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Effect of internal curing with super absorbent polymers on the relative humidity of early-age concrete

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HIGHLIGHTS

- The IRH of early-age internally cured concrete with SAPs were investigated.
- The critical time of the IRH of concrete increased with the increase of IC water.
- A formula was proposed for the IRH of early-age internally cured concrete with SAPs.

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ABSTRACT

High-performance concrete is used extensively in practice. However, the water-to-cement ratio of this concrete is low and causes self-desiccation. Due to moisture diffusion and this self-desiccation, internal relative humidity (IRH) decreases in concrete structures that are exposed to ambient air and induces autogenous shrinkage. Internal curing with super absorbent polymer (SAP) is used to mitigate this shrinkage in high-performance concrete; nonetheless, IRH variation influences changes in the autogenous shrinkage of concrete with SAPs. Although tests have been performed to mitigate the autogenous shrinkage of concrete that was internally cured through SAPs, experimental study on IRH variation in such concrete remains lacking. Thus, such a study was conducted to determine the effect of internal curing with SAPs on the IRH of early-age concrete under sealed and unsealed conditions, as detailed in this paper. Test results showed that: (1) the IRH of concrete that was internally cured with SAPs increased with an increase in the content of internal curing water 28 days after casting under sealed and unsealed conditions. (2) The degree of decrease in the IRH of internally cured concrete was lower under sealed conditions than under unsealed conditions 28 days after casting. (3) The critical time of the IRH of internally cured concrete increased with increases in the content of internal curing water under both sealed and unsealed conditions. (4) The decrease rate of the IRH in early-age concrete that was internally cured with SAPs dropped with an increase in the content of internal curing water under sealed and unsealed conditions. (5) A formula was proposed to calculate the IRH of early-age concrete that was internally cured with SAPs in consideration of the content of internal curing water under unsealed conditions. This formula indicates the good accuracy of the experimental results.

1. Introduction

The use of high-performance concrete (HPC) mixtures has increasingly been promoted due to potential long-term performance benefits. Modern HPC normally has a low water-to-cement (w/c) ratio of 0.20:0.35 [1]; however, self-desiccation is induced when such concrete does not contain enough water to support unrestricted cement hydration [2]. Although a fine pore system can increase strength [3] and limit fluid transport [4,5], networks with fine pores can enhance volumetric changes in sealed systems through self-desiccation. This volume change is problematic because it can result in cracking if the free shrinkage of concrete is restrained [6]. The internal relative humidity (IRH) of concrete decreases significantly. Furthermore, remarkable

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self-desiccation results in autogenous shrinkage when w/c ratio is lower than a critical value [7]. As concrete shrinks, tensile stresses develop in the structure due to restraints imposed by adjacent material, connected members, or the shrinkage gradient. These stresses may overcome tensile strength and may cause concrete to crack [8]. Studies on the cracking of concrete structures at early age indicate that this period is among the most critical in the life time of cementitious materials [9]. To avoid this risk of cracking in early-age HPC, the decrease of IRH must be prevented during cement hydration [7].

To avoid shrinkage-induced cracking in HPC structures, the moisture caused by cement hydration must be compensated. Internal curing (IC) is used to prevent the detrimental effects of autogenous shrinkage by producing a dense, crack-free microstructure that supplies additional water [10]. The benefits of IC include a capability to limit sealed concrete shrinkage [11,12], reduce cracking potential [11,13] and increase durability [14].

Several IC methods have been developed. One example is based on the addition of lightweight aggregates (LWAs) to concrete [15,16]. Another example involves the incorporation of super absorbent polymers (SAPs) [17]. Although prewetted LWAs that are saturated with water can mitigate self-desiccation, the combination of IC with LWAs is connected to major problems, including difficulties in controlling consistency and significant reductions in strength and in elastic moduli [17]. Moreover, the IC of concrete with SAPs weakly affects concrete strength and elastic modulus [18]. Thus, SAPs are used as IC material in the present study.

During water mixing, SAPs absorb water and swell. An internal water reservoir is built into fresh concrete and serves as a curing agent by gradually releasing the water absorbed during the hydration process. Additional curing water is thus produced through SAPs, and the decrease in the IRH within concrete is counteracted [17,19,20]. In view of this finding, investigation into the variations of IRH in concrete with SAPs addition is fundamental to evaluating the cracking performance of internally cured concrete. Although tests have been performed on mitigating the autogenous shrinkage of internally cured concrete with SAPs [21,22], experimental studies on the variation of IRH in concrete internally cured with SAPs remain lacking.

The IRH of concrete without IC has been investigated under sealed and unsealed conditions [23–25]. In these conditions, the IRH of concrete is influenced by self-desiccation alone and by the combination of drying and self-desiccation [6]. The water movement induced by moisture diffusion reduces relative humidity (RH) further when concrete is exposed to environmental conditions [23]. The moisture distribution in low-strength concrete with high w/c ratio is mainly influenced by moisture diffusion as a result of drying rather than as a result of self-desiccation. By contrast, self-desiccation considerably influences moisture distribution in high-strength concrete with low w/c ratio [24]. Therefore, the changes in the IRH of concrete under the effects of self-desiccation and moisture diffusion are of considerable practical importance [26]. IC significantly affects the variations in the IRH of concrete; similarly, the addition of LWAs strongly influences the length of the water–vapor saturated stage in high-strength concrete with 100% RH. This humidity-saturated stage is vital to the successful application of IC methods [8]. In high-strength concrete under sealed conditions, the drop in internal humidity as a result of the self-desiccation effect is notably postponed by the addition of SAPs [27]. Nonetheless, only a few results have been reported in current literature regarding the influence of SAPs on the water–vapor saturated stage. Hence, a theoretical formula that determines the mass of IC water to adequately compensate for the chemical shrinkage of concrete matrices has been presented in consideration of saturation degree [16]. The initial moisture contents of SAPs prior to mixing affect IC efficiency on concrete [28]. Thus, the IRH of IC concrete must be determined under the addition of different levels of SAPs to understand IRH variations.

The intense autogenous shrinkage that occurs during the acceleration period of cement hydration is associated with the initiation of microcracking [29]. Early-age cracking may lead to severe problems in concrete structure durability. Thus, a prediction model must be developed for the autogenous shrinkage of HPC. Several such models have been established for the autogenous shrinkage of early-age concrete on the basis of experimental data on RH changes in concrete [8,30]. Thus far, experiments have been performed to determine the RH variation of concrete with LWAs [31,32]; however, experiments to detect the variation of concrete RH with SAPs remain lacking. Furthermore, no formula has been generated that expresses the variations of the IRH in internally cured concrete in terms of initial IC water content.

Moreover, the majority of available studies concerned with the IRH of concrete under sealed and unsealed conditions do not consider the effect of IC with SAPs. Some concrete structures that were internally cured with SAPs have been built virtually [33,34]. Thus, whether or not and how IC influences the IRH of concrete must be determined under sealed and unsealed conditions. The effect of IC on the critical time, decrease rate, and decrease trend of IRH with age, as well as the relationship between IRH and the initial IC water content of SAPs, must also be examined further to clarify the variation of IRH in concrete that is internally cured with SAPs under sealed and unsealed conditions.

2. Experimental program

2.1. Mixture proportions

Four concrete mixtures with low w/c were used in the current study. The mixture proportions, which were designated as SAP0, SAP5, SAP15, and SAP25, are presented in Table 1. Mixture SAP0 represented a reference concrete without IC, whereas Mixtures SAP5, SAP15, and SAP25 underwent IC through SAPs. The concrete compositions were varied by the addition of SAPs (0.05%, 0.15%, and 0.25% by weight of cement for Mixtures SAP5, SAP15, and SAP25, respectively). In the reference concrete mixture (SAP0) without IC, the w/c ratio was fixed as 0.33. The ratio of IC water entrained by SAPs to cement (w_{ic}/c) of Mixtures SAP5, SAP15, and SAP25 varied respectively as 0.01, 0.03, and 0.05. That is to say, the total water-to-cement ratios varied from 0.33 to 0.39.

2.2. 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 physical and chemical compositions of this cement are provided in Table 2, as are its strength characteristics. The initial setting time is 168 min, and the final

Table 1
Compositions and properties of fresh mixtures

Mixture composition	SAP0	SAP5	SAP15	SAP25
Identifications of specimens	SAP0-S SAP0-U	SAP5-S SAP5-U	SAP15-S SAP15-U	SAP25-S SAP25-U
W/C	0.33	0.33	0.33	0.33
Water, kg/m^3	171	171	171	171
Cement, kg/m^3	512	512	512	512
Fine aggregate (sand), kg/m^3	636	636	636	636
Coarse aggregate (stone), kg/m^3	1131	1131	1131	1131
SAP, g/m^3	0	267.5	803.0	1339.0
Internal curing water, kg/m^3	0	5.35	16.06	26.78
Superplasticizer, kg/m^3	3.6	3.6	3.6	3.6
Slump, mm	100	110	105	110