EXPERIMENTAL PREDICTION OF TEMPERATURE RISE OF MASS CONCRETE BASING ON SEMI-ADIABATIC TEST

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ABSTRACT

For hot weather construction, the maximum temperature rise in massive concrete structure due to cement heat of hydration can be extremely high leading to the risk of thermal cracks. Therefore, it is important to reduce the rate of hydration and maximum temperature rise during early hydration of mass concrete. This paper investigated the temperature rise due to heat of hydration of concrete containing low-heat Portland cement and silica fume (SF). Time-temperature curves of 3 concrete mixtures were recorded in adiabatic and semi-adiabatic conditions. Semi-adiabatic tests were conducted by using a commercially available calorimeter, while a dry-oven was used to provide adiabatic environment for the adiabatic test. Trend-lines of temperature rise in semi-adiabatic and adiabatic conditions were analysed and compared to each other. The results showed that the use of silica fume increased the reaction rate of temperature rise in both semi-adiabatic and adiabatic tests. Correlations between test results from semi-adiabatic and adiabatic tests were strong and can be used to predict the concrete adiabatic temperature rise.

Keywords: mass concrete, adiabatic, semi-adiabatic, heat of hydration, low-heat Portland cement, silica fume

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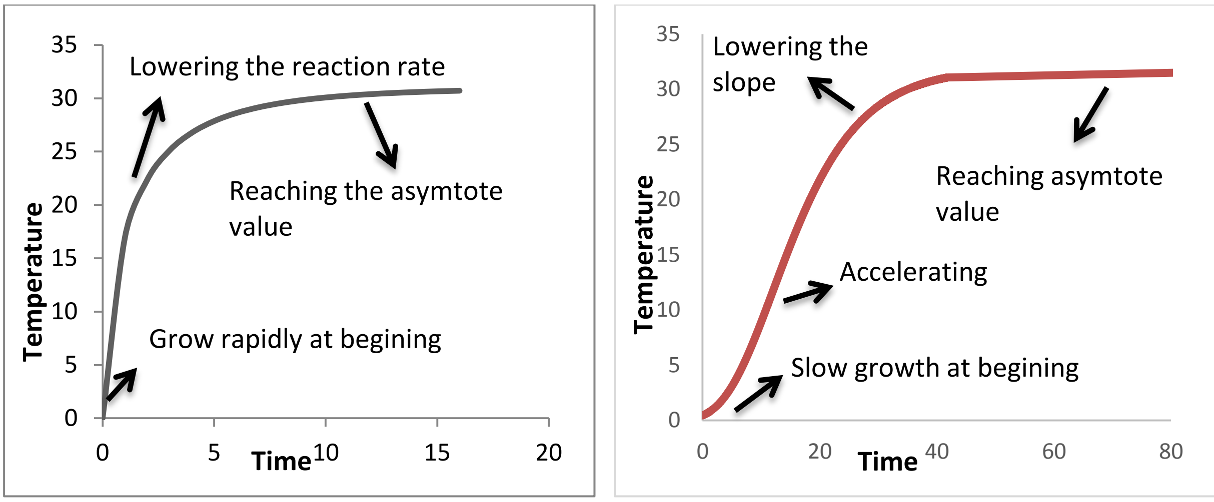
1. INTRODUCTION

In terms of large concrete structure construction, mass-concrete placement is difficult to be avoided. Apparently, the cement heat of hydration will be accumulated inside the concrete structure creating a temperature difference between the concrete's core and concrete's surface. Especially for hot weather concreting, the high initial temperature of concrete due to the solar radiation increases the reaction rate of cement hydration [1]. Hence, the peak temperature rise of concrete also increases significantly. As a result, thermal cracking may appear and affect the durability of concrete.



a. Growing rapidly at begining b. Growing slowly at beginning

Figure 1. Adiabatic temperature rise curve of concrete

There are numerous studies about predicting the adiabatic temperature rise of mass concrete. The adiabatic temperature rise of concrete is the measurement of the temperature rise of concrete in the early hydration period, in which the temperature loss of the sample is less than 0.02 K/h [2]. Therefore, the temperature rise in the adiabatic test increases gradually until it reaches the asymptote maximum temperature. For many years, well-known empirical equations to predict the concrete adiabatic temperature rise were constructed based on exponential functions or hyperbolic functions [3,4] as follow:

$$\theta_\tau = \theta_0(1 - e^{-m\tau}) \quad \text{(exponential formula)} \tag{1}$$

$$\theta_\tau = \frac{\theta_0 \tau}{n\tau} \quad \text{(hyperbolic formula)} \tag{2}$$

$$\theta_\tau = \theta_0(1 - e^{-a\tau^b}) \text{ (complex exponential formula)} \tag{3}$$

Where θ_τ is the adiabatic temperature at time τ, θ_0 is the maximum adiabatic temperature, a, b, m, n are constants which can be obtained from experiments. These formulas and some modified equations related to them had been used to study the properties of concrete adiabatic temperature rise in numerous studies [5,6,7] or had been suggested in technical guideline [8]. The depiction of adiabatic temperature rise based on these formulas is presented in Figure 1.a, in which the temperature increases rapidly at the beginning. However, in other to reduce the maximum temperature rise inside the large volume concrete structure, low-heat cement or low-content cement is widely used in concrete proportions. Furthermore, the use of retarding admixtures is popular in other to prevent slump loss during transporting. Therefore, the initial reaction rate of concrete adiabatic temperature rise can be very slow (Figure 1.b) leading to the need of finding fitting models for illustrating the slow reaction rate of concrete at the beginning.

The semi-adiabatic temperature rise test (semi-test) is a procedure to measure the concrete sample temperature history in the early hydration period. In contrast to truly adiabatic temperature rise test, the semi-test allows heat loss to occur but it has to be less than 100J/(h.K) [2]. The test procedure is less complicated than the adiabatic temperature rise test and the temperature curve can give good estimations about the hydration process. Figure 2 depicts the temperature rise in semi-adiabatic condition of concrete. After an initial rise due to the hydration of aluminates (C_3A), the dormancy period appears because of the interaction of gypsum and C_3A. This dormancy period extents with the increase of retarding admixture or the use of supplementary materials such as fly ash to replace cement. It seems reasonable that the long retarding period in the semi-test commensurate with the slow growth at beginning in adiabatic test.

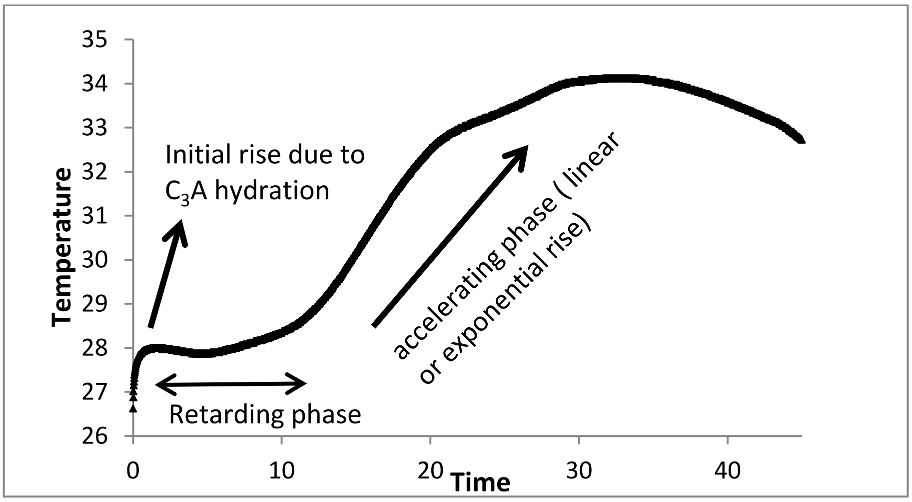


Figure 2. Depiction of temperature rise in semi-adiabatic test

The use of low-heat portland cement or fly ash in mass concrete proportion bring a lot of advantages in preventing thermal cracking. However, the low degree of hydration affects the compressive strength in early ages. Using SF to replace cement can significantly increase the concrete compressive strength, especially in early ages[9,10]. At 7 days, 5% of SF using cement replacement can increase the compressive strength of high volume fly ash concrete to 5%, while 10% of SF which replaced cement increased its compressive strength to 6%[11]. But the pozzolanic reaction of silica fume with $Ca(OH)_2$ is exothermic. The cumulative hydration heat of concrete with 10% SF as cement replacement was higher than reference concrete [12]. Therefore, the dosage of SF in mass concrete should be in an appropriate range to benefit both criteria, the compressive strength and concrete heat of hydration requirements.

In this study, the adiabatic temperature rise and semi-adiabatic temperature rise test were conducted on concrete containing moderate low-heat PC cement with or without silica fume. The adiabatic temperature rise will be analyzed based on the concept of Gompertz equation which can illustrate the slow reaction rate at the beginning of the temperature rise. The aims of this study were to analyze the trend-lines of temperature rise from both tests and propose a method to predict the adiabatic temperature rise by using results from semi-adiabatic test.

2. EXPERIMENTAL PROGRAM

2.1 Material and mix proportions

The experimental study was carried out on concrete containing moderate Low-heat Portland cement and silica fume (SF). Crushed stone (D_{max} = 20mm) was used as coarse aggregate, crushed sand and river sand were used as fine aggregate. Three concrete mixtures were designed in compliance with the ACI 211.1-91 (Table 1). Control mix was the mixture without the use of SF, the SF-Adding represented that SF was added to the mixture at 4% of the total binder mass while the SF-Replacing represented that the cement was replaced by 4% of SF (by mass). Heat of hydration of moderate low-heat Portland cement was 298 kJ/kg at 28 days and the chemical compositions of cement and silica fume are presented in Table 2.

Table 1. Concrete mixture proportions

Mix Name	Binder Kg/m^3	Cement kg/m^3	SF %	Water to Binder ratio
Control	450	450	0	0.35
SF-Adding	468	450	4%	0.35
SF-Replacing	450	432	4%	0.35

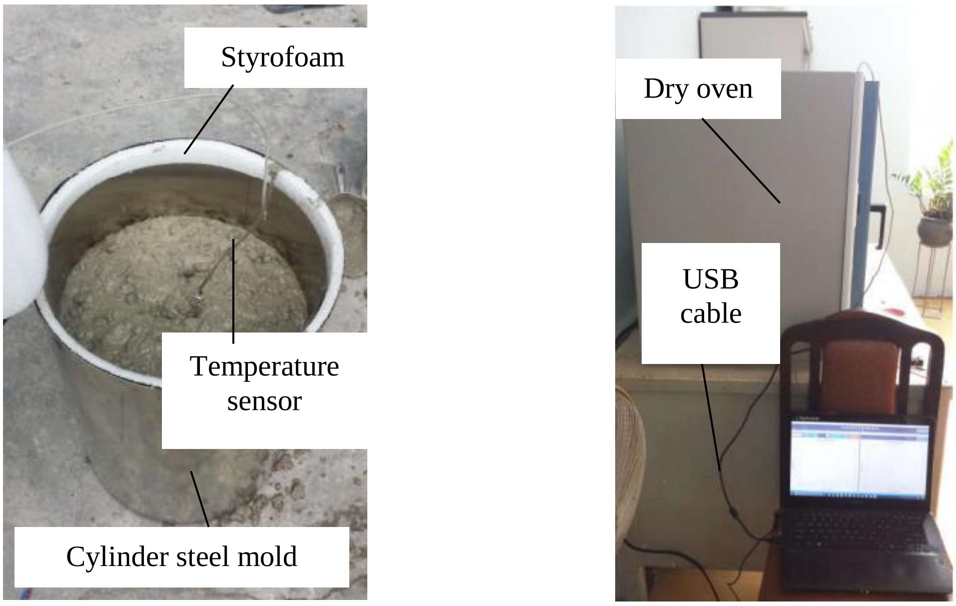
Table 2. Chemical compositions of cement and silica fume

Composition (%)	Moderate Low-heat Portland cement	Silica fume (SF)
SiO_2	28.98	93.4
Al_2O_3	11.57	0.45
Fe_2O_3	2.57	0.25
CaO	48.31	-
MgO	4.12	0.79
SO_3	2.53	0.46
K_2O	0.15	1.27
Na_2O	0.28	0.61
C	-	0.45
LOI	0.74	2
Insoluble residue content	0.75	-

2.2 Testing methods

2.2.1 Adiabatic temperature rise test.

The concrete adiabatic testing times were last for around 4 days for each concrete mixture. The container of the concrete sample has a cylinder shape with a volume of 30 litters. Styrofoam was used as a heat-insulating layer which put inside and around the cylinder container. Concrete after mixing will be poured immediately inside the container and the temperature of the sample will be recorded by using a temperature measurement sensor that is placed at the centre of the concrete cylinder sample. To provide the adiabatic environment for the test, the cylinder container was placed inside a dry oven which was already programmed to provide the same temperature as the temperature inside the centre of the sample. Initial temperatures of fresh concrete after mixing were controlled from 29^{o}C to under 30^{o}C.



a. Concrete sample

b. Recording temperature rise of concrete sample

Figure 3. Adiabatic temperature rise test

2.2.2 Semi-adiabatic temperature rise test

The semi-test was conducted with the support of a commercially available calorimeter (F-Cal 4000). The concrete samples after mixing were poured into plastic bags and placed inside the channels of the calorimeter. The thermal sensors placed at the bottom of each channel recorded the temperature of the concrete sample. The duration time for this experiment was around 2 days and all temperature rise data can be observed anytime by using the USB cable to connect the calorimeter with the personal computer (Figure 4). The semi-adiabatic device was placed in a room with constant temperature at 28^{o}C.

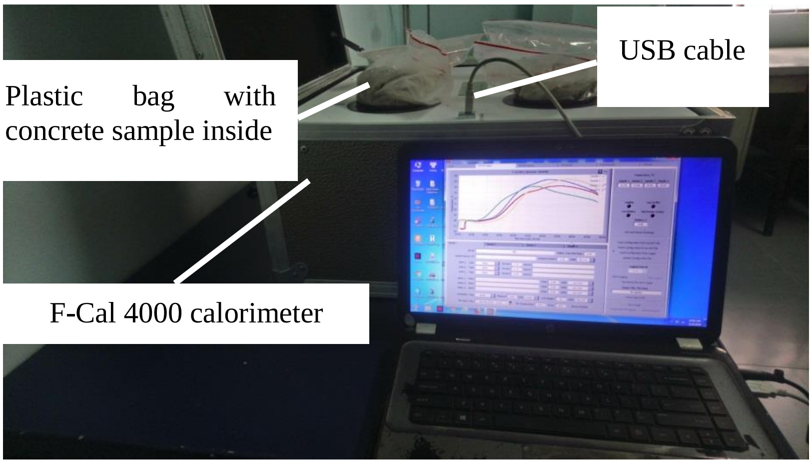


Figure 4. Semi-adiabatic test

2.3 Gompertz curve formula

The mathematic formula used in this study for analysing the raw data of adiabatic temperature rise was the Gompertz formula. This formula describes the slow growth at the begin time following by an accelerating period and then reaching the maximum adiabatic temperature rise. The equation is as follow [13]:

$$T_a = T_m e^{-be^{-ct}} \tag{4}$$

Where T_a is the adiabatic temperature rise at time t, T_m is the peak temperature value, e is the Euler's number (e=2.71828), b, and c are constants describing the rate of temperature rise. The T_m, b and c are determined by experiment and have the relationship as follow:

Time to reach peak rate of temperature rise:

$$t_i = \frac{lnb}{c} \tag{5}$$

Peak rate at time t_i:

$$R_m = \frac{T_m c}{e} \tag{6}$$

Growth-rate:

$$R = cT_a ln\frac{T_m}{T_a} \tag{7}$$

By substituting experimental data from the adiabatic test into Eq. (4), the raw data can be converted into the Gompertz curve. As the Gompertz curve inflects at t_i (see Figure 5) [14], it is promising to apply this formula for the concrete adiabatic temperature rise if the raw data of concrete adiabatic temperature rise also inflects around this point. The disadvantage of this method in studying the adiabatic temperature rise of concrete is that the equation cannot equal to "0" because of the natural mathematic of itself, the study on reproducing the equation to a modified one should be done in the future to make the adiabatic temperature rise based on Gompertz equation become more accurate.

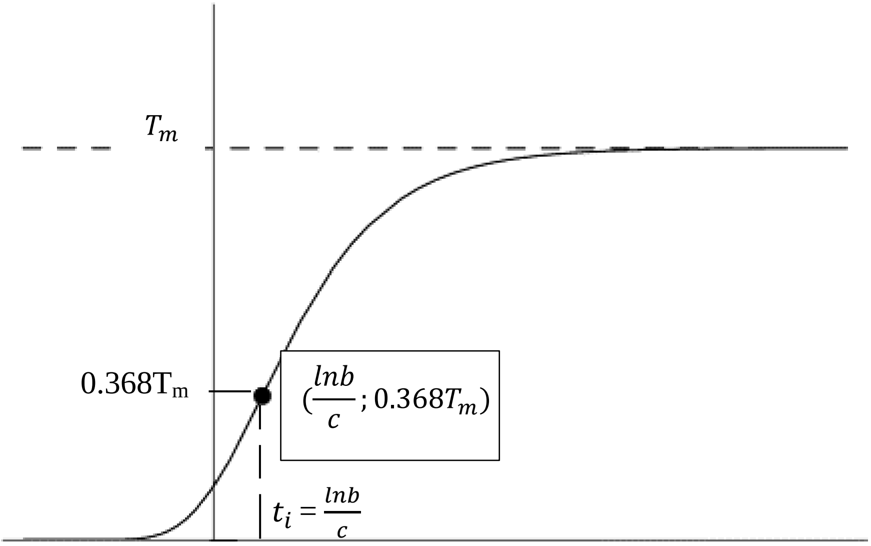
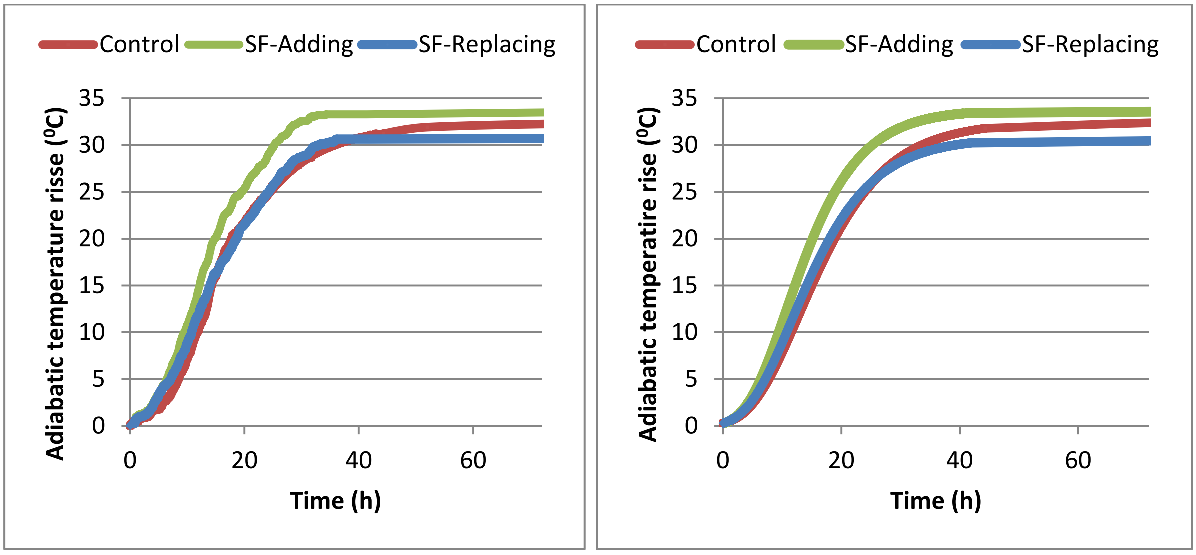


Figure 5. Inflection point in Gompertz Curve

3. RESULTS AND DISCUSSION

3.1 Concrete adiabatic temperature rise

The temperature rises of concrete in adiabatic tests were showed in Figure 6a. Comparing with the Control-mix, the mixture adding 4% of SF experienced the higher value of maximum temperature rise (33.8°C) while using 4%SF as cement replacement showed the lowest temperature rise (30.88°C). Because the binder content is the major factor influencing the adiabatic temperature rise of concrete [15], the results were logical and can be explained by the fact that adding SF made the grain matrix become denser , hence, reducing the distance of binder particles. The hydrated products formed on the surface of cement and silica fume grains just need to grow in a very short distance to reach the adjacent cement particle [16]. As a result, it increases the rate of temperature rise and the peak value of temperature during cement hydration. In terms of the mixture using 4%SF as cement replacement, the effect of SF in increasing the rate of hydration process was easy to be observed at the beginning due to its physical effect on creating nucleation site [17]. However, the lower content of cement in concrete proportion comparing to other mixtures made it rise at a slower rate in the later time. At the end, it reached the lowest peak adiabatic temperature.



a. Raw data

b. Fiting curves by using Gompertz equation

Figure 6. Adiabatic temperature rise results

By applying the least square method, the temperature rise can be expressed by Gompertz equation. The coefficients to construct the curve for each concrete mixture are presented in Table 2 and the Gompertz curves are presented in Figure 6b.

Table 2. Gompertz curve coefficients

	Equation: $T_a = T_m e^{-be^{-ct}}$		
	T_m	b	c
Control	32.5	4.817931	0.121704
SF-Adding	33.8	4.88961	0.147243
SF-Replacing	30.8	4.691538	0.132429

Figure 6 showed that the adiabatic temperature rises had the S-Shape curves and it is difficult to determine the inflection point (Figure 5). Using Eq. (7) to create growth-rate graphs of concrete adiabatic temperature rise (Figure 7), the highest value of growth-rate was belonged to the SF-Adding (1.83) with the shortest time to reach the peak rate (10.77 hours). It means that the temperature rise of SF-Adding will inflect after 10.77 hours. The sooner to reach this point, the sooner the temperature rise will reach the asymptote peak adiabatic temperature. The Control-mix experienced the longest duration (12.9 hours) for reaching the peak rate (1.46). The SF-Replacing showed a shorter time to reach the peak value (11.67 hours) and higher peak value (1.50) comparing to the Control mix.

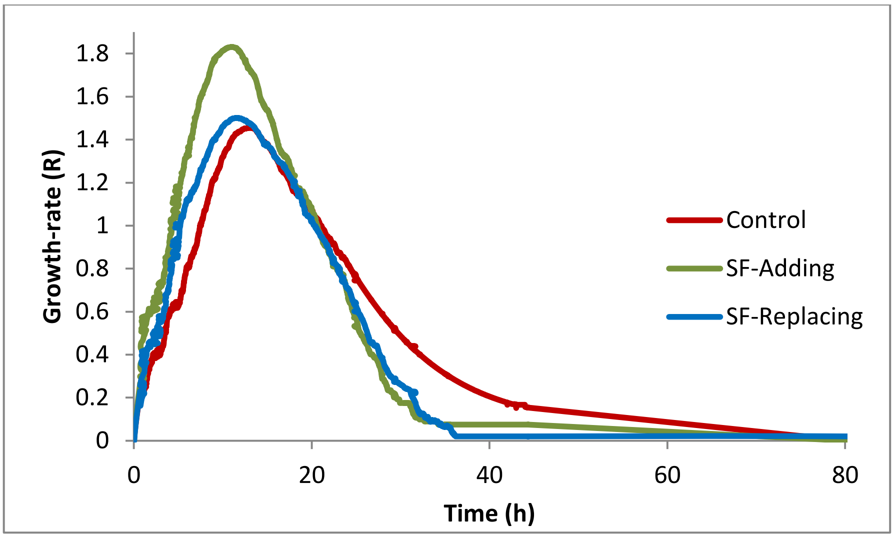


Figure 7. Growth-rate of adiabatic temperature rise

3.2 Semi-adiabatic temperature rise

The semi-adiabatic results of 3 mixtures are shown in Figure 8. With the highest content of binder, the SF-Adding experienced the highest maximum value of temperature (35.23^{0}C), following by the Control-mix with 34.76^{0}C. The SF-Replacing showed the lowest peak temperature (34.12^{0}C). Time to reach the peak temperature, as well as reaction rate of each mixture, were showed in Table 3. The effect of SF on promoting cement hydration was clearly observed. The Control mix with no SF experienced the longest duration of the retarding phase while the SF-Replacing and SF-Adding turned from the retarding phase to the accelerating phase sooner than the Control mix. Time to reach temperature rise was quicker for the mixture had SF, especially the SF-Adding mix.

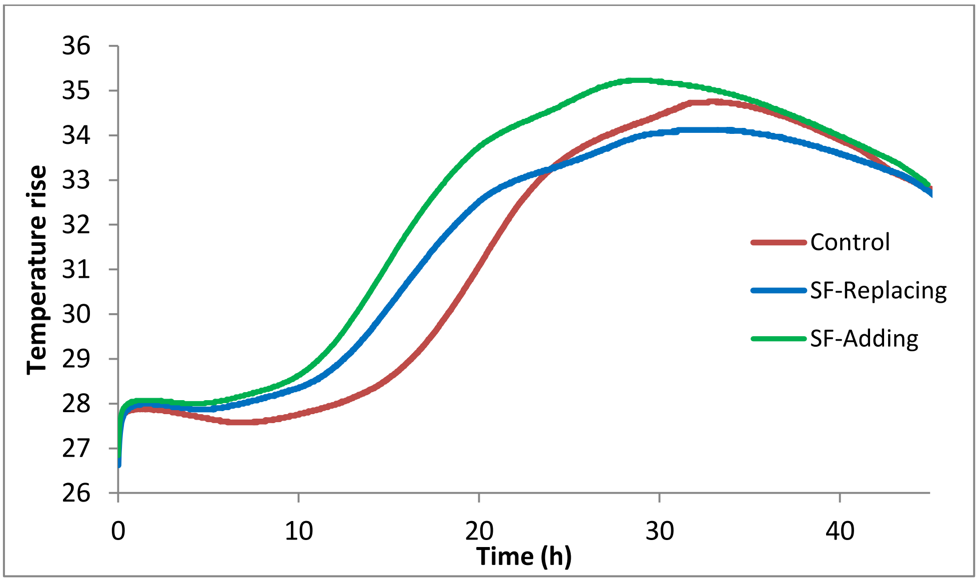


Figure 8. Semi-adiabatic temperature rise

Table 3. Results of Semi-adiabatic temperature rise

	Time to reach peak temperature value (h)	Reaction rate (^{o}C/h)	Temperature rise (^{o}C)
Control	32.7	0.238	7.9

SF-Adding	28.4	0.291	8.39
SF-Replacing	31.1	0.241	7.5

As the semi-adiabatic curves were too complicated to be modeled by using a mathematical function, the reaction rate of the semi-test will be simply calculated by dividing *the peak temperature rise value* to *the time to reach peak temperature value*. Similar to the peak growth-rate in the adiabatic test, the reaction rate of the semi-test experienced the highest value at the SF-Adding (0.291^{o}C/h). The SF-Replacing placed at second with the value of 0.241^{o}C/h and the Control mixture slightly placed below the SF-Replacing with the reaction rate of 0.238^{o}C/h.

3.3 Comparison between adiabatic test and semi-adiabatic test results

3.3.1 Peak temperature rise

The results of temperature rise in both tests were related as shown in Figure 9. Higher temperature results in semi-adiabatic tests led to higher results in adiabatic tests. The linear function with a very high R^2-value indicated that the results of the semi-test were possible to predict the adiabatic temperature rise of the concrete sample. The same results were also observed from a previous study [7], in which the researchers proposed a strong correlation (R^2 = 0.99) between the concrete adiabatic temperature rise and mortar semi-adiabatic temperature rise. As all the semi-tests were controlled in the same condition such as curing, heat loss to the environment, concrete weight, room temperature, the results among semi-test mixtures were relevant to compare to each other, and can be used to create good estimation to the adiabatic temperature rise.

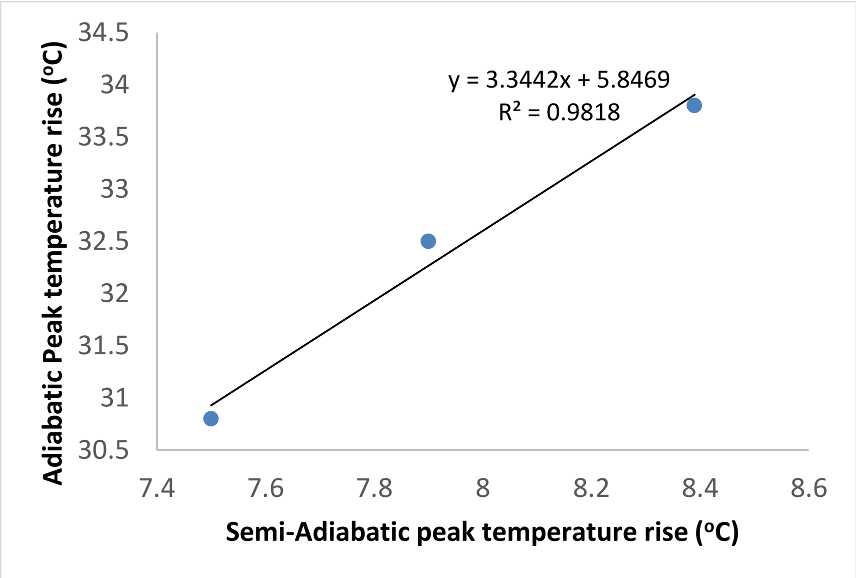


Figure 9. Correlation between peak temperature in both test

3.3.2 Peak growth-rate in adiabatic test vs. Reaction rate in semi-test

The maximum rate of increase of Gompertz curve is a function of peak temperature and the rate of temperature rise as shown in Eq. (6). As can be seen in Figure 6 and Figure 7, higher value in the maximum rate of increase of the SF-Adding made its adiabatic curve grow more steeply and reach a higher value of asymptote adiabatic temperature than the Control and SF-Replacing. In terms of semi-test, the reaction rate can be simply presented as an average of reaction over a time interval. Calculation of reaction rate and maximum rate of increase involved the peak temperature rise from semi-test and adiabatic test, respectively. The relationship between the reaction rate of the adiabatic and semi-adiabatic test are presented in Figure 10. As the values of reaction rates in the semi-test were commensurate with the maximum rate of increase in adiabatic test in a strong linear manner, it is promising that the semi-test can be used to illustrate the growth-rate of the adiabatic test.

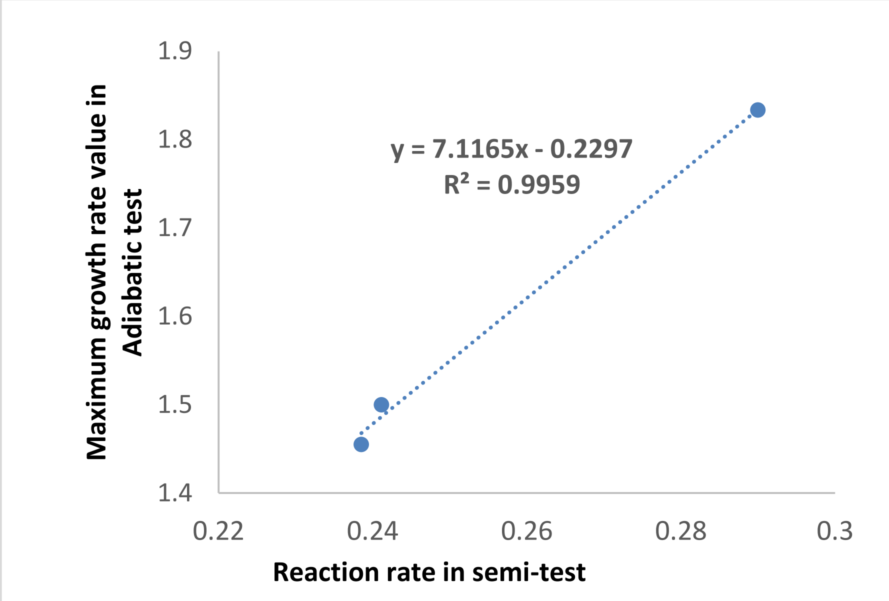


Figure 10. Peak growth-rate in adiabatic test vs. Reaction rate in semi-test

3.3.3 *Time to reach peak growth-rate vs. Time to reach peak temperature rise in semi-test*

Besides that, as the maximum rate of increase of Gompertz curve is also the point of inflection, the time to reach the maximum rate of the increase reflects how long it takes the rising curve to reach its maximum value. Figure 11 shows the correlation between the points of the maximum rate of increase in the adiabatic test with the durations to reach peak temperature rise in the semi-test given the result of high R^2-value (0.94). Otherwise speaking, a shorter period of reaching peak temperature in the semi-test resulted in a shorter duration to reach the maximum growth-rate in the adiabatic tests. The reaction rate of concrete adiabatic temperature rise will be increased as it took a shorter time to reach the maximum adiabatic temperature.

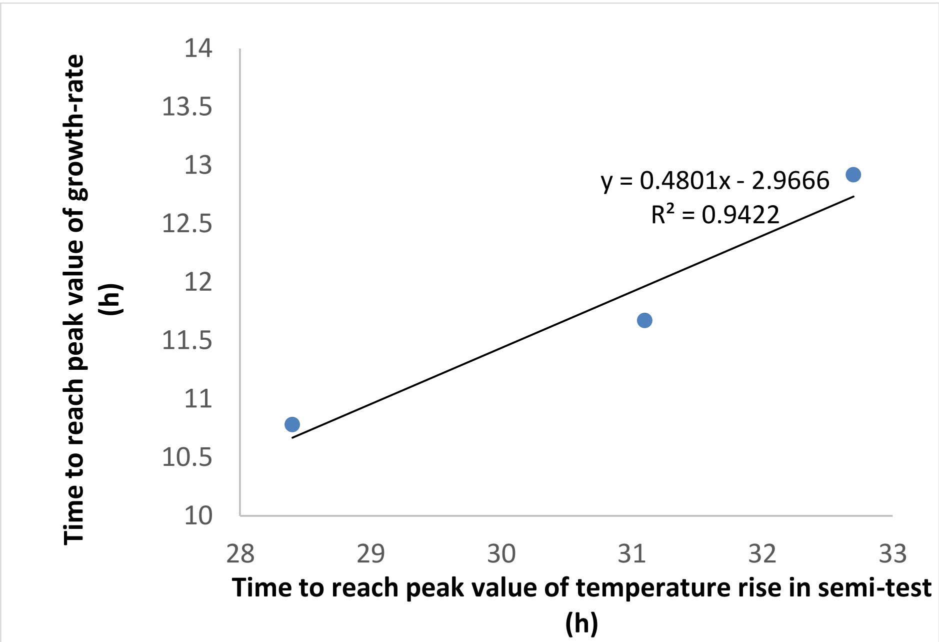


Figure 11. Time to reach peak growth-rate vs. Time to reach peak temperature rise in semi-test

3.4 Prediction method of concrete adiabatic temperature rise based on semi-test data

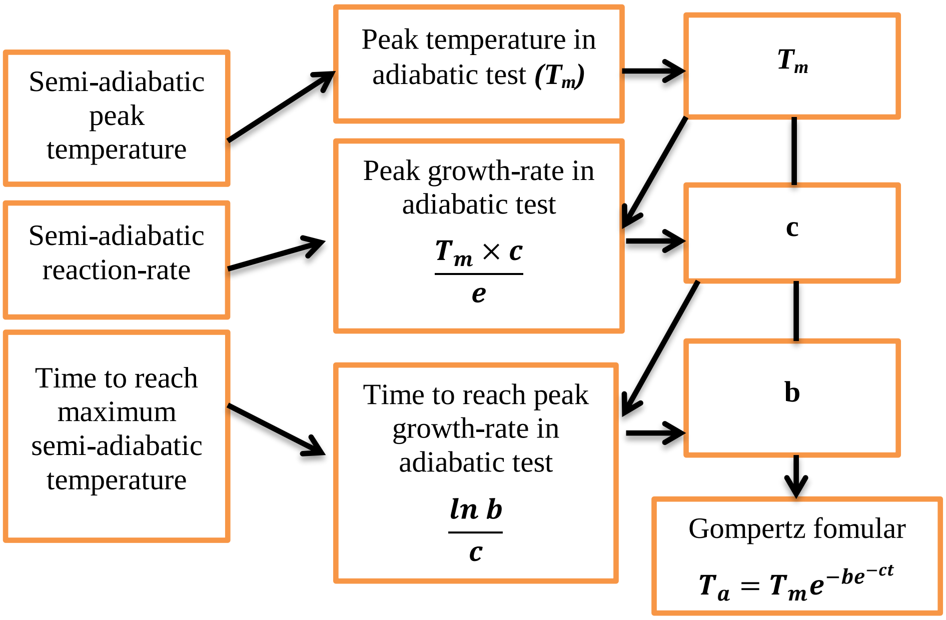


Figure 12. Proposed method for predicting concrete adiabatic temperature rise based on semi-test

Figure 12 presents the proposed method for predicting the adiabatic temperature rise of concrete based on Gompertz function. All the semi-test results can be converted to parameters of adiabatic temperature rise by using the correlations that have been created. Finally, all the constants of the Gompertz curve (T_m, b, c) could be obtained. The result is expected to apply in concrete proportion using low-heat cement and high-volume fly ash cement because these concrete proportions can produce the S-Shape of the adiabatic temperature-time curve based on Gompertz function. It is concerning that more investigations should be carried to strengthen the correlation between two test results in other to make this prediction method become applicable in the future.

4. CONCLUSIONS

By investigating the trend-line development of concrete temperature rise in adiabatic and semi-adiabatic conditions, the following conclusions could be drawn:

- Silica fume was the main factor influencing the reaction rate of both test conditions. Meanwhile, the peak temperature rise values were attributed mostly by the binder content.
- Semi-adiabatic test and adiabatic test showed strong correlations in terms of the maximum value of temperature rise and the reaction rate. The results might be applied for concrete proportions that produce a low degree of hydration when using low-heat cement or high volume of class-F fly ash. Concrete with high content of cement is not recommended as its adiabatic temperature rise curve may not suitable to apply the Gompertz equation.
- Gompertz equation can be significantly used to construct the concrete adiabatic temperature rise. As a disadvantage of this function is that the temperature value cannot be "0" at a time "t=0", future research can focus on creating modified Gompertz equation for prediction of concrete adiabatic temperature rise.
- The proposed method to predict adiabatic temperature rise was promising if the correlation between both test methods could be strengthened.

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