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Prediction model for relative humidity of early-age internally cured concrete with pre-wetted lightweight aggregates

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HIGHLIGHTS

- The internal relative humidities of internally cured concrete were investigated.
- A model for critical time considering working w/c ratio was proposed.
- A model for working w/c ratio of internally cured concrete was proposed.
- A model for relative humidity of early-age internally cured concrete was proposed.

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ABSTRACT

The decrease of internal relative humidity (IRH) in high-performance concrete (HPC) induces autogenous shrinkage, which is fundamental to evaluate the cracking resistance. Internal curing (IC) with pre-wetted lightweight aggregates (LWAs) is used to mitigate the shrinkage of HPC, and prediction of shrinkage of HPC requires knowledge of the IRH variations. Although investigations on IRH in concrete have been conducted, the prediction model for IRH in internally cured concrete with LWAs considering IC remains lacking. Experimental research and analysis on IRH in early-age concrete with pre-wetted LWAs were conducted. Test results show that: (1) the average value of IRH decrease rate in internally cured concrete with pre-wetted LWAs decreased nonlinearly with the increase of IC water-to-cement (w/c) ratio; (2) the prediction models for critical time and working w/c ratio were proposed; (3) a prediction model for the IRH in early-age internally cured concrete was proposed considering the working w/c ratio, critical time, and age. These models showed the good accuracy of the experimental results.

1. Introduction

Modern construction projects increasingly rely on the use of high-performance concrete (HPC) due to its high strength and reduced permeability. HPC normally has a low water-to-cement (w/c) ratio, 0.20–0.35 [1]. The self-desiccation is induced when such concrete does not contain enough water for the unrestricted hydration of cement [2,3]. Due to moisture diffusion and this self-desiccation, internal relative humidity (IRH) decreases in HPC structures and induces shrinkage [4,5]. As concrete shrinks, tensile stresses will develop in the structure due to restraints [6,7]. The stresses may overcome the tensile strength and lead HPC to crack [8]. Cracks allow water and other chemical agents to enter through the cover layer and come into contact with the reinforcement, then lead to corrosion of the reinforcement [9]. Studies on the cracking of HPC structures at early age indicate that the early-age is among the most critical periods of the lifetime of the cementitious materials [10]. Thus, in order to avoid early-age cracking in HPC, the decrease of IRH must be prevented during cement hydration [11]. Internal curing (IC) is an effective technique to reduce early-age cracking of concrete with low w/c ratio [12,13], which implies distributing IC water reservoirs in the concrete [14,15]. Super absorbent polymer (SAP) which is a class of polymeric material with super-high water absorption capacity or lightweight aggregate (LWA) can serve as IC water reservoirs to provide curing water to compensate the moisture loss of hydrating cement paste [16–18], and thus reduce the effects of self-

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desiccation and prevent the relative humidity (RH) from decreasing in concrete [19]. Benefits of IC have also been shown to include reduced potential for cracking [20,21] and increased durability [22]. However, only a few results have been reported in current literatures regarding the effect of IC on IRH. Therefore, investigation on the IRH variations in early-age internally cured concrete with pre-wetted LWAs is fundamental to evaluate its cracking resistance.

The IRH in concrete has been investigated under unsealed condition [23,24]. In this condition, the IRH in concrete is influenced by the combination of moisture diffusion and self-desiccation [5]. The IRH decreases due to self-desiccation during cement hydration. In addition, the water movement induced by moisture diffusion will result in an additional decrease of IRH when the concrete is exposed to environmental condition [25]. Therefore the IRH variations in concrete under unsealed condition are of considerable practical importance [26]. Although the IRH variations in concrete are significantly affected by IC w/c ratio [8] and the length of the water-vapor saturated stage with 100% RH (defined as critical time in [8]) in HPC is affected by the addition of pre-wetted LWAs, the model for calculating the critical time of IRH in early-age internally cured concrete with pre-wetted LWAs is still lacking. The IRH in concrete is also influenced by the IRH decrease rate [27]; however, investigation on the IRH decrease rate in internally cured concrete with pre-wetted LWAs remains lacking. Thus, the critical time and IRH decrease rate in early-age internally cured concrete under unsealed condition must be investigated.

The intense autogenous shrinkage during the acceleration period of cement hydration was associated with the beginning of microcracking [28]. Early-age cracking may lead to severe problems with respect to the durability of the concrete structures. Thus, a prediction model for autogenous shrinkage of HPC must be developed to evaluate the cracking resistance of concrete [29]. Thus far, some experiments have been performed to determine the IRH variations in ordinary concrete [4,30]. Several prediction models for autogenous shrinkage of concrete are proposed using the experimental data on IRH variations [29,31,32]. A linear model for the prediction of IRH in hardened concrete is proposed in [33], and this model is improved by adjusting some parameters in [34]. Models for the prediction of IRH in concrete are also proposed in some literatures [30,35,36] considering the w/c ratio and concrete age. Moreover, the theoretical models for the prediction of IRH and cement hydration in concrete are also proposed in [37,38]. Results reported in [39] show that the IC water is much more effective in increasing the IRH in concrete than the corresponding additional mixing water. Thus these models for IRH in ordinary concrete are not suitable for calculating the IRH variations in internally cured concrete with pre-wetted LWAs. Moreover, the working w/c ratio (the w/c ratio that actually affects the IRH in concrete) may be higher than the total w/c ratio [39,40] which is in combination of both the effective w/c ratio [40] and the IC w/c ratio [8]. Although the effect of IC water provided by SAPs on working w/c ratio has been proved in [39], the model for calculating the working w/c ratio is still lacking. Thus the working w/c ratio which considers the effect of IC water provided by pre-wetted LWAs should be investigated. The models utilized for description of phenomena taking place during IC are proposed in [16,41] and a model for IRH in internally cured concrete with SAPs considering amounts of IC water is also proposed in [42]. However, the model for the IRH in early-age internally cured concrete with pre-wetted LWAs in consideration of working w/c ratio remains lacking.

Moreover, investigation on the model for IRH in concrete under unsealed condition considering the effects of IC with LWAs remains lacking [25,30,31]. Thus, that how IC with LWAs influences the IRH in concrete under unsealed condition should be investigated. The effects of IC w/c ratio on IRH and IRH decrease rate, models for calculating the working w/c ratio and critical time, as well as an accurate prediction model for IRH in internally cured concrete under unsealed condition in consideration of working w/c ratio and critical time must be studied further for better understanding the cracking resistance of internally cured concrete with pre-wetted LWAs.

2. Experimental program

2.1. Materials

Ordinary Portland cement (Cement II 52.5R) was employed with a Blaine fineness of 375 m^2/kg in accordance with China National Standard GB 175-2009. The initial setting time was 168 min, and the final setting time was 223 min. Moreover, the compressive strength of this cement was 36.4 MPa after 3 days, and that after 28 days was 66.9 MPa. The fine aggregate applied to these mixtures was natural river sand with a fineness modulus of 1.83 and a maximum size of 1.5 mm. The coarse aggregate used was crushed limestone with maximum particle sizes of 20 mm, and the apparent density was 2660 kg/m^3.

The LWA used in mixtures was a manufactured rotary kiln expanded clay [43]. The lightweight aggregate had a dry-bulk density of 1050 kg/m^3 and a 24-h absorption value of 12.0% by mass of dry material. The crushing strength of dry lightweight aggregates was 1.18 MPa [44,45]. The particle size of lightweight aggregate used in experiments was 4.7–12.5 mm. Fig. 1 shows the photograph and sieving curve of the pre-wetted LWAs used in experiments. Also a liquid polycarboxylate-based superplasticizer was used to adjust workability of different mixtures. Tap water was used as mixture water and IC water.

2.2. Mixture proportions

Results reported in [6,8,40] show that all the experimental cases with four to six concrete mixtures are tested without employing ternary blended cements or high volume supplementary cementing materials (SCMs). Six concrete mixtures with different w/c ratios were used in the present study, which were designed in accordance with results in [6,8,40]. The mixture proportions, which were designated as RC33-0, RC40-0, RC50-0, IC33-10, IC33-30, and IC33-50, are shown in Table 1. Mixtures RC33-0, RC40-0, and RC50-0 were ordinary concrete without pre-wetted LWAs and the corresponding w/c ratio was 0.33, 0.40, and 0.50, respectively. Mixtures IC33-10, IC33-30, and IC33-50 were internally cured concrete with pre-wetted LWAs and the corresponding volume of pre-wetted LWAs was 10%, 30%, and 50% of the total volume of coarse aggregates, respectively, as reported in [46].

The ratio of water provided by pre-wetted LWAs to cement is defined as IC w/c ratio in [8] and the ratio of mixing water (without IC water) to cement in concrete is defined as effective w/c ratio in [40]. Although results reported in [13,19,47] show that not all extra water in LWAs is immediately available for IC and some water in LWAs is only removed at low RH. The ratio of total water (mixing water and IC water) to cement is defined as total w/c ratio in [39,40]. In the reference concrete mixture (RC33-0), the effective w/c ratio (w_e/c) was fixed as 0.33. Thus the total w/c ratio (w_t/c) is in combination of both the effective w/c ratio (w_e/c) and the IC w/c ratio (w_{ic}/c) [39] and could be expressed as:

$$w_t/c = w_e/c + w_{ic}/c \quad (1)$$

where w_t/c is the total w/c ratio; w_e/c is the effective w/c ratio; and w_{ic}/c is the IC w/c ratio.

Thus, the IC w/c ratios (w_{ic}/c) were 0.01, 0.03, and 0.05 and the total w/c ratios (w_t/c) were 0.34, 0.36, and 0.38 for Mixtures IC33-