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Analysis of compressive strength development of concrete containing high volume fly ash

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HIGHLIGHTS

- Calculate calcium silicate hydrate (CSH) content and phase volume fractions.
- Evaluate compressive strength of hardening concrete.
- Valid for concrete with high water to binder ratios and low water to binder ratios.
- Valid for concrete containing high volume fly ash and low volume fly ash.
- Valid for early-age concrete and late-age concrete.

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ABSTRACT

Fly ash is a principal by-product of the coal-fired power plants and is well accepted as a pozzolanic material that may be used as a mineral admixture in concrete. High-volume fly ash (HVFA) concrete, which has typically 50–60% fly ash as the total cementitious materials' content, is widely used to achieve the sustainable development of concrete industry. Compressive strength development is the most important engineering property of hardening concrete. This paper presents a numerical procedure to evaluate the compressive strength development of HVFA concrete. The numerical procedure starts with a blended hydration model considering cement hydration, fly ash reaction, and interactions between cement hydration and fly ash reaction. Using the hydration model, the hydration degree of cement and reaction degree of fly ash are determined as functions of curing age. Furthermore, calcium silicate hydrate (CSH) contents of hardening HVFA concrete are calculated using reaction degrees of binders and mixing proportions of concrete. Finally, the compressive strengths of hardening HVFA concrete are determined using CSH contents. The proposed numerical procedure is valid for concrete with different water to binder ratios (ordinary strength concrete and ultra high strength concrete) and different fly ash contents (low volume fly ash and high volume fly ash).

1. Introduction

Fly ash consists of finely divided ashes produced by burning pulverized coal in power stations, and can be categorized as a normal type of pozzolan to produce high strength and high performance concrete. To achieve the sustainable development of concrete industry, high-volume fly ash (HVFA) concrete, which has typically 50–60% fly ash as the total cementitious materials' content, is widely used. The incorporation of high volume of fly ash in concrete has many advantages, such as reducing the water demand, improving the workability, minimizing cracking due to thermal and drying shrinkage, and enhancing durability to reinforcement corrosion, sulfate attack, and alkali-silica expansion [1].

Compressive strength is the most important property of concrete; other properties such as tensile strength, flexural strength, elasticity modulus, water tightness and durability all are related to compressive strength closely. Abundant experimental studies have been done about compressive strength development of hardening HVFA concrete. Lam et al. [2,3] and Poon et al. [4] found that fly ash contributed little to compressive strength at early ages, and at the later ages, the contribution of fly ash to compressive strength became larger. The contribution of fly ash in concrete mixes prepared at a lower W/CM (water to cementitious materials ratio) was greater than those prepared at a higher W/CM. Narmluk and Nawa [5] found that at commonly encountered curing temperatures (not higher than 35 °C), the presence of fly ash at all

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replacement ratios accelerates hydration of cement due to the cement dilution effect; and at higher curing temperatures (50 °C) and high fly ash replacement ratios, the pozzolanic reaction of fly ash becomes important. Ramezanianpour and Malhotra [6] found that the strength of the concretes containing fly ash appears to be more sensitive to poor curing than the control concrete. The reduction in the moist-curing period results in lower strengths, higher porosity and more permeable concretes. Summarily, the experimental investigations [2–6] show that the compressive strength of HVFA concrete relates to water to binder ratios, fly ash replacement ratios, and curing conditions. To evaluate compressive strength of HVFA concrete, cement dilution effect and fly ash pozzolanic reaction should be considered.

Compared to abundant experimental studies of compressive strength of HVFA concrete, theoretical models for evaluation strength of fly ash blended concrete are limit. Papadakis [7–8] proposed efficiency factors for evaluating compressive strength of matured concrete incorporating various supplementary cementing materials (SCM), such as silica fume, fly ash, slag, and natural pozzolans. The efficiency factor is defined as the part of the SCM in an SCM-concrete that can be considered as equivalent to Portland cement. Using an apparent activation energy function, Han et al. [9] evaluated the development of compressive strength of hardening fly ash blended concrete. The influences of fly ash replacement content and water–binder ratio on the apparent activation energy were investigated. Based on experimental results concerning the compressive strength development of concrete containing fly ash, Hwang et al. [10] derived an estimation equation for compressive strength development. The equation used a coefficient to indicate the activity of fly ash as a binder, in the form of a function of age, fly-ash content, and Blaine specific surface area of fly ash. Using artificial neural networks, Topcu and Sarıdemir [11] evaluated the compressive strength development of fly ash blended concrete with different curing ages, Portland cement contents, water contents, fine aggregate and coarse aggregates contents, water reducing agent contents, fly ash replacement ratios, and CaO contents. On the other hand, it should be noticed that current models have some weak points. First, most current models [7–10] mainly focus on evaluating the strength of concrete containing low volume fly ash (fly ash contents are less than 30% of total binder). For HVFA concrete, more investigations and validations are necessary. Second, current models [7–11] focus on modeling of macro properties (compressive strength) of concrete. The microstructures of concrete, such as calcium silicate hydrate (CSH) contents and phase volume fractions, are not detailed considered. Third, a lot of parameters were necessary to build the input layer and hidden layer of artificial neural networks [11]. The physical meaning of these parameters is not clear.

To overcome the shortcomings of current models [7–11], a new numerical procedure is proposed for evaluating the compressive strength of HVFA concrete. This numerical procedure consists of blended hydration model and strength evaluation model. Using blended hydration model, the reaction degrees of cement and fly ash, calcium silicate hydrate (CSH), and phase volume fractions, are calculated as functions of curing age. Furthermore, the compressive strength of hardening HVFA concrete is evaluated through CSH contents.

2. Hydration model of cement–fly ash blends

2.1. Hydration model of Portland cement

The shrinking-core model, which was originally developed by Tomosawa [12] and modified by Park [13] and Maruyama [14], is used in this study to simulate the development of cement hydration. This model is expressed as a single equation consisting of three coefficients: k_d the reaction coefficient in the induction period; D_e the effective diffusion coefficient of water through the C-S-H gel; and k_{ri} a coefficient of the reaction rate of mineral compound of cement as shown in Eqs. (1) and (2) below:

$$\frac{d\alpha_i}{dt} = \frac{3(S_w/S_0)\rho_w C_{w\text{-free}}}{(v + w_g)r_0\rho_c} \frac{1}{\left(\frac{1}{k_d} - \frac{r_0}{D_e}\right) + \frac{r_0}{D_e}(1-\alpha_i)^{\frac{-1}{3}} + \frac{1}{k_{ri}}(1-\alpha_i)^{\frac{-2}{3}}} \tag{1}$$

$$\alpha = \frac{\sum_{i=1}^{4}\alpha_i g_i}{\sum_{i=1}^{4} g_i} \tag{2}$$

where α_i (i = 1,2,3, and 4) represents reaction degree of mineral compound of cement C_3S, C_2S, C_3A, and C_4AF respectively; α is the degree of cement hydration and can be calculated from the weight fraction of mineral compound g_i and reaction degree of mineral compound α_i; ν is the stoichiometric ratio by mass of water to cement (=0.25); w_g is the physically bound water in C-S-H gel (=0.15); ρ_w is the density of water; ρ_c is the density of the cement; $C_{w\text{-free}}$ is the amount of water at the exterior of the C-S-H gel; r_0 is the average radius of cement particles in dry state. In Eq. (1), the cement particles are assumed to be spherical and of uniform size with an average radius of $r_0 = \frac{3}{S\rho_c}$ [13]. The terms S stands for the Blaine surface area of the cement.

At the start of the hydration process, the surface of the cement particle has enough water for hydration to proceed. As the hydration proceeds, the cement particle grows gradually and the contact areas between free water and hydration products are dependent on the volumes of hydration products. Because of the increase in interconnections among cement particles, the contact area between cement particles and the surrounding water reduces, and the hydration rate decreases. This effect is accounted for by the term (S_w/S_0) in Eq. (1) where S_w is the effective surface area of the cement particles in contact with water and S_0 is the total surface area if the surface area develops unconstrained [13,14].

When the hydration products surrounding individual cement particles are not in contact with each other, the effective surface area between the free water and the cement particle is

$$S_w = 4\pi R^2, \quad R < \frac{l}{2} \tag{3}$$

where R is the radius of cement particle including the outer hydration products [13,14], and l is the length of the cube that corresponds to the volume of cement paste [13,14].

If the hydration products around the particles are in contact with each other:

$$S_w = 4\pi R^2 - 12\pi R\left[R - \frac{l}{2}\right] = -8\pi R^2 + 6\pi R l, \quad \frac{l}{2} < R < \frac{\sqrt{2}l}{2} \tag{4}$$

As the cement particle grows further, the interfacial area becomes

$$S_w = \int_{\sqrt{R^2 - \frac{l^2}{2}}}^{\frac{l}{2}} \int_{\sqrt{R^2 - \frac{l^2}{4}x^2}}^{\frac{l}{2}} \frac{R}{\sqrt{R^2 - x^2 - y^2}} dy dx, \quad \frac{\sqrt{2}l}{2} < R < \frac{\sqrt{3}l}{2} \tag{5}$$

S_0 describes the total surface area if the surface area develops unconstrained. The value of S_0 can determined as follows:

$$S_0 = 4\pi R^2 \tag{6}$$

The reaction coefficient k_d is assumed to be a function of the degree of hydration as shown in Eq. (7) where B and C are the coefficients determining this factor; B controls the rate of the initial shell formation and C controls the rate of the initial shell decay.

$$k_d = \frac{B}{\alpha^{1.5}} + C\alpha^3 \tag{7}$$