Implementing ternary supplementary cementing binder for reduction of the heat of hydration of concrete

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ABSTRACT

The purpose of the present study was to examine the high-volume use of by-products as supplementary cementitious materials (SCMs) in order to control the hydration heat of concrete and enhance its sustainability. The prepared ternary binders were composed of varying combinations of fly ash, ground granulated blast-furnace slag, and ordinary Portland cement (OPC). Isothermal hydration tests were conducted on the pastes produced using the prepared ternary binders and OPC under constant temperatures (T) of 13, 23, and 33 °C. Adiabatic hydration tests were also conducted on the concrete mixes at T of 23 °C. The heat production rate curve clearly showed that the induction and acceleratory periods increased with increasing SCM amount, whereas the maximum value of the curve and the decelerator period decreased; as a result, the activation energy of the cementitious pastes tended to increase with increasing SCM amount. The maximum values of total heat production determined from the adiabatic hydration tests also increased with increasing water–to–binder ratio. The relationship between the degree of reaction and the compressive strength development of the concrete was very similar in both the isothermal and the adiabatic hydration tests. The environmental impact assessment demonstrated that the very-high-volume SCM concrete had a reduction in global warming potential of 75–86% and in abiotic depletion of 73–82% as compared with OPC concrete.

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1. Introduction

It is well understood that the hydration of cement evolves energy of up to 500 J/g (120 cal/g) (Snelson et al., 2008), which is accompanied by the generation of heat. The heat of hydration results in a temperature differential between the surface of the concrete element and the core because the thermal conductivity of concrete is relatively low, meaning that the temperature differential increases with increasing volume of the concrete element. This differential may result in thermal stress and undesirable thermal cracking for concrete elements with internal or external restraints. The heat of hydration also has a negative effect on the durability of concrete owing to the volume changes of the elements, resulting in internal microcrack formation (Chandara et al., 2012). With increasing construction of high-rise and large-space structures,

reducing the heat of hydration at the core of massive concrete elements is becoming more important.

The heat of hydration and the rate of heat evolution in concrete commonly increase with increasing C_3S and C_3A contents in compound compositions of cement. On the other hand, the pozzolanic reaction is slower than C_3S hydration and it produces less heat than does cement hydration (Nili and Salehi, 2010). As a result, concrete containing supplementary cementitious materials (SCMs) normally experiences slow hydration, accompanied by a small increase in temperature owing to the heat of hydration. Bamforth (1980) reported that mass concrete with fly ash (FA) or ground granulated blast-furnace slag (GGBS) as a partial replacement for ordinary Portland cement (OPC) generates a lower temperature rise and a slower rate of increase than OPC mass concrete. Schindler and Folliard (2003) showed that the use of FA and GGBS retard the hydration process and reduces the amount of heat generated during the acceleration stage. Wang and Lee (2010) demonstrated that FA is more effective in reducing the heat of hydration in concrete than GGBS because the potential heat production capacity of the former is significantly lower than that of the latter. Atiş (2002) showed that 50% FA reduces the peak temperature of concrete by

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23% as compared with OPC, indicating that the moderate levels (10–30%) of FA currently used in cement production may not provide sufficient reduction in the heat evolution of concrete. This implies that high-volume SCMs as an OPC replacement can effectively control the temperature increase in mass concrete. The use of large amounts of SCMs also significantly contributes to the sustainability (Yang et al., 2014; Mo et al., 2015) of concrete in terms of low CO_2 emissions, recycling of by-products, and conservation of natural resources as well as the enhancement of workability and durability of concrete (Zhao et al., 2015). Rashad (2015) pointed out that high-volume FA concrete had better fire resistance than OPC concrete. Arezoumandi and Volz (2013) found that the shear behavior of reinforced concrete beams with 50% and 70% replacement of OPC with Class C FA is essentially identical to that of conventional concrete beams. Because of these promising results, very-high-volume SCM concrete has become increasingly attractive in the construction industry. However, the available test data on the temperature increase owing to the heat of hydration in very-high-volume SCM concrete are very limited, and the optimization of high-volume SCMs needs to be qualified in order to meet the required specifications for the intended application of the concrete. Furthermore, a reliable understanding of the time evolution for the heat production curve is still lacking in high-volume SCM concrete, and an accurate model to simulate the curve is essential for thermal stress analysis in mass concrete.

The objective of the present study was to evaluate the hydration heat performance of very-high-volume SCM concrete developed for low-heat-mass concrete elements. To produce very-high-volume SCM concrete, 80 and 90% of OPC was replaced with 40% FA and 40–50% GGBS, with reference to previous experimental results (Yang et al., 2014). The time evolution for the heat production rate (in J/g·h) and total heat production (in J/g) in sample pastes was measured from the isothermal hydration tests at temperatures of 13, 23, and 33 °C. Using the heat production rate curves under the different temperatures, the apparent activation energy was calculated for the prepared binders. Furthermore, adiabatic hydration tests were conducted on the concrete at a temperature of 23 °C and the results were compared with the heat production curves measured from the isothermal hydration tests of the pastes. Ultimately, the degree of reaction of the very-high-volume SCM concrete was calculated over time and examined to establish the relationship between the binder type and the compressive strength gain of the resulting concrete. In particular, the various environmental impacts of the test mixes were assessed in order to demonstrate the sustainability of the very-high-volume SCM binder.

2. Simple equations for the degree of reaction

It is difficult to schematically determine the time evolution for the degree of hydration of cementitious materials through hydration heat tests. For this reason, the degree of reaction (r) is frequently defined as the fraction of the heat of hydration released at any point during testing (Yang et al., 2014). From this definition, the time evolution for r of a ternary-type binder (OPC with FA and GGBS) can be written as follows:

$$r(t) = \frac{Q(t)}{Q_{max}} = \frac{Q(t)}{Q_{max\_C} \cdot (1 - R_F - R_G) + Q_{max\_F} \cdot R_F + Q_{max\_G} \cdot R_G} \tag{1}$$

where $Q(t)$ is the cumulative heat production (in J/g) at a specified time t (in h), Q_{max_C}, Q_{max_F}, and Q_{max_G} are the potential capacities of hydration heat production of OPC, FA, and GGBS, respectively, and R_F and R_G are the weight ratios of FA and GGBS to total binder.

Bogue (1955) observed that the value of Q_{max_C} depends on the heats of hydration of the individual compounds. Considering the typical values of the heat of hydration of pure compounds, which can be theoretically determined from the enthalpies of complete hydration, Q_{max_C} can be calculated as follows (Taylor, 1990):

$$Q_{max\_C} = 517(C_3S) + 262(C_2S) + 1672(C_3A) + 418(C_4AF) \tag{2}$$

where C_3S is tricalcium silicate ($3CaO \cdot SiO_2$), C_2S is dicalcium silicate ($2CaO \cdot SiO_2$), C_3A is tricalcium aluminate ($3CaO \cdot Al_2O_3$), and C_4AF is tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$). The pure compound composition of OPC can be calculated from its oxide composition. On the other hand, there is very little data, if any, dealing with the relationship between the potential capacity of hydration heat production and the chemical composition of FA and GGBS in the available literature. Maekawa et al. (1998) analyzed the experimental results of the amount of chemically bound water, adiabatic temperature rise, and temperature of small semi-adiabatic blocks. Based on the analysis, they roughly determined the theoretical values of Q_{max_F} and Q_{max_G} to be 209 J/g and 460 J/g, respectively, for complete hydration. The cumulative heat production commonly shows a parabolic curve converging toward a potentially maximum value after the induction period. The induction period and slope at the ascending branch of the curve are significantly affected by the curing temperature. Considering the effect of curing temperature, the development of hydration heat is commonly expressed as a function of the corresponding equivalent age (t_e) of the concrete mixes based on the Arrhenius equation, as follows (Nili and Salehi, 2010):

$$Q(t) = Q_{max} \cdot \exp\left[-\left(\frac{\tau_e}{t_e}\right)^\alpha \right] \tag{3}$$

$$t_e = \sum_{i=1}^{n} \exp\left[\frac{E_a}{R}\left(\frac{1}{273 + T_f} - \frac{1}{273 + T}\right)\right] \Delta t_i \tag{4}$$

where τ_e and α are the experimental parameters, E_a is the apparent activation energy, R (=8.314 J/mol/K) is the gas constant, T_f is the reference temperature, and T is the mean curing temperature (in °C). Overall, the values of the parameters, Q_{max}, τ_e, and α, are empirically determined for a given concrete mixture using the measured heat production curve, and then $r(t)$ can be straightforwardly calculated by an exponential function of such parameters, as given in Eqs. (1) and (3).

3. Experimental program

3.1. Materials

To produce a ternary-type binder, OPC (ASTM Type I) was partially replaced with commercially available FA and GGBS powders. As given in the chemical compositions of Table 1, determined by X-ray fluorescence (XRF) analysis (Yang and Jeon, 2014), FA belongs to Class F of ASTM C618 and GGBS conforms to ASTM C989 (2012). The specific gravity and specific surface area were 3.15 and 3466 cm^2/g, respectively, for OPC, and 2.23 and 3720 cm^2/g for FA, and 2.91 and 4497 cm^2/g for GGBS. From the chemical composition of OPC, the theoretical value of Q_{max_C} was calculated to be 507 J/g.

Locally available natural sand with a maximum particle size of 5 mm and crushed granite with a maximum particle size of 25 mm were used for fine and coarse aggregates, respectively. The specific gravity and water absorption were 2.61 and 1.16% for the fine aggregate and 2.62 and 1.78% for the coarse aggregate. The