in temperature histories that differ from the true adiabatic response [7, 8, 9]. Although such measurements do not provide direct information on the adiabatic temperature rise, they offer valuable experimental insight into the combined effects of heat generation and heat dissipation. For this reason, semi-adiabatic calorimetry is frequently used in laboratories and field-oriented studies, especially where simplicity and cost-effectiveness are essential [9, 10].

Despite its practical advantages, the interpretation of semi-adiabatic temperature data remains challenging. The measured temperature curves are influenced not only by hydration kinetics but also by heat loss mechanisms associated with specimen geometry, insulation quality, and ambient conditions. Consequently, semi-adiabatic temperature histories should not be interpreted solely in terms of peak temperature, but rather through a set of characteristic thermal indicators that describe both the heating and cooling stages of early-age concrete. A clearer experimental understanding of these characteristics is necessary to support the rational use of semi-adiabatic calorimetry in engineering applications.

In addition, the incorporation of supplementary cementitious materials, such as fly ash (FA), has a pronounced influence on the thermal behavior of concrete [11, 12]. Fly ash generally reduces the rate and magnitude of heat evolution due to cement dilution and delayed pozzolanic reactions, making it particularly attractive for mass concrete construction. While the effect of fly ash on adiabatic temperature rise has been extensively reported, its influence on semi-adiabatic temperature development and associated heat dissipation characteristics has not been sufficiently clarified from an experimental standpoint.

The objective of this study is to experimentally investigate the semi-adiabatic temperature development of concrete with different fly ash replacement levels. Using a laboratory calorimeter operated under semi-adiabatic mode, temperature histories of concrete specimens are measured and analyzed to identify key thermal characteristics, including peak temperature, time to peak, and post-peak cooling behavior. The results aim to support the use of semi-adiabatic calorimetry as a simple experimental method for comparative thermal assessment and preliminary evaluation of early-age thermal behavior, rather than as a direct substitute for adiabatic calorimetry in numerical thermal simulations.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials and mixture proportions

Ordinary Portland cement (OPC) and Class F fly ash were used as the cementitious materials in this study. The chemical and mineralogical compositions of the cement, together with the chemical composition of the fly ash, are summarized in Tables 1–3 [12]. Crushed limestone with a nominal maximum aggregate size of 12.5 mm was employed as coarse aggregate, while natural river sand was used as fine aggregate.

Table 1. Cement chemical composition (%).

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Amount	21.49	5.40	3.49	63.56	1.40	1.65	0.15	0.70

Table 2. Mineralogical composition of cement (%).

Phase	C_3S	C_2S	C_3A	C_4AF
Amount	51.74	24.2	8.16	10.35

Table 3. Chemical composition of FA (%).

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	MnO	P_2O_5
Amount	56.69	25.14	6.3	1.25	1.54	0.15	0.34	3.66	0.94	0.06	0.16

Table 4. Mix proportions of concrete.

Mix	% FA replacement	w/cm	Water (l)	Cement (kg)	FA (kg)	Coarse aggregate (kg)	Sand (kg)	HRWR (l)
FC00	0%	0.32	170	530	0	1049.5	723.5	5.0
FC10	10%	0.32	170	477	53	1049.5	709.5	5.0
FC20	20%	0.32	170	424	106	1049.5	695.5	5.0
FC30	30%	0.32	170	371	159	1049.5	680.5	5.0

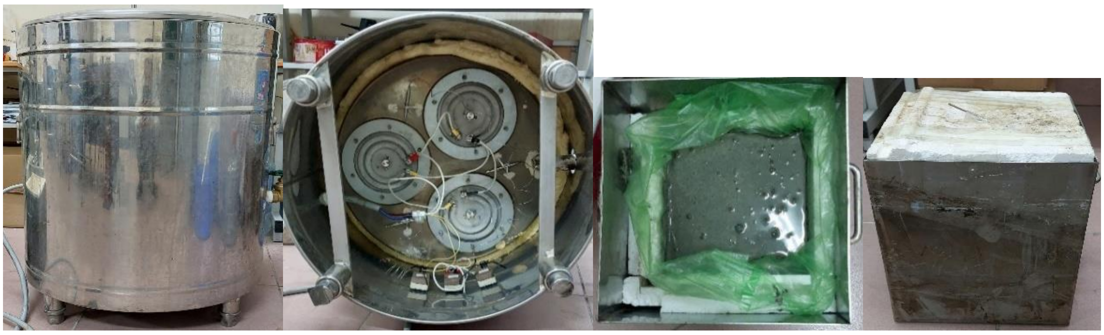
w/cm = water to cementitious materials ratio; HRWR = High Range Water Reducing & Retarding admixture

Four concrete mixtures were prepared with fly ash replacement levels of 0%, 10%, 20%, and 30% by mass of the total cementitious materials. The mixtures were designated as FC00, FC10, FC20, and FC30, respectively. To isolate the influence of fly ash content on early-age thermal behavior, a constant water-to-cementitious materials ratio (w/cm) of 0.32 was adopted for all mixtures. A high-range water-reducing and retarding admixture was incorporated to achieve adequate workability and to maintain consistent fresh concrete properties among the mixtures. The detailed mixture proportions are presented in Table 4.

2.2 Semi-adiabatic calorimetry setup

Semi-adiabatic temperature measurements were carried out using a laboratory calorimeter chamber that was originally designed and constructed for adiabatic calorimetry testing (Fig. 1) [13]. The chamber (Fig. 1a) consists of a cylindrical container with internal thermal insulation, accommodating a cubic concrete mold with dimensions of 250 × 250 × 250 mm (Fig. 1d). In its original adiabatic configuration [13], the system is equipped with electrical heating elements (Fig. 1b) and a temperature control unit to maintain the surrounding medium at the same temperature as the concrete specimen.

In the present study, the calorimeter was intentionally operated in a semi-adiabatic mode. A schematic representation of the semi-adiabatic configuration and thermocouple locations is provided in Fig. 2. The heating system was completely deactivated, and no external temperature control was applied. As a result, the concrete specimen was surrounded by static air within a closed and insulated chamber, allowing heat generated by cement hydration to dissipate gradually to the surrounding air and chamber walls. The heat loss can be represented by an equivalent heat transfer coefficient. However, the primary objective of this study is to perform a comparative evaluation of semi-adiabatic temperature development of different concrete mixtures under consistent thermal conditions, rather than to explicitly characterize the insulation performance of the calorimeter system.



a) b) c) d)

Figure 1. Semi-adiabatic calorimetry setup: (a) insulated calorimeter chamber originally developed for adiabatic testing; (b) inside the bottom of the chamber (heater not activated); (c) fresh concrete sample; and (d) sample mold to be placed in the chamber.

Fresh concrete was cast into the cubic mold, and a thermocouple was embedded at the geometric center of the specimen to monitor the internal concrete temperature. Type K thermocouples with a measurement range of 0–400 °C and a resolution of 0.1 °C were used for temperature monitoring. A second thermocouple was installed inside the chamber to measure the air temperature. After casting, the mold was immediately placed inside the chamber, which was tightly sealed to minimize air exchange with the external laboratory environment.

Temperature data from both thermocouples were recorded at 1-minute intervals throughout the testing period. Under this configuration, the measured temperature histories reflect the combined effects of heat generation due to cement hydration and heat loss through convection and radiation to the surrounding air and chamber boundaries. This setup represents a practical semi-adiabatic testing condition commonly encountered in laboratory-scale thermal measurements of concrete.

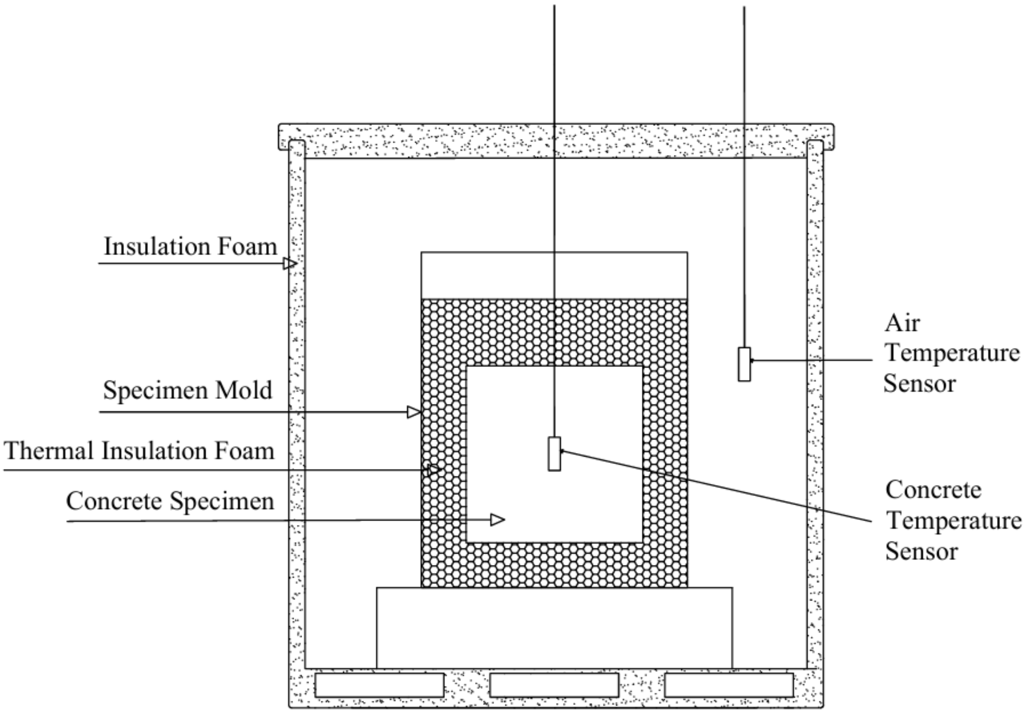


Figure 2. Schematic illustration of the semi-adiabatic configuration.

2.3 Test procedure and data processing

All concrete specimens were prepared and tested under identical laboratory conditions to ensure consistency among the mixtures. Immediately after casting, each specimen was placed inside the semi-adiabatic chamber, and temperature monitoring was initiated without delay.

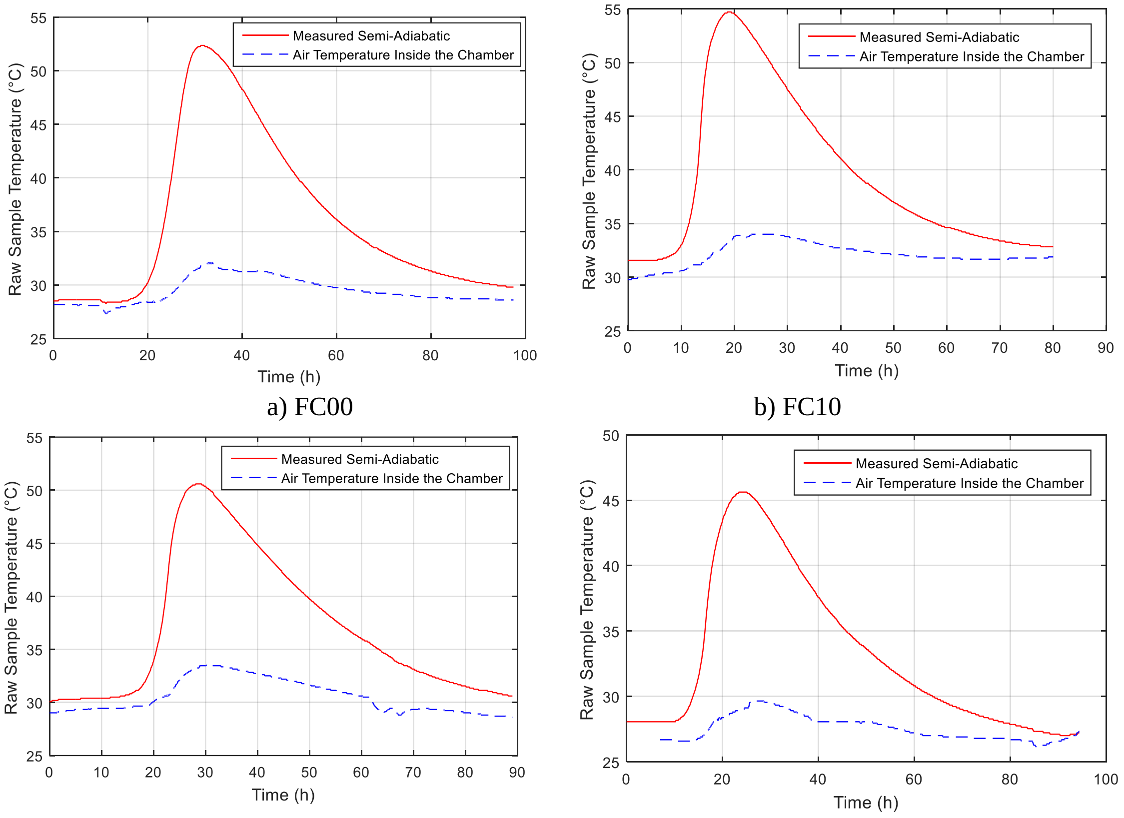
To assess the repeatability of the experimental setup, repeated tests were performed on a representative mixture under identical conditions. The results showed very good agreement in terms of temperature evolution, peak temperature, and overall curve shape, indicating that the measurement system provides consistent and reliable results. Based on this verification, the same procedure was applied to all mixtures.

Due to minor variations in initial concrete temperature (see Table 5) and ambient conditions, the raw semi-adiabatic temperature histories exhibited slight differences in the onset time of temperature rise. To enable a meaningful comparison of hydration-related thermal evolution, the measured temperature curves were temporally aligned by shifting the time origin to the onset of temperature increase for each mixture. This normalization procedure preserves the original shape and magnitude of the temperature histories while facilitating a consistent comparison of key thermal characteristics, including peak temperature, time to peak, and post-peak cooling behavior. It should be noted that such time-shifting may affect the interpretation of the absolute timing of hydration processes. Therefore, the normalized time axis is used in this study only for comparative purposes and not for deriving intrinsic hydration kinetic parameters.

It should be emphasized that the semi-adiabatic temperature data obtained in this study are interpreted as experimental indicators of early-age thermal behavior, rather than as direct inputs for hydration parameter identification or numerical heat transfer simulations. Owing to the presence of uncontrolled heat loss to the surrounding air and chamber boundaries, the analysis focuses on comparative evaluation and physical interpretation of the measured temperature histories under consistent semi-adiabatic conditions.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Semi-adiabatic temperature histories



a) FC00

b) FC10

c) FC20

d) FC30

Figure 3. Measured semi-adiabatic temperature histories of concrete mixtures with different fly ash replacement levels and air temperature inside the chamber: a) FC00; b) FC10; c) FC20; d) FC30.

Fig. 3 presents the measured semi-adiabatic temperature histories of the concrete specimens (designated as FC00, FC10, FC20, and FC30) together with the corresponding air temperature inside the chamber for the four mixtures. For all mixtures, a characteristic temperature rise associated with cement hydration is observed, followed by a gradual cooling stage caused by heat dissipation to the surrounding air and chamber boundaries. The accompanying air temperature curves confirm that the tests were conducted under semi-adiabatic conditions, with a clear temperature gradient developing between the concrete specimen and the chamber air during the main hydration period.

At very early ages, the concrete and air temperatures remain close, indicating a limited net heat accumulation during the induction period, and the induction period is quite long due to the retarding effect of the chemical admixture. As hydration accelerates, the concrete temperature increases rapidly while the air temperature responds more slowly, reflecting the combined effects of internal heat generation and external heat dissipation. This initial temperature convergence highlights the dominant role of boundary conditions and heat loss mechanisms during the induction period under semi-adiabatic testing.

When the temperature histories are compared on a common time scale (Fig. 4), the influence of fly ash becomes more evident in the overall thermal evolution. Mixtures containing fly ash exhibit a slower temperature rise and a more gradual cooling phase, indicating moderated early-age heat development. These features are beneficial for reducing thermal gradients in concrete elements and highlight the practical value of semi-adiabatic calorimetry for comparative assessment of early-age thermal behavior.

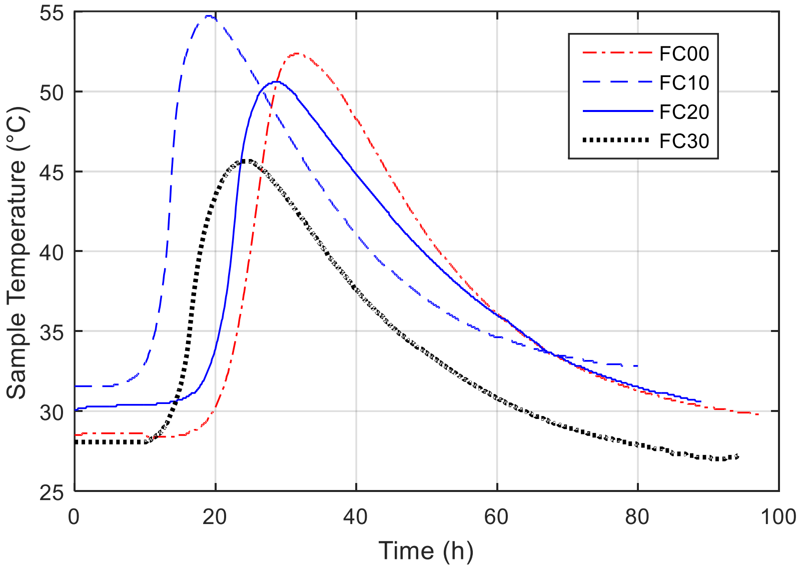


Figure 4. Measured semi-adiabatic specimen temperatures of 4 mixtures.

The time to reach peak temperature is generally related to the duration of the induction period, which may be influenced by factors such as initial concrete temperature, admixture dosage, cement composition, water–cement ratio, and mixing intensity [14, 15]. However, under the semi-adiabatic conditions of the present study, the time to peak does not exhibit a clear monotonic relationship with fly ash replacement level, suggesting that the observed peak timing results from the combined and competing effects of hydration kinetics and heat dissipation rather than material reactivity alone.

Table 5 summarizes the initial concrete temperature, peak temperature, and the corresponding temperature rise (ΔT) for each mixture. Although the initial concrete temperatures vary within a relatively narrow range (28.1–31.6 °C), noticeable differences are observed in both peak temperature and ΔT. The control mixture FC00 and FC10 exhibit high peak temperatures of 52.4 °C and 54.7 °C, respectively, whereas FC30 exhibits the lowest peak temperature of 45.6 °C. Mixtures with increasing fly ash replacement generally show lower temperature rise, with ΔT decreasing from 23.9 °C (FC00) to 17.5 °C (FC30). This reduction reflects the combined effects of cement dilution and the delayed contribution of pozzolanic reactions at early ages under semi-adiabatic conditions.

Overall, the semi-adiabatic temperature histories presented in Figs. 3 and 4, together with the peak temperature indicators summarized in Table 5, provide meaningful insight into the relative thermal performance of the mixtures. The results should be interpreted as comparative indicators rather than intrinsic adiabatic properties.

From an engineering perspective, mixtures with lower peak temperature and temperature rise (ΔT) are expected to reduce thermal gradients and the risk of early-age thermal cracking. However, the present results are intended for comparative evaluation, as actual field behavior depends on structural and boundary conditions.

Table 5. Initial concrete temperature, peak semi-adiabatic temperature, and corresponding temperature rise (ΔT) of the tested concrete mixtures.

Mix	Initial Concrete Temperature (°C)	Peak Temperature (°C)	Time to Peak Temperature (h)	ΔT (°C)
FC00	28.5	52.4	31.2	23.9
FC10	31.6	54.7	18.7	23.1
FC20	30.1	50.6	28.1	20.5
FC30	28.1	45.6	23.4	17.5

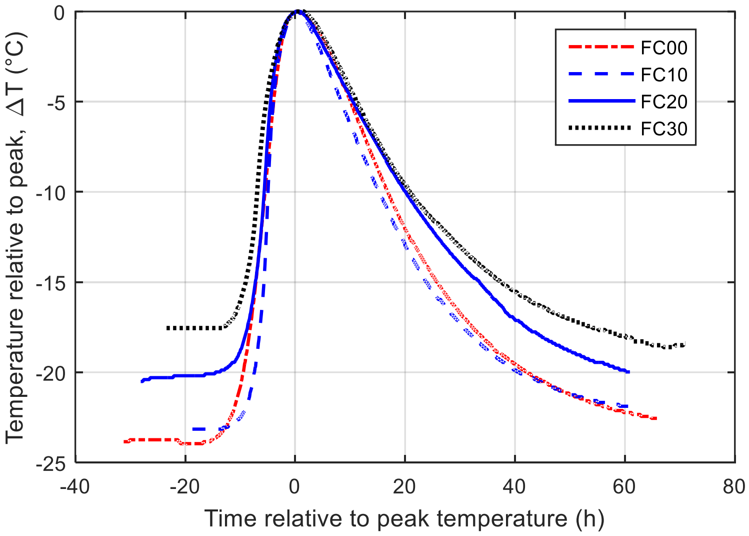


Figure 5. Shifted semi-adiabatic temperature histories of the four concrete mixtures.

To further examine the post-peak thermal behavior, Fig. 5 compares the temperature histories after shifting both time and temperature so that all mixtures share a common peak temperature. Under this representation, clear differences in the post-peak cooling slopes can be observed among the mixtures. Mixtures with higher fly ash replacement exhibit a more gradual temperature decay, whereas the control mixture shows a steeper cooling slope. This behavior suggests that, after the peak temperature, mixtures with higher fly ash content may experience a prolonged balance between residual hydration heat release and environmental heat loss, leading to a slower apparent cooling rate under semi-adiabatic conditions.

The observed differences in post-peak cooling slopes are consistent with the governing heat dissipation mechanism under semi-adiabatic conditions, where the cooling rate is primarily driven by the temperature difference between the concrete specimen and the surrounding air. Mixtures exhibiting lower peak temperatures therefore experience a reduced thermal driving force for heat loss, resulting in a more gradual post-peak temperature decay.

3.2. Discussion

The experimental results demonstrate that semi-adiabatic temperature measurements capture essential features of early-age thermal behavior, particularly the influence of fly ash replacement on temperature magnitude and overall hydration development. However, the measured temperature histories do not represent intrinsic material properties, as they are inherently affected by heat loss to the surrounding environment.

The observed differences in post-peak cooling behavior further highlight the coupled nature of hydration heat generation and environmental heat dissipation under semi-adiabatic conditions. While mixtures with higher fly ash replacement exhibit a more gradual cooling trend, this response should not be interpreted as a direct measure of continued hydration intensity. Instead, it reflects the combined influence of reduced peak temperature, ongoing hydration at later ages, and a lower thermal driving force for heat loss.

Under consistent testing conditions, key thermal indicators such as peak temperature, temperature rise, and post-peak cooling trends can be effectively used for comparative evaluation of different concrete mixtures. Nevertheless, these indicators should be interpreted as experimental responses rather than intrinsic adiabatic hydration characteristics, and caution is required when extrapolating the results to numerical modeling or parameter identification.

From an engineering perspective, semi-adiabatic calorimetry provides a simple and reliable experimental tool for preliminary assessment of early-age thermal behavior and mixture optimization, especially in laboratories where full adiabatic calorimetry is not readily available.

4. CONCLUSIONS

This study experimentally examined the early-age thermal behavior of concrete mixtures incorporating different fly ash replacement levels using semi-adiabatic calorimetry. Under consistent testing conditions, increasing the fly ash replacement from 0% to 30% led to a clear reduction in both peak temperature and overall temperature rise. The peak semi-adiabatic temperature decreased from 52.4 °C (FC00) to 45.6 °C (FC30), while the corresponding temperature rise (ΔT) decreased from 23.9 °C to 17.5 °C. Although the fly ash replacement levels increased linearly, the reduction in temperature rise did not follow a strictly linear trend. Nevertheless, the results confirm that higher fly ash content effectively moderates early-age thermal development under semi-adiabatic conditions.

The measured temperature histories are influenced by environmental heat loss and therefore do not represent intrinsic adiabatic hydration properties. However, when applied consistently, semi-adiabatic temperature measurements provide robust comparative indicators for evaluating mixture-dependent early-age thermal behavior.

From an engineering standpoint, semi-adiabatic calorimetry offers a practical and accessible experimental approach for preliminary thermal assessment and mixture optimization, particularly where full adiabatic calorimetry is not available. Future work should focus on developing appropriate frameworks to relate semi-adiabatic temperature data to hydration-related thermal parameters for predictive modeling of early-age concrete behavior.

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