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Maturity model for early-age compressive strength estimation of fly ash concrete considering the effect of temperature

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ABSTRACT

The significant effect of temperature on the early-age compressive strength development of fly ash concrete was investigated through experimental study and modelling calculations in this paper. The compressive strengths of concrete specimens with different fly ash to binder ratios, cured at three different temperatures, were tested at various ages. The experimental results demonstrate a significant difference in strength development between ordinary concrete and fly ash concrete, indicating that the existing maturity model for normal concrete is unsuitable for predicting the compressive strength of fly ash concrete. To further quantitatively analyse the effect, the maturity model, which takes into account the different curing temperature histories for fly ash concrete, was modified by reevaluating the coefficient "s" with reference to the fib Model Code 2010. This modification allows for the real-time prediction of compressive strength development based on regression analysis of experimental data obtained in this study. The results indicate that, compared to the original strength function, the compressive strength of fly ash concrete predicted by the modified maturity model is more accurate, demonstrating that the modified model can effectively monitor and predict the real-time compressive strength of fly ash concrete at construction sites.

1. INTRODUCTION

Concrete is one of the most widely used construction materials for buildings and infrastructure development globally, underpinning modern infrastructure development.

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However, its production imposes substantial environmental costs, contributing to global carbon dioxide (CO_2) emissions and intensive consumption of natural resources (Adesina 2020). To address these challenges, industrial by-products like pulverized-fuel ash (PFA), also known as fly ash, which is a residue from coal-fired power plants, have been increasingly utilized as partial cement replacements (Yao 2015, Bouzoubaa 2001 and Poon 2000). Incorporating PFA reduces clinker content, thereby lowering greenhouse gas emissions while enhancing long-term durability by refining pore structure and mitigating alkali-silica reactions (Sun 2023 and Nath 2011). Despite these advantages, PFA modifies cement hydration kinetics, resulting in distinct early-age strength development patterns that challenge conventional strength prediction methods (Soutsos 2017 and Barnett 2006).

The compressive strength of concrete is a critical indicator for structural safety, determining the timing of formwork removal and construction scheduling. Real-time strength monitoring is particularly vital for PFA concrete due to its slower early-age strength development compared to ordinary Portland cement (OPC) concrete (Kwon 2014 and Hwang 2004). Furthermore, recent studies highlight the complex interplay between temperature, PFA content, and hydration mechanisms. Studies indicate that elevated temperatures accelerate the early pozzolanic reaction of PFA but may impair long-term strength development (Sun 2023 and Miller 2022). Traditional compressive strength testing fails to capture continuous strength evolution under variable curing conditions.

Maturity methods address this gap by correlating strength development with the time-temperature history, offering a practical approach for non-destructive in-situ strength estimation (Sun 2023 and 2021). The fib Model Code 2010 provides a widely adopted maturity-based strength function, however, these models face limitations when applied to PFA-modified systems (Vollpracht 2018 and Vijaya Bhaskara 2018), which restrict reliable in-situ strength monitoring for PFA concrete, risking premature formwork removal or delayed construction progress.

In this study, the coupled effects of temperature and PFA-to-binder ratio (PFA/b) on early-age compressive strength were quantified through experimentation. Then, the fib Model Code's strength model is recalibrated by re-evaluating coefficient "s" using regression analysis of real-time strength data. The refined model enables precise prediction of compressive strength for PFA concrete, enhancing construction quality control and facilitating optimised formwork scheduling. By integrating material-specific parameters and curing history, this work advances sustainable construction practices.

2. **EXPERIMENTAL PROGRAMME**

2.1 Materials

52.5N ordinary Portland cement, conforming to the requirements of the standard BS EN 197-1, supplied by Green Island Cement (Holdings) Limited, was used. Tap water, natural river sand with a fineness modulus of 2.4, and coarse aggregate of crushed granite with a maximum size of 10mm were used.

A series of concrete cubes (100mm) with three PFA-to-binder ratios (PFA/b = 25%, 30%, and 35%) were tested in this project, and a control mix (0% PFA) was included for baseline comparison. The properties of PFA are shown in Table 1. For monitoring concrete temperature, sensors have been embedded into two cubes per batch. It is one of the purposes to study the effectiveness of data collected at various depths of embedment.

Table 1 Properties of PFA

Fineness	Particle Density	Sulphuric anhydride content (as SO_3)	Loss-on ignition (L.O.I.)	Moisture Content	Calcium oxide content
9.3%	2350kg/m^3	0.58%	2.2%	0.1%	5.41%

2.2 Curing and testing procedures

In order to reflect the effect of temperature on the concrete specimens at early age, all concrete cubes were directly moved to their corresponding curing water tanks with a constant temperature after casting, as shown in Fig. 1(a). Three levels of temperature (25℃, 40℃, and 55℃) were designed for this study. The demolding of the specimens was performed after 16-24 hours after casting. Subsequently, all cubes were moved to the corresponding automatic curing chambers with a constant temperature and immersed in water, as shown in Fig. 1(b).

(a) Curing water tank

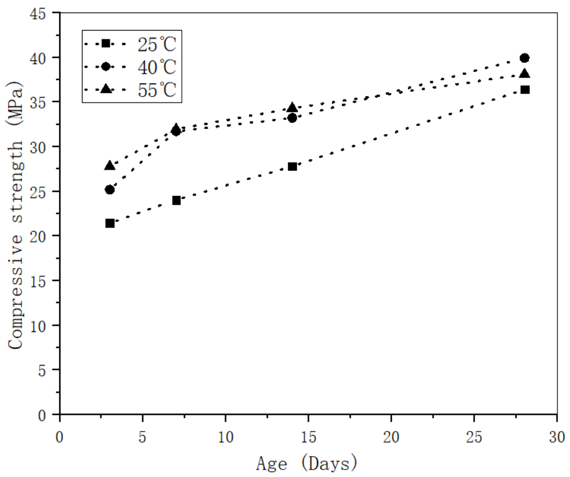
(b) Automatic curing chamber

Fig.1 Detailed demonstration of specimens curing

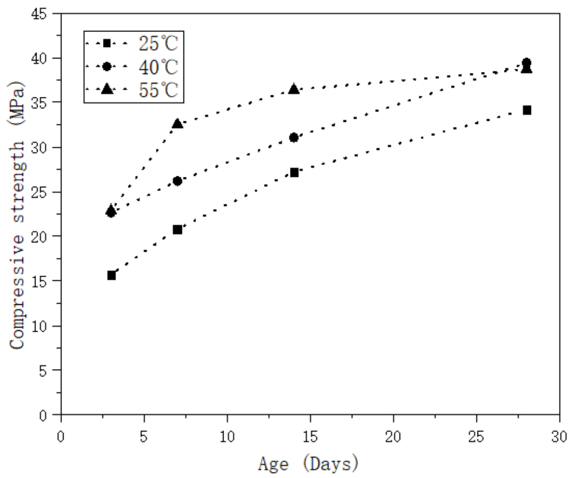
Compressive strength tests will be performed at the curing intervals of 3 days, 7 days, 14 days, and 28 days. The load shall be applied steadily and without shock such that the stress is increased at a rate of 0.6 MPa/s for all of the compressive strength tests in this study.

3. TEST RESULTS

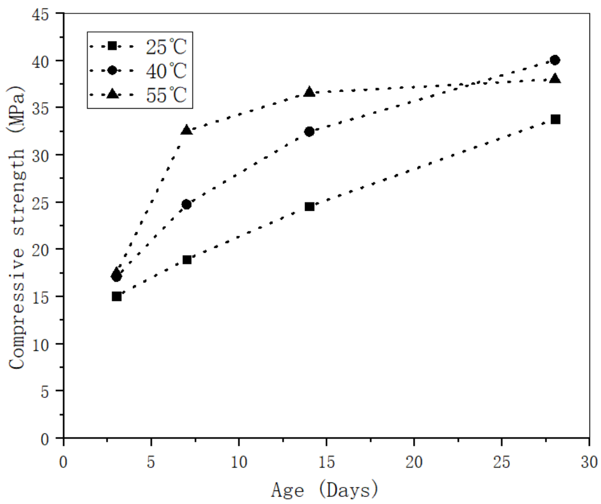
3.1 Influence of temperature



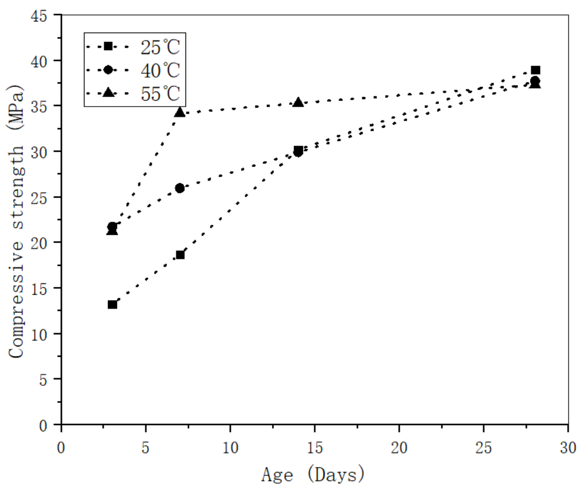
(a) Ordinary concrete (0% PFA)



(b) 25% PFA concrete



(c) 30% PFA concrete

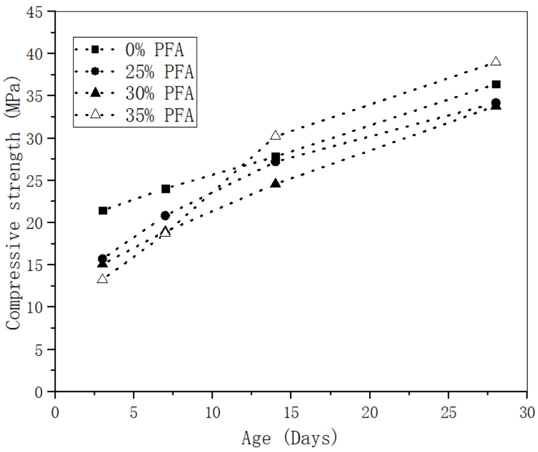


(d) 35% PFA concrete

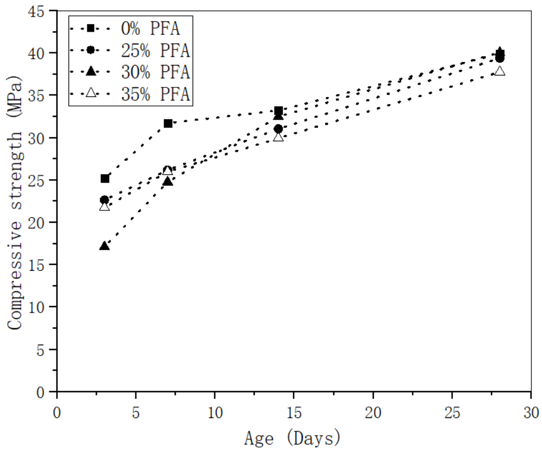
Fig.2 Compressive strengths of specimens under different temperatures

Temperature plays a pivotal role in shaping the development of compressive strength of concrete, as highlighted by the maturity theory. Understanding this relationship can enhance the effectiveness of concrete mix designs and applications, ultimately leading to stronger, more durable constructions. To investigate the influence of temperature on strength development of PFA concrete, all tested cubes were placed directly in their corresponding curing environment after casting in this project.

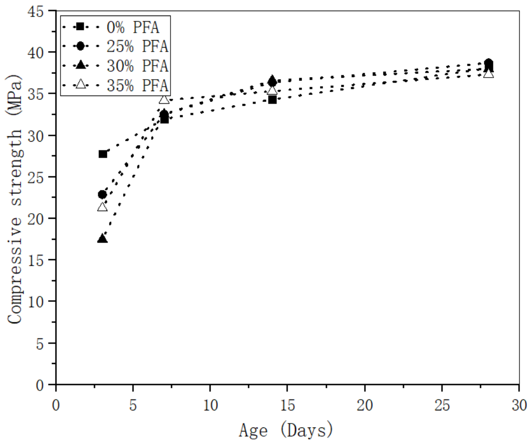
Fig. 2 illustrates the compressive strengths of the concrete specimens under different temperatures, indicating that temperature has a highly noticeable impact on the strength development of PFA concrete. Some of the salient characteristics are specifically identified and discussed in this research.



(a) Curing at 25℃



(b) Curing at 40℃



(c) Curing at 55℃

Fig. 3 Compressive strength of concrete with different PFA content

It can be seen that, when the temperature varied from 25°C to 55°C, the early-age compressive strength of concrete at low temperatures was obviously lower than that at high temperatures. Furthermore, for the 28-day compressive strength, the experimental results show that the compressive strength at 40°C is higher than that at 55°C. This is explained by the “crossover effect” which illustrates that a higher temperature at early-age can result in concretes presenting a higher initial strength and lower long-term strength.

3.2 Influence of PFA content

Fig. 3 illustrates the development of compressive strength in concrete with varying PFA content. The experimental results demonstrate that the early-age strength development of PFA concrete, particularly before the 14-day curing period, exhibits significantly lower compressive strength compared to OPC concrete. Furthermore, concrete containing 35% PFA shows markedly reduced early strength relative to its 25% PFA counterpart. These discrepancies highlight a critical limitation: traditional maturity models prove inadequate for predicting the early-strength development of fly ash concrete, necessitating the development of modified predictive frameworks.

4. MODIFIED MATURITY MODEL

4.1 Modification of the strength prediction model

The prediction of concrete strength development primarily focuses on the relationship between time and strength under varying temperatures. The fib Model Code 2010 provides a simple time-strength relationship to determine the compressive strength of concrete at various ages, as shown in Eq. (1).

$$f_{cm}(t) = \beta_{cc}(t) \times f_{cm} \tag{1}$$

$$\beta_{cc}(t) = e^{\left\{s\times\left[1-\left(\frac{28}{t}\right)^{0.5}\right]\right\}} \tag{2}$$

where $f_{cm}(t)$ is the compressive strength of concrete in MPa at a certain age t (in days); f_{cm} is the compressive strength of concrete at the age of 28 days; $\beta_{cc}(t)$ describes the compressive strength development over time; t is the concrete age in days; “s” is a coefficient related to the strength class of cement, given in fib Model Code as below.

- $f_{cm} \leq 60$ MPa, CEM 32.5 N: s = 0.38,
- $f_{cm} \leq 60$ MPa, CEM 32.5 R & 42.5 N: s = 0.25,
- $f_{cm} \leq 60$ MPa, CEM 42.5 R, 52.5 N, & 52.5 R: s = 0.2,
- $f_{cm} > 60$ MPa, all strength class: s = 0.2.

This equation allows for easy prediction of concrete compressive strength.

However, it may not be applied to fly ash concrete due to the different strength development characteristics. Therefore, in this study, the “s” values are obtained by fitting the experimental compressive strength through Eq. (1) and Eq. (2).

Vollpracht (2018) proposed the calculation of coefficient “s” with a linear function as below.

$$s = c_1 \times \frac{w}{b} + c_2 \times \frac{PFA}{b} \qquad (3)$$

where *w/b* is water-to-binder ratio and PFA/b is PFA-to-binder ratio; c_1 and c_2 are fitting parameters.

Sun (2021) proposed a new function to calculate the coefficient “s” by a Power's type function as below.

$$s = a \times X^b \qquad (4)$$

Where *X* is *w/b* ratio and PFA/b ratio of concrete; *a* and *b* are the fitting parameters of the regression analysis.

As previously mentioned, temperature has a highly noticeable impact on the strength development of concrete. The effect of temperature on the early-age compressive strength development of concrete would be carried out by calculating the equivalent age of concrete through the maturity method of concrete (Hansen 1977), which can be determined by Eq. (5). Therefore, the concrete age *t* (in days) in Eq. (2) was replaced by the equivalent age of concrete at each curing temperatures.

$$t_e = \Sigma e^{\frac{E_a}{R}(\frac{1}{T_a} - \frac{1}{T_S})} \Delta t \qquad (5)$$

where t_e is the equivalent age at the reference temperature; E_a is the apparent activation energy (J/mol); *R* is the universal gas constant (J/K·mol); T_a is the average concrete temperature over the time interval Δt (K); T_s is the specified temperature (K).

For some current models (fib 2013; ACI committee 209 2008), a constant value of 33,256 J/mol is given to the apparent activation energy (E_a) for normal strength concrete. Then, Eq. (5) is transformed into Eq. (6):

$$t_e = \Sigma e^{13.65 - [\frac{4000}{273+T}]} \Delta t \qquad (6)$$

4.2 Determination of coefficient “s”

To determine the value of coefficient “s” of each mixing proportion, the regression analyses based on Eq. (1) and Eq. (2) were utilized to fit the compressive strength at every testing age. In the fitting procedure, the f_{cm} was fixed as the 28-day test compressive strength results of the concrete reported above, and the fitting results are presented in Table 2.

Table 2 Regression analysis results of the coefficient “s”

Temperature (℃)	OPC	25% PFA	30% PFA	35% PFA
25	0.33	0.43	0.49	0.61
40	0.24	0.33	0.44	0.32
55	0.16	0.23	0.29	0.21

To further calibrate the calculation of the value of coefficient “s”, the regression analyses based on Eq. (3) and Eq. (4) were utilised. The fitting results are listed in Table 3. The results of this study presented in Table 2 show that the distribution of coefficient “s” seems to follow a nonlinear tendency with W/b ratio or PFA/b ratio, which is similar to the result obtained through the curve fitting using Eq. (3) and Eq. (4) that the fitting deviation of calculation Eq. (3) is much larger than those of calculation Eq. (4).

Table 3 Regression analysis results of curve fitting parameters

Temperature (℃)	$s = c_1 \times \frac{w}{b} + c_2 \times \frac{PFA}{b}$ Eq. (3)		$s = a \times X^b$ Eq. (4)	
	c_1	c_2	a	b
25	-0.04	1.8	1.85	1.07
40	0.5	-0.1	0.35	-0.03
55	0.43	-0.2	0.2	-0.18

4.3 Accuracy of the maturity model

Once the coefficient “s” is determined, the development of the early-age compressive strength of fly ash concrete can be predicted by substituting the coefficient “s” into Eq. (1) and Eq. (2) along with the 28-day compressive strength “f_{cm}” of concrete with different PFA/b ratios.

It should be noted that the calculated strength development with time is the strength development of concrete with its equivalent age. Therefore, the equivalent age, which is dominated by temperature, needs to be calculated first. After calculating by Eq. (1) to Eq. (6), the predicted compressive strengths were compared to the measured compressive strengths of the specimens with different PFA/b ratios.

A significant positive correlation exists between the predicted and measured compressive strengths. Regardless of the temperature and PFA/b ratio, there is a good agreement between the experimental compressive strength of the concrete and the predicted strength. The results indicate that the modified maturity model presents good prediction accuracy.

5. CONCLUSION

The effect of temperature on early-age compressive strength development of fly ash concrete was studied in this project. Based on the analysis of the test results and the comparison with the predicted results of the modified maturity model, the following conclusions are drawn.

(a) The temperature has a significant effect on the compressive strength development of concrete. The early-age compressive strength of concrete at high temperatures was obviously higher than that at low temperatures. It should be noted that excessive temperature at the early age can result in concretes presenting a higher initial strength and lower long-term strength.

(b) The partial replacement of ordinary Portland cement with fly ash reduces the early strength of concrete, and the reduction in early strength is more pronounced in concrete with 35% PFA.

(c) An exponential function was applied to modify the coefficient “s” in the fib Model Code 2010 model, and the correlation between “s” and varying fly ash content in concrete can be effectively established. Comparative analysis demonstrates that the modified maturity model exhibits good predictive accuracy for early-age strength development in fly ash concrete.

6. ACKNOWLEDGEMENT

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