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Effect of internal curing with super absorbent polymers on residual stress development and stress relaxation in restrained concrete ring specimens

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HIGHLIGHTS

- The cracking resistance of concrete with SAPs was investigated by ring test.
- The residual stress of concrete decreased with the increase of SAPs amount.
- The relaxed stress of concrete increased with the increase of SAP amount.
- The ratio of relaxed to elastic stress increased with the increase of SAPs amount.
- The time to cracking for concrete increased with the increase of SAPs amount.

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ABSTRACT

The early age cracking of concrete is a persistent problem for structures. Internal curing was developed to mitigate the shrinkage of low w/c concrete in recent decades by introducing additional water into concrete. Although shrinkage development and the early age cracking resistance of internally cured concrete under restraint were investigated, result on stress relaxation of internally cured concrete with super absorbent polymers (SAPs) by ring test is still lacking. Tests on the cracking resistance of concrete with different amounts of SAPs (0%, 0.05%, 0.16%, and 0.26% by weight of cement) were conducted using restrained ring test in present study. Test results showed that: (1) the strain in the restrained steel ring decreased with the increase of amount of SAPs; (2) the residual stress of concrete ring decreased with the increase of amount of SAPs; (3) the stress rate decreased with the increase of amount of SAPs; (4) the relaxed stress increased with the increase of amount of SAPs after the initiation of drying; and (5) the time to cracking for concrete increased with the increase of amount of SAPs.

1. Introduction

High-performance concrete (HPC) has been increasingly promoted for use because of its potential long-term performance benefits. Modern HPC normally has a low water-to-cement (w/c) ratio of 0.20–0.35 [1]. However, water is insufficient to promote complete hydration of cement under sealed conditions in concretes with a w/c ratio below 0.42 [2]. Then, the autogenous shrinkage is induced when concrete with low w/c ratio does not contain enough water for the hydration of cement [3]. Although concrete with a lower w/c ratio has higher strength and lower permeability, these mixtures may be particularly susceptible to early age cracking [4]. This early age cracking may develop in concrete for many reasons, with the restraint of the thermal and autogenous volume changes being significant contributors. Restraint of this volumetric change by surrounding elements generates tensile stress inside the concrete that may lead to cracking [5–9]. Cracking of concrete structures at early ages has indicated that the early age is one of the most critical periods in the lifetime of cementitious materials

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[10]. As concrete shrinks, tensile stresses develop in the structure because of restraints from connected members, or shrinkage gradient. The stresses may overcome the tensile strength and result in cracks in the concrete [11]. Internal curing (IC) – whereby water stored in the mixture components (that is, not the mixture water) becomes available for hydration reactions has emerged as a possible complement to the ordinary curing methods for the challenges of promoting cement hydration and pozzolanic reactions in HPC [12]. Promotion of these reactions may decrease permeability, and reduce shrinkage of concrete [13–15]. These reservoirs can absorb significant amount of water either before or during mixture and release water gradually during concrete hardening [16]. The released water contributes in restoring part of the water that has been lost through autogenous or drying shrinkage. The two IC methods most often described in the literature are the use of prewetted lightweight aggregates (LWAs) and the use of super absorbent polymers (SAPs) [12,17–19]. SAPs are a group of polymeric materials that have the ability to absorb a significant amount of liquid from the surroundings and to retain the liquid within their structure chain [19]. Experimental investigations on the properties of concrete with SAPs have been conducted by plastic shrinkage tests. The results show that SAPs can effectively reduce shrinkage [14,19–23], cracking potential [24–26], and change the rheology of the fresh material [27,28]. The effects of IC on concrete shrinkage can help in the effort to extend the life of concrete structures as well as reducing costly repairs or replacements whose structural integrity or serviceability is weakened through the influence of shrinkage cracking [29]. However, result on the effects of IC with SAPs on early age residual stress development and stress relaxation of HPC is still lacking. Thus, investigations on the internally cured HPC with SAPs were necessary for better understanding cracking resistance.

The early age cracking resistance of concrete is influenced by several factors, including shrinkage, stress rate, and stress relaxation properties [30–32]. The cracking tendency is relatively great for young concrete because of the significant autogenous shrinkage and low strain capacity [33,34]. There are two types of shrinkage, such as autogenous shrinkage and drying shrinkage. Drying shrinkage occurs because water in concrete evaporates when the environmental humidity is lower than the humidity inside concrete. And autogenous shrinkage occurs when the moisture loss is through cement hydration [32]. During hardening, the internal relative humidity will drop in these mixtures and autogenous shrinkage will occur if no external water source is presented. The cracks interconnect flow paths for water and gases, possibly containing harmful substances [35,36]. The stress rate is another major contributing factor to the development of early age cracking in concrete [37–39]. The duration of drying before the specimen cracks correlates well with the stress rate of residual tensile stress at the time to cracking [40,41]. The stress rate development is potentially linked to the fundamental aspects of moisture gradient effects as the concrete specimen is dried from one surface [38]. That a slower rate of shrinkage permits the specimen a longer period to relax stresses as they arise (i.e., lower effective modulus of elasticity) thereby further reducing cracking potential [37]. Both strain in restrained steel ring and stress rate induced by shrinkage are influenced by the amount of SAPs and its water content. Compared with a plain one, internally cured concrete with SAPs shows a lower risk of cracking. In restrained ring test, internally cured concrete shows lower residual stress and later time to cracking than that of plain sample [29,42,43]. The more IC water is, the later the time to cracking is. Plastic shrinkage can also be mitigated with IC [44]. However, result on the effects of IC with SAPs on strain in restrained steel ring and stress rate of concrete are still lacking. Thus, investigations on strain in restrained steel ring and stress rate of internally cured HPC with SAPs were necessary.

The early age creep related stress relaxation parameters is important for prediction of stresses induced by shrinkage and further to evaluate the cracking resistance of concrete structures at an early age [45,46]. Shrinkage and thermal deformations in restraint concrete members cause tensile stresses in the structure whereas tensile creep counteracts these deformations and relieves part of the induced stresses, which should be benefit for prevention of early age cracking in the concrete structures [32]. Although the creep of hardened concrete is extensively studied, the available experimental data and theoretical approaches on the stress relaxation of concrete at early age are very limited. In addition, the majority of past work on the concrete creep has been concerned with compressive creep behavior. The early age creep of concrete is difficult to measure because physical and chemical properties simultaneously change at early ages [47]. Very few studies on tensile creep of early age concrete are found in literature [48,49]. The tensile creep of early age concrete is influenced by mixture proportion [48,49], and age-dependent when loading occurs within the first 72 h [32]. The stress relaxation behavior in tension of concrete at early age is investigated [49–51]. The early age compressive creep of internally cured concrete under constant restraint degree has been studied [52]. Ring tests are used to evaluate the cracking resistance of concrete or mortar mixtures when they are restrained from shrinking freely [53–55]. Due to its simplicity and economy, the ring test has been developed into both AASHTO and standards [56,57]. The ring tests have also been used to assess residual stress development and stress relaxation of concrete in tension at early age [32,55,58–60]. Although the tensile creep of concrete that is internally cured with LWAs under changing restraint degree has been conducted with the dual ring test [52,60], the effect of SAPs on stress relaxation of HPC is still lacking. Thus, investigations on early age stress relaxation of internally cured HPC with SAPs by ring test were necessary for better understanding cracking resistance.

Although autogenous shrinkage and internal relative humidity of internally cured concrete with SAPs have been studied [3,18,61], the effects of SAPs on stress relaxation and cracking resistance of internally cured HPC are still lacking. Thus, whether and how IC influences the stress relaxation and cracking resistance of HPC with SAPs need to be investigated by restrained ring test. For better understanding the cracking resistance of HPC modified with SAPs, the effect of IC on strain in restrained steel ring, residual stress development, stress rate, stress relaxation development, and the time to cracking needs for further investigations.

2. Experimental program

2.1. Mixture proportions

Four low *w/c* concrete mixtures were used in present study. Mixture proportions designated as SAP0, SAP05, SAP15, and SAP25 are shown in Table 1. Mixture SAP0 was one reference concrete with no IC, while Mixture SAP05, SAP15, and SAP25 used IC with SAPs [4,60]. The concrete compositions were varied by the addition of SAP (0.05%, 0.16%, and 0.26% by weight of cement for Mixtures SAP05, SAP15, and SAP25, respectively). All mixtures had a basic *w/c* ratio of 0.33.

Table 1
Mix proportions of concrete.

Mixture composition	SAP0	SAP05	SAP15	SAP25
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 (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)	81	83	86	89