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Prediction of internal relative humidity in concrete modified with super absorbent polymers at early age

Dejian Shen [a,b,*], Mingliang Wang [a,b], Ying Chen [a,b], Wenting Wang [a,b], Jinyang Zhang [c,b]

[a] College of Civil and Transportation Engineering, Hohai Univ., No. 1, Xikang Rd., Nanjing 210098, China
[b] Jiangsu Engineering Research Center of Crack Control in Concrete, No. 1, Xikang Rd., Nanjing 210098, China
[c] Anhui and Huai River Water Resources Research Institute, No. 771, Zhihuai Rd., Bengbu 233000, China

HIGHLIGHTS

- A model for working w/c ratio of concrete internally cured with SAPs was proposed.
- A model for critical time considering effective and IC w/c ratios was proposed.
- A model for IRH of early-age concrete internally cured with SAPs was proposed.

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ABSTRACT

Shrinkage of high-performance concrete (HPC) mixtures may ultimately lead to early-age cracking and a reduction of service life of concrete structures. Autogenous and drying shrinkage are direct consequences of the decrease of internal relative humidity (IRH) due to self-desiccation and external drying. Therefore prediction of shrinkage of HPC requires the knowledge of IRH variations. Internal curing (IC) with super absorbent polymers (SAPs) is utilized to mitigate the shrinkage of HPC. Although investigations on IRH in concrete have been conducted, the prediction model for IRH in early-age concrete internally cured with SAPs in consideration of both water-to-cement (*w*/*c*) ratio and critical time is still lacking. Therefore investigations on predicting the IRH in early-age concrete internally cured with SAPs were conducted in present study and results showed that: (1) a prediction model for the working *w*/*c* ratio in early-age concrete internally cured with SAPs was proposed in consideration of age, effective and IC *w*/*c* ratios of concrete; (2) a prediction model for the critical time of IRH was proposed in consideration of both effective and IC *w*/*c* ratios; (3) a prediction model for the IRH in early-age concrete internally cured with SAPs was proposed in consideration of working *w*/*c* ratio, critical time, and age. These models showed the good accuracy of the test results.

1. Introduction

High-performance concrete (HPC) mixtures have been increasingly promoted for use due to its superior mechanical and durable properties. HPC mixtures are normally characterized by low water-to-cement (*w*/*c*) ratio and low permeability [1–3]. When such concrete does not contain enough water to support cement hydration, the self-desiccation will occur [4,5]. Internal relative humidity (IRH) in concrete exposed to ambient air decreases due to self-desiccation and external drying [6]. Furthermore, the decrease of IRH results in autogenous and drying shrinkage when *w*/*c* ratio is lower than a critical value [7,8]. As concrete shrinks, tensile stresses will be developed in HPC structures due to restraints [9]. The stresses become higher than the tensile strength, which lead the HPC to crack [10,11]. Studies on the early-age cracking of HPC structures indicate that it is one of the most critical periods of cementitious materials [12]. In order to avoid the shrinkage-induced cracking of HPC structures at early age, the decrease of IRH must be prevented during cement hydration [13]. For HPC mixtures with low porosity and permeability [14], traditional external curing method is not effective because the curing water penetrates only the surface layer of the concrete [15]. Internal curing (IC) with super absorbent polymers (SAPs) is an effective method to reduce the decrease of IRH by supplying additional

* Corresponding author at: College of Civil and Transportation Engineering, Hohai Univ., No. 1, Xikang Rd., Nanjing 210098, China.

E-mail addresses: shendjn@163.com (D. Shen), wmlhehai@163.com (M. Wang), cy383297739@126.com (Y. Chen), wtwanghhu@163.com (W. Wang), jyjy60085@vip.sina.com (J. Zhang).

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water [16–18], and to prevent the detrimental effects of shrinkage by producing a dense crack-free microstructure [19–21]. The benefits of IC also include reduced cracking potential [22–24] and increased durability [25,26]. IC with SAPs permits free design of the pore shape and the pore size distribution [27,28]. However, the effect of IRH on cracking resistance of early-age concrete internally cured with SAPs is still lacking. Therefore, investigation on the IRH variations in early-age concrete internally cured with SAPs is necessary to evaluate its cracking resistance.

The IRH in concrete without IC has been investigated under unsealed condition [29,30]. The IRH in concrete exposed to ambient air decreases due to external drying during drying period [31]. In addition, the self-desiccation due to cement hydration reduces IRH further [6]. Therefore the IRH variations in concrete under the combined effects of self-desiccation and external drying are of considerable practical importance [32]. The IRH variations in concrete are significantly influenced by IC with SAPs; similarly, the addition of SAPs strongly affects the length of the water-vapor saturated stage with 100% relative humidity (RH) in concrete (defined as critical time in [10,16]). The critical time is important to the successful application of IC methods [10]. Although the influences of critical time on IRH variations have been reported in [10,16], the model for calculating the critical time of IRH in early-age concrete internally cured with SAPs under unsealed condition remains lacking. Therefore the critical time of IRH in early-age concrete internally cured with SAPs under unsealed condition must be investigated.

The intense autogenous shrinkage during the acceleration period of cement hydration is associated with the beginning of micro cracking. Early-age cracking may lead to severe problems with respect to the durability of the HPC structures [33], a prediction model for autogenous shrinkage of HPC is necessary for better understanding the cracking resistance [34]. Several prediction models for autogenous shrinkage of concrete at early age are proposed using the experimental data on IRH variations in ordinary concrete [6,35–38]. A linear model for predicting the IRH in hardened concrete is proposed in [39,40]. The models for predicting the IRH in consideration of both the w/c ratio and age are also proposed in [37,38,41]. Moreover, the theoretical models for predicting the IRH in concrete are also proposed in [42,43]. The IC water is much more effective in increasing the IRH in concrete than the corresponding additional mixing water [44]. The working w/c ratio [45] (the w/c ratio that actually affects the IRH in concrete) may be higher than the total w/c ratio (effective w/c ratio [46] + IC w/c ratio [10,44]). Moreover, the models for IRH in ordinary concrete proposed in [37–43] are not suitable for predicting the IRH variations in early-age concrete internally cured with SAPs. Therefore the working w/c ratio must be investigated for better understanding the variations of IRH in early-age concrete internally cured with SAPs. The model for IRH in early-age concrete internally cured with SAPs considering the amount of IC water is proposed in [16], and the model proposed in [47] is utilized for description of the influence of IC on hydration and self-desiccation in concrete. However, the prediction model for IRH in early-age concrete internally cured with SAPs in consideration of working w/c ratio remains lacking.

Although tests on the IRH variations in concrete internally cured with SAPs at early age have been conducted [16,42], the prediction model for IRH in consideration of critical time and age remains lacking. Therefore the effects of IC w/c ratio provided by SAPs on IRH, models for the working w/c ratio and critical time, as well as IRH in early-age concrete internally cured with SAPs under unsealed condition in consideration of working w/c ratio, critical time, and age must be studied further to evaluate the shrinkage and cracking resistance.

2. Experimental program

2.1. Materials

Ordinary Portland Cement (Cement II 52.5R) was utilized as the cementitious material with a Blaine fineness of 375 m^2/kg, which was in accordance with China National Standard GB 175-2009. Table 1 shows the physical and chemical compositions of this cement, as are its strength characteristics. The initial and final setting time of this cement was 168, and 223 min, respectively. The compressive strength of this cement was 36.4, and 66.9 MPa at the age of 3, and 28 days after casting, respectively. Natural river sand with a fineness modulus of 1.83 and a maximum size of 1.5 mm was utilized as the fine aggregate. Crushed limestone with a maximum particle size of 20 mm and an apparent density of 2660 kg/m^3 was utilized as the coarse aggregate.

The SAPs utilized in HPC mixtures were comprised of polymeric materials that could absorb a significant amount of liquid from surroundings and retain the liquid within their structures without dissolution. A suspension-polymerized, covalently cross-linked acrylamide/acrylic acid copolymer as a SAP with a dry-bulk density of 850 kg/m^3 was utilized in present study. The diameters of spherical particle of SAPs were varied from 125 μm to 150 μm in the dry state. A liquid polycarboxylate-based superplasticizer was utilized to adjust the workability of different mixtures. Tap water was utilized as mixing and IC water.

2.2. Mixture proportions

Six concrete mixtures with different w/c ratios were investigated in present study. The mixture proportions, which were designated as RC33-0, RC40-0, RC50-0, IC33-5, IC33-15, and IC33-25, are shown in Table 2. Mixtures RC33-0, RC40-0, and RC50-0 represented ordinary concrete without IC. Mixtures IC33-5, IC33-15, and IC33-25 underwent IC through SAPs. The IRH variations in Mixtures RC33-0, IC33-5, IC33-15, and IC33-25 have been reported in [16]. The ordinary concrete compositions were varied by w/c ratio (0.33, 0.40, and 0.50 for RC33-0, RC40-0, and RC50-0, respectively). The internally cured concrete compositions were varied by the amounts of SAPs (0.05%, 0.15%, and 0.25% by weight of cement for Mixtures IC33-5, IC33-15, and IC33-25, respectively).The ratio of IC water provided by SAPs to cement is defined as IC w/c ratio [10] and the ratio of mixing water (without IC water) to cement in concrete is defined as effective w/c ratio [46]. The ratio of total water (mixing water and IC water) to cement is defined as total w/c ratio [44,46]. The formula for calculating the total w/c ratio(w_t/c) could be expressed as follows:

Table 1
Physical and chemical properties of cement.

Chemical Composition	Unit	Ordinary Portland Cement
SiO_2	%	19.9
Al_2O_3	%	4.6
Fe_2O_3	%	3.0
CaO	%	64.6
MgO	%	0.78
SO_3	%	2.37
Na_2O	%	0.06
K_2O	%	0.65
Cl^-	%	0.01
Loss on ignition	%	3.11
Blaine fineness	m^2/kg	375
Compressive strength, 3 days	MPa	36.4
Compressive strength, 28 days	MPa	66.9