EXPERIMENTAL DETERMINATION OF ADIABATIC TEMPERATURE RISE AND HYDRATION PARAMETERS FOR CONCRETE

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Abstract: *In this study, adiabatic temperature rise for three normal-strength concrete mixtures were experimentally determined using an adiabatic calorimeter. The hydration parameters including the time (τ) and slope (β) parameters, and the total heat (Q_c) of the concrete samples were also computed using the measured adiabatic temperature rise and the curve fitting method. The results show that the degree of hydration increases with the decrease of the w/c ratio in the mixture. The heat of hydration parameters can be used as inputs in numerical models for predicting temperature and stress development in a concrete structures such as bridge piers, footings, decks, and box girder segments. The methodology and the hydration parameters for concrete are of great significance for civil engineers in the design and construction of modern concrete materials (e.g., high-strength and high-performance concrete) for minimizing risk of cracking in the structures and optimizing the construction schedules.*

Keywords: *Porland cement concrete, adiabatic temperature rise, adiabatic calorimeter, heat of hydration parameters, degree of hydration, total heat, activation energy*

Received: 22/05/2020 Accepted: 1/06/2020 Published online: 14/06/2020

1. INTRODUCTION

Portland cement concrete is a widely used construction material all over the world. Its service life relates to its mechanical strength, durability and serviceability. The selection of appropriate raw materials and mix proportions is a vital key for producing concrete that can meet strength and durability requirements. In order to achieve a high-quality concrete, its early-age properties need to be seriously considered and adequate curing schemes should be implemented [1-4]. The "early age" is the first few days after concrete casting, which are characterized by two main processes: setting (progressive loss of fluidity) and hardening (gaining strength). During these processes, the fluid multiphase structure of the fresh concrete transforms into a hardened structure due to the progress of hydration reactions, leading to the development of mechanical properties, heat liberation and deformations [1].

During cement hydration, heat is generated causing an internal temperature rise in concrete. If the concrete dimensions are large enough to require that measures be taken to cope with the heat from cement hydration and attendant volume change, and to minimize cracking, the concrete is called mass concrete [5,6]. Therefore, the determination of heat of hydration is essential to evaluate the temperature evolution, early-age thermal stress and associated cracking risk in concrete structures [7-12].

This study aimed to experimentally determine the adiabatic temperature rise (ATR) and the heat rate during cement hydration for several normal concrete mixes used in bridge construction in Vietnam. The hydration parameters such as time and shape parameters (τ and β, respectively) for the concrete mixes were then determined and compared. These hydration parameters are key inputs used in numerical models for predicting temperature, thermal stresses and cracking risk in concrete bridge structures. They can also be effectively used in temperature control of concrete during construction in order to ensure its integrity and long-term durability.

2. MATERIALS AND METHODS

2.1. Materials

The compositions of the three concrete mix designs used in the experiment are shown in Table 1. The chemical and mineralogical compositions of the cement are listed in Tables 2 and 3, respectively. The chemical admixture “Sika ViscoCrete-8900” was used that meets requirement of ASTM C494 Type F (High Range Water Reducing admixture) [13].

Table 1. *Mix design for concrete (kg/m^3)*

Mixture	w/c	Water	Cement	Coarse aggregate	Sand	HRWR (l)
Mix 1	0.50	167	332	1017	862	2.66
Mix 2	0.44	167	378	1017	822	3.02
Mix 3	0.40	167	417	1162	677	3.34

HRWR = High Range Water Reducing admixture; w/c= water-to-cement content ratio

Table 2. *Cement chemical composition (%)*

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O_{eq}	Blaine (m^2/kg)
Amount	21.49	5.40	3.49	63.56	1.40	1.65	0.15	0.70	0.61	375

Table 3. *Mineralogical composition of cement (%)*

Phase	C_3S	C_2S	C_3A	C_4AF
Amount	51.74	24.2	8.16	10.35

2.2. Adiabatic Temperature Rise Testing

The concrete mixes were tested to obtain the adiabatic temperature rise (ATR). The ATR was measured using an adiabatic calorimeter developed by the authors based on the concept described by Gibbon et al. (1997) [14] and improved by Lin and Chen (2015) [15]. The basic principle of adiabatic calorimetry is to keep the concrete sample temperature and the ambient temperature the same by minimizing the heat exchange. The adiabatic calorimeter, sketched in Figure 1, automatically matches the water temperature with the concrete sample temperature in order to remain the hydration heat unchanged. There are 2 Resistance Temperature Detectors (RTD) sensors that continuously measure the concrete sample and the water temperatures at 10 Hz frequency. Two heaters will automatically turn on and off based on the difference between the water and the sample temperatures (0.1°C in this set up). The system, therefore, is very close to an adiabatic condition that can obtain ATR of the concrete sample. The adiabatic calorimeter developed at the University of Transport and Communications, Vietnam is shown in Figure 2 [16].

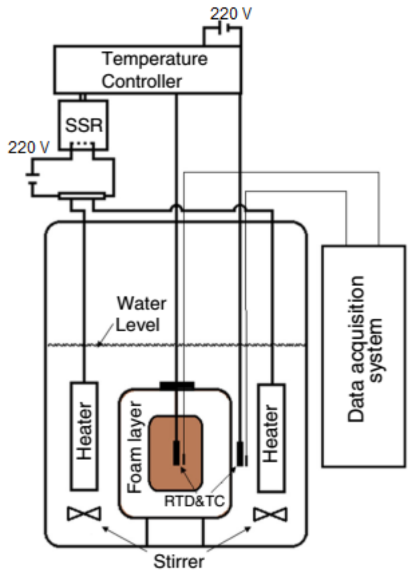


Figure 1. *Schematic diagram of adiabatic calorimeter (Lin and Chen, 2015)*

Figure 2. *Placing concrete sample in adiabatic calorimeter.*

During the hydration, the rate of heat of hydration depends on temperature of the concrete. Higher temperature accelerates the rate of the cementitious material hydration reactions. Van Breugel [17] and Schindler and Folliard [18] reported that the cement degree of hydration was proportional to the heat released, as shown in Eq. (1):

$$\alpha(t) = \frac{H(t)}{H_u} \tag{1}$$

where $\alpha(t)$ is the degree of hydration, H(t) is the cumulative heat released by the cement (J/g), and H_u is the total heat available for reaction (J/g) as calculated from the cementitious properties in Eq. (2) and (3):

$$H_u = H_{cem} p_{cem} + 461 p_{slag} + 1800 p_{FA} p_{FA-CaO} \tag{2}$$

$$H_{cem} = 500 p_{C_3S} + 260 p_{C_2S} + 866 p_{C_3A} + 420 p_{C_4AF} + 624 p_{SO_3} + 1186 p_{FreeCa} + 850 p_{MgO} \tag{3}$$

where H_{cem} = total heat of hydration of the cement (J/g); p_{FA} = percentage of fly ash in the cementitious materials; p_X = percentage of *X* component in the cement (cem = cement, C_3A, C_4AF, SO_3, MgO); $p_{FA\text{-}CaO}$ = percentage of CaO in fly ash; and p_{slag} = percentage of slag in the cementitious materials.

A mathematical (three-parameter) degree of hydration model expressed in Eq. (4) [19] has been effectively used to estimate temperature evolution in concrete since it incorporates the temperature effect via the equivalent age.

$$\alpha(t_e) = \alpha_u \exp\left(-\left[\frac{\tau}{t_e} \right]^{\beta} \right) \tag{4}$$

where $\alpha_u = \frac{1.031 w/c}{0.194 + \mathrm{w}/c}$ is ultimate degree of hydration [20]; τ and β = hydration parameters; and t_e = equivalent age of concrete (h) (or maturity), as described in Eq. (5) [21]:

$$t_e = \int_0^t \exp\left(\frac{E_a}{R} \left(\frac{1}{T_r} - \frac{1}{T_c(t)} \right) \right) dt \tag{5}$$

where E_a = apparent activation energy (J/mol), estimated from the chemical composition using Eq. (6) [22]; *R* = universal gas constant (8.314 J/mol-K); $T_c(t)$ = concrete temperature (K); and T_r = reference temperature (K).

$$\begin{aligned} E_a &= 41230 + 1416000\left(p_{C_3A} + p_{C_4AF} \right) p_{cem} p_{SO_3} p_{cem} - 347000 p_{Na_2O_{eq}} \\ &-19.8 Blaine + 29600 p_{\mathrm{FA}} p_{\mathrm{FA\text{-}CaO}} + 16200 p_{slag} - 51600 p_{SF} \end{aligned} \tag{6}$$

where p_{SF} = percentage of silica fume in the cementitious materials; Blaine = fineness of cement (m^2/kg); p_X = percentage of *X* component in the cement (cem = cement, C_3A, C_4AF, SO_3); and p_{Na2Oeq} = percentage of Na_2O_{eq} in cement (0.658 × %K_2O + %Na_2O).

In order to use the hydration model in Eq. (4), the α_u, τ, and β parameters are determined by fitting Eq. (4) with the calculated degree of hydration from the measured ATR. The cumulative heat of hydration for plugging into Eq. (2) for the computation of the degree of hydration can be derived using Eq. (7):

$$H(t) = \frac{m_s}{m_{cm}} c_p T(t) \tag{7}$$

where m_s = mass of the concrete test sample; m_{cm} = mass of the cementitious materials in the sample; and $T(t)$ = experimental adiabatic temperature rise.

The cumulative heat released $Q(t_e)$ can be calculated from the degree of hydration $\alpha(t_e)$ as shown in Eq. (8). The heat rate then can be computed using Eqs. (9) and (10).

$$Q(t_e) = Q_c.\alpha(t_e) \tag{8}$$

$$q(t_e) = \frac{dQ}{dt_e} = Q_c.\alpha(t_e).\left(\frac{\tau}{t_e}\right)^{\beta}.\frac{\beta}{t_e} \tag{9}$$

$$q(t) = \frac{dQ}{dt} = \frac{dQ}{dt_e}.\frac{dt_e}{dt} = Q_c.\alpha(t_e).\left(\frac{\tau}{t_e}\right)^{\beta}.\frac{\beta}{t_e}.\exp\left(\frac{E_a}{R}\left(\frac{1}{T_r} - \frac{1}{T_c(t)}\right)\right) \tag{10}$$

where Q_c = total available heat per unit volume (J/m^3).

3. RESULTS AND DISCUSSION

3.1. Adiabatic Temperature Rise Testing

The measured ATR histories of the three mixes are plotted in Figure 3. The initial concrete temperatures of Mixes 1, 2 and 3 were 28.6°C, 26.8°C and 22.4°C, respectively. The maximum temperature increases (max. ATR minus the initial temperature) in the samples of Mixes 1, 2, and 3 were 38.5°C, 47.7°C and 52.2°C, respectively. Because the mixes use the same cement type and the same chemical admixture, the shapes of the ATRs for the 3 mixes are very similar. The only difference among them is the magnitude of the temperature.

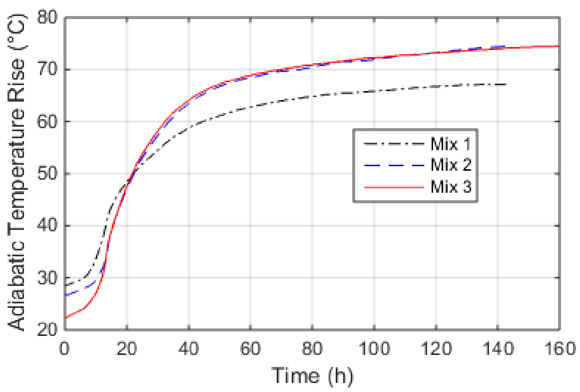


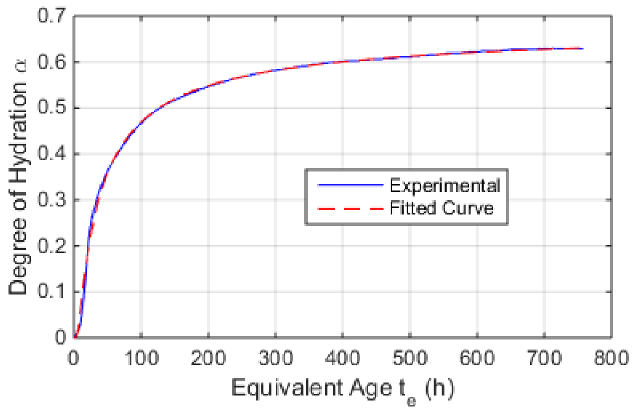
Figure 3. *Measured ATR for mixes.*

3.2. Hydration parameters

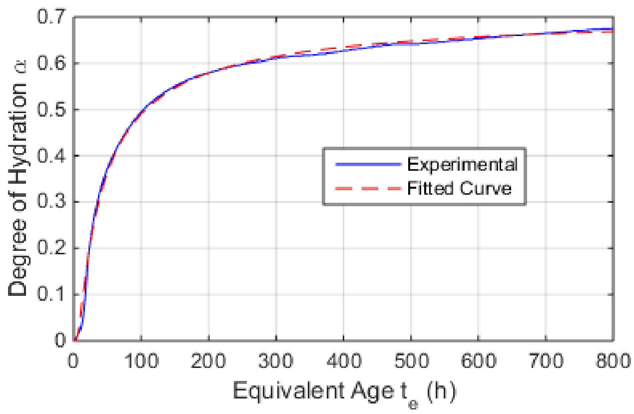
The calculated activation energy (E_a) and the total heat available (H_u, Q_c) are given in Table 4. The hydration parameters (α_u, τ, and β) were determined using the least-squares method and are shown in Table 4. The experimental degree of hydration curves for the concrete mixtures versus the fitted curves are plotted in Figure 4. It is noticed that the mixes have similar hydration parameters (τ and β) resulting in similar shapes of the degree of hydration curves. The significant difference among the three mixes is the values for the total heat available (Q_c). It is clear that the more cement content, the more total heat releases for a concrete mix. In addition, the degree of hydration increases with the decrease in the w/c ratio for the normal concrete mixes tested as shown in Figure 5, which also conforms to the research results reported by Mills [20].

Table 4. *Heat of hydration parameters*

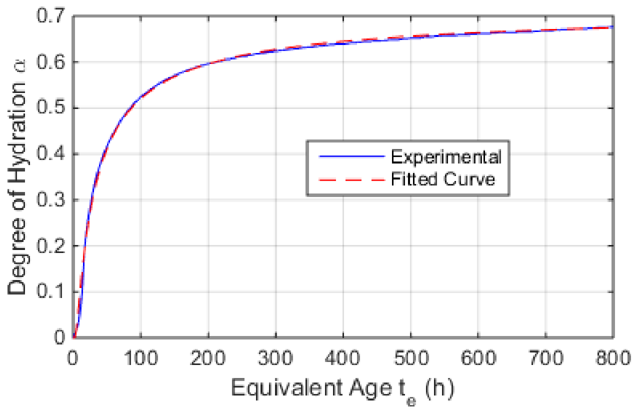
Mixture	τ (h)	β	α_u	H_u (J/g)	Q_c (J/m^3)	E_a (J/mol)
Mix 1	28.53	0.7977	0.6781	459.73	1.53×10^8	36,011
Mix 2	31.22	0.8412	0.7138	459.73	1.74×10^8	36,011
Mix 3	23.85	0.7908	0.7178	459.73	1.92×10^8	36,011



a) Mix 1



b) Mix 2



c) Mix 3

Figure 4. *Fitted curves for experimental degree of hydration for concrete mixes.*

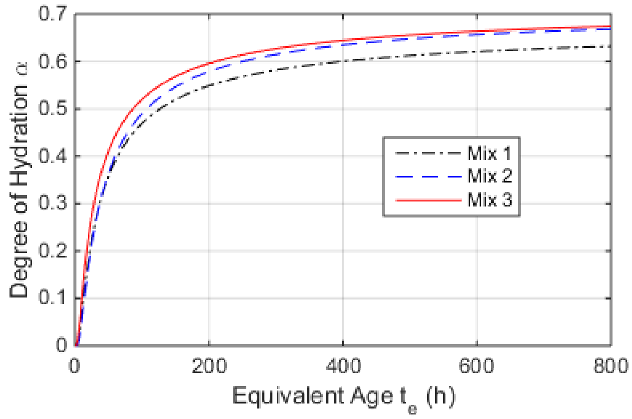


Figure 5. *Degree of hydration curves for 3 concrete mixes.*

4. CONCLUSIONS

The ATRs for three normal-strength concrete mixtures were experimentally tested using an adiabatic calorimeter developed at the University of Transport and Communications. The hydration parameters (τ and β) and the total heat (Q_c) of the concrete samples were also determined using the measured ATR and the curve fitting method. The results show that the degree of hydration increases with the decrease of the w/c ratio in the mixture.

The methodology and the hydration parameters for concrete are of great significance for civil engineers in the design and construction of modern concrete materials (e.g., high-strength and high-performance concrete) for minimizing risk of cracking in the structures and optimizing the construction schedules.

Acknowledgments

This research is funded by the University of Transport and Communications (UTC) under grant number T2019-CB-011TĐ.

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