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Evaluation of compressive strength development and carbonation depth of high volume slag-blended concrete

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HIGHLIGHTS

- Calculate phase volume fractions of cement-slag blends.
- Evaluate strength and carbonation of high volume slag blended concrete.
- Using high volume slag in concrete with a lower to binder ratio is a rational option.
- Initial curing periods present significant influence on carbonation.

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ABSTRACT

Compressive strength development and carbonation are critical topics for using high volume slag concrete rationally. The objective of this study is to present a numerical procedure that evaluates compressive strength and carbonation depth of high volume slag concrete. This numerical procedure consists of a blended hydration model and a carbonation reaction model. The amount of carbonatable materials, such as calcium hydroxide (CH) and calcium silicate hydrate (CSH), is calculated using the blended hydration model. Compressive strength development of cement-slag blends is evaluated from CSH content. By considering the effects of material properties and environmental conditions, the carbonation reaction model analyzes the diffusivity of carbon dioxide and the carbonation depth of concrete. The results of the analysis show that regarding compressive strength, the contribution of slag mixes prepared at a lower water to binder ratio was greater than the contribution of slag mixes prepared at a higher water to binder ratio. Regarding carbonation, with an increase in slag content or reducing the initial curing period, carbonation depth increases. The results of this study are useful for optimum mixing proportional design and carbonation durability design of concrete incorporating a high volume slag.

1. Introduction

Slag is a byproduct from steel manufacture and can be used as a mineral admixture to make high performance concrete. High-volume slag concrete, which typically has 70–80% slag as the content of binder material, is increasingly used for sustainable development in the concrete industry. Concrete containing slag has many engineering and environment advantages, such as lower water permeability, better chloride and sulfate resistance, and lower carbon dioxide emissions.

Compressive strength is the fundamental property of hardening concrete. Other mechanical properties and construction management are closely related to compressive strength development. For reinforced concrete structures, due to carbonation, the pH of the capillary pore water reduces to a low value of 9, the passive layer on the steel rebar surface becomes unstable, and corrosion of steel rebar is initiated. Therefore, compressive strength development and carbonation are critical research topics for material selection, durability design and maintenance of reinforced concrete structures [1].

Many experimental studies have been performed on strength development and carbonation of high volume slag concrete. Oner and Akyuz [2] found that the compressive strength of slag-blended concrete increases when the amount of slag increases. After an optimum point, at approximately 55% of the total binder content, the addition of slag does not improve the compressive strength. Barnett et al. [3] found that for strength development, concrete with a lower water to binder ratio can benefit more from high volume slag addition than concrete with a higher water to

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binder ratio. However, Gruyaert [4] and Sisomphon [5] found that carbonation of high volume slag-blended concrete relates to both the mixing proportions of concrete and the curing conditions. Slag-blended concrete shows a much higher carbonation depth than control concrete [6]. When the initial curing period before carbonation tests increases, the carbonation depth decreases [7]. References [2–7] show that the strength and carbonation of high volume slag concrete relates closely to the material properties of concrete, such as water to binder ratio, slag replacement ratio, and curing period.

Compared with abundant experimental studies, theoretical models for evaluating strength development and carbonation of high volume slag concrete are limited. Based on isothermal hydration tests and adiabatic hydration tests, De Schutter [8,9] analyzed the degree of hydration of high volume slag-blended concrete. Furthermore, early-age strength development of hardening concrete was evaluated using degree of hydration [8,9]. Using an artificial neural network, Billim [10] predicted strength development of concrete with different mixing proportions, such as three different water to binder ratios (0.3, 0.4, and 0.5), three different binder dosages (350, 400, and 450 kg/m^3) and four partial slag replacement ratios (20%, 40%, 60%, and 80%). Younsi [11] evaluated the carbonation rate of high volume slag concrete considering carbonatable compound content and carbon dioxide diffusivity. Papadakis [12,13] proposed a simplified scheme to determine the final chemical composition of fully hardened concrete incorporating different supplementary cementing materials (SCMs). Carbonation depth of concrete incorporating SCMs was predicted considering both material properties and conditions of exposure. However, the effect of curing conditions on carbonation is not considered in Papadakis' model [12,13]. Summarily, current models [8–13] are valid only for single property evaluation of high volume slag-blended concrete, considering either strength development evaluation or carbonation evaluation. An integrated model that can evaluate both compressive strength development and carbonation is necessary.

To overcome weak points in former studies [8–13], this paper presents a numerical procedure to evaluate strength development and carbonation depth of high volume slag concrete. The flowchart of the numerical procedure is shown in Fig. 1. By using a slag-blended cement hydration model, the amounts of calcium hydroxide (CH), chemically bound water, and calcium silicate hydrate (CSH) are determined as functions of curing ages. Compressive strength development of cement-slag blends is evaluated from CSH content. Furthermore, by considering the effects of material properties and environmental conditions, the diffusivity of carbon dioxide and carbonation depth of concrete are calculated. The authors believe that this detailed study dealing with the compressive strength and carbonation is very useful for optimum mixing proportional design and carbonation durability design of high volume slag concrete.

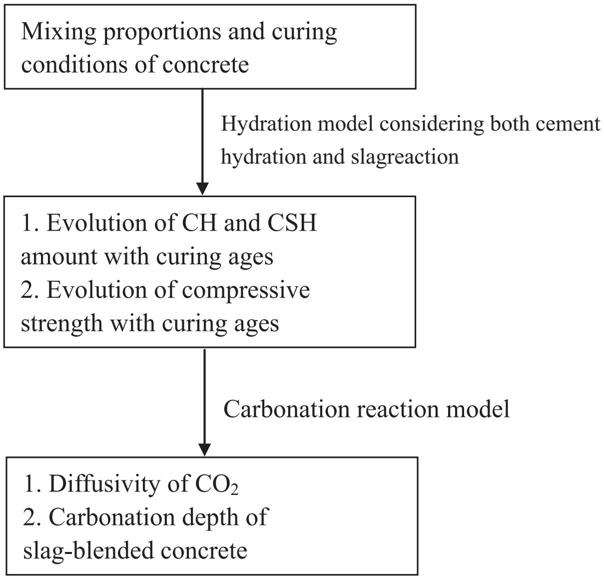

Fig. 1. The flowchart of the numerical procedure.

2. Hydration model of slag-blended cement

2.1. Hydration model of Portland cement

Wang and Lee [14] revised Tomosawa's original hydration model [15] and proposed an improved shrinking-core model to simulate Portland cement hydration. Tomosawa's original model [15] does not consider the influence of capillary water on cement hydration. Tomosawa's model [15] is valid only for low or ordinary strength concrete that has a higher water to cement ratio. Wang and Lee [14] revised Tomosawa's model by considering the influence of the water to cement ratio, cement compound composition, and capillary water content on cement hydration. The revised model has a wide application and is valid for various concretes with different strength levels, different cement compound compositions, and different curing processes. The revised equation is shown as follows:

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

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

where α_i (i = 1, 2, 3, and 4) denotes the degree of reaction of the mineral component of cement C_3S, C_2S, C_3A, and C_4AF, respectively; α denotes the degree of cement hydration; k_d is the reaction coefficient in the initial dormant period; D_e means the effective diffusion coefficient of capillary water through the C–S–H gel; k_{ri} is the reaction coefficient of the boundary reaction process; ν denotes the stoichiometric ratio of mass of water to mass of cement (=0.25); w_g denotes the physically bound water in hydration products (=0.15); ρ_w denotes the density of water; ρ_c denotes the density of the cement; C_{w-free} denotes the amount of capillary water at the exterior of hydration products; r_0 denotes the radius of the unhydrated cement particles; S_w denotes the effective contacting surface area between the cement particles and capillary water; and S_0 denotes the total surface area if hydration products develop unconstrained.

As shown in Eq. (2), the degree of reaction of cement α can be calculated from the mineral component weight fractions g_i and mineral component reaction degree α_i .

During the initial dormant period, the formation of an initial impermeable layer lowers the rate of hydration, and the destruction of this impermeable layer increases the rate of hydration. The reaction coefficient k_d in the initial dormant period can be determined as follows:

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

where B describes the rate of the initial shell formation, and C describes the rate of the initial shell decay.

The effective diffusion coefficient of water D_e relates to the tortuosity of the gel pores and the radii of gel pores in the reaction