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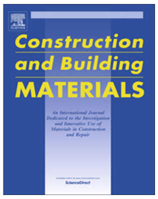

Influence of curing temperature on autogenous shrinkage and cracking resistance of high-performance concrete at an early age

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HIGHLIGHTS

- The cracking resistance of HPC considering curing temperature was studied by TSTM.
- The ratios of cracking stress to tensile strength for HPC were all lower than 1.0.
- The autogenous shrinkage of HPC increased with the increase of curing temperature.
- A model for autogenous shrinkage of HPC was proposed considering curing temperature.
- The HPC specimens cured at isothermal 20 °C showed better cracking resistance.

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ABSTRACT

High-performance concrete (HPC) is widely used in practice. The water-to-cement ratio of HPC is low, and self-desiccation occurs which will induce marked autogenous shrinkage. Autogenous shrinkage usually increases the risk of cracking if the concrete is restrained from shrinking freely at early age. The autogenous shrinkage and cracking resistance of early-age concrete is influenced by curing temperature. However, the effect of curing temperature on autogenous shrinkage of early-age concrete is not in consistency and how the curing temperature affects the cracking resistance of concrete remains lacking. Thus, investigation on the effect of curing temperature on cracking resistance of early age concrete must be further studied. In this study, experimental studies on early-age cracking of concrete under 100% restraint and different curing temperatures were carried out using Temperature Stress Test Machine (TSTM). The present study investigated autogenous shrinkage of early-age HPC cured at different curing temperatures. The experimental results indicate that (1) the ratios of cracking stress to tensile strength for HPC specimens were all lower than 1.0; (2) the autogenous shrinkage of HPC increased with the increase of curing temperature; (3) a prediction model for autogenous shrinkage of HPC was presented considering the effect of curing temperature; (4) cracking temperatures and stress reserves were selected as the main cracking evaluation indicators of TSTM, and the HPC specimen cured at isothermal 20 °C showed better cracking resistance than that at isothermal 45 °C and adiabatic condition.

1. Introduction

With the increasing promoted use of high-performance concrete (HPC), decreasing water-to-cement (w/c) ratio is being applied in practice [1–4]. Although HPC can offer high strength and low permeability, this lower w/c ratio comes with other drawbacks, including high self-desiccation [4,5]. Self-desiccation, which induces marked autogenous shrinkage, leads to higher stress if HPC is restrained and higher cracking potential [6,7]. Thus, it is necessary to evaluate the cracking resistance of HPC reasonably.

The autogenous shrinkage of HPC at early age was influenced by curing temperature. The effect of curing temperature on autogenous shrinkage of the cement pastes [8] and mortar [9] were investigated. The equivalent age equation was used to estimate the autogenous shrinkage of concrete cured at isothermal condition, and the temperature history was ranging from 20 to 60 °C [10,11]. The maturity concept was used to estimate the isothermal autogenous shrinkage of cement paste measured using the

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volumetric method between 10 and 40 °C, and autogenous shrinkage was solely dependent on the degree of hydration in [12]. Although maturity concept may be able to investigate the effect of temperature on autogenous shrinkage for certain cement pastes within a limited temperature range, in general they are inadaptable to describe the effect of temperature on autogenous shrinkage [3,8,13]. The autogenous shrinkage of the specimens at very early stages before the inflection point, showed a larger increase when subjected to lower temperature histories while that of the specimens after the inflection point, showed a larger increase when subjected to higher temperature histories in [4]. Therefore, that the effect of temperature on autogenous shrinkage is inconsistent. Thus, investigation on the influence of temperature on the autogenous shrinkage of HPC must be further studied for better understanding the cracking resistance.

The curing temperature influences the cracking resistance of HPC at early age. The cracking resistance of early-age concrete was investigated at isothermal 20 °C condition using ring test [14], and at semi-adiabatic condition using Temperature Stress Test Machine (TSTM) [1,15–17]. Test results showed that the cracking potential of early-age concrete cured under quasi-adiabatic condition was higher than that under isothermal condition using cracking frame [18].Test results also showed that the concrete cured at isothermal 23 °C cracked later than that at semi-adiabatic and adiabatic conditions using ring test [19]. The lower placing temperature leads to higher cracking resistance of early-age concrete according to TSTM test [20]. However, investigations on the cracking resistance of early-age HPC cured at different temperatures using TSTM remains lacking. Therefore the effect of curing temperature on the cracking resistance of early-age HPC using TSTM must be further studied.

Cracking temperature and stress reserve are important indicators for evaluating the cracking resistance of early-age concrete using TSTM [18,20–23]. The cracking temperature was used to evaluate the cracking resistance of concrete with different contents of cement and fly ash [18], concrete with or without reinforcement [20], and concrete with different types of fine aggregates [21]. Test results of concrete with different types of binder materials showed that highest stress reserve is an indicator of best cracking resistance [22]. The stress reserve was also used to evaluate the cracking resistance of concrete with different ratios of water-to-binder [23] and concrete with or without reinforcement [20]. However, investigations on the cracking temperature and stress reserve of early-age HPC under different curing temperatures remains lacking. Thus, the cracking temperature and stress reserve of early-age HPC under different curing temperatures must be further investigated for better understanding the cracking resistance.

TSTM is often used to study the cracking resistance of early-age HPC [1,16,24,25]. The characteristics of early-age concrete, including autogenous shrinkage, temperature change, strain, and restrained stress, can be determined in one TSTM test [1,24]. However, investigations on the effect of curing temperature on the autogenous shrinkage and cracking resistance of early-age HPC under 100% restraint remain lacking [15,19]. Thus, the effect of curing temperature on autogenous shrinkage, cracking stress, cracking temperature, and stress reserve must to be studied further to better understand the cracking resistance of HPC.

2. Experimental program

2.1. Mixture proportions and materials

The mixture proportions are presented in Table 1. Ordinary Portland cement (Cement II 52.5R) with a Blaine fineness of 375 m^2/kg was employed in accordance with China National Standard GB 175-2009. The physical and chemical compositions of the cement are provided in Table 2. The strength characteristics of the cement are shown in Table 3; the initial setting time is 167 min, the final setting time is 221 min, the compressive strength in 3 d is 35.5 MPa, and the compressive strength in 28 d is 66.9 MPa. Normal weight river sand with a fineness modulus of 2.05 and a maximum size of 1.8 mm was used. The coarse aggregate used was crushed limestone with maximum particle sizes of 26 mm. The apparent density was 2660 kg/m^3. A liquid polycarboxylate-based superplasticizer was employed to adjust the workability of HPC. Tap water was used as mixture water.

Table 1
Mix proportions of concrete.

Cement (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Coarse aggregates (kg/m^3)	Superplasticizer (%)
512	636	171	1131	0.6

In the concrete mixture preparation, the first step was adding all dry materials to the mixer in the following order: coarse aggregate, fine aggregate, and cement. Dry materials were mixed for about 2.5 min, until ingredients were mixed uniformly. Subsequently, the tap water with liquid polycarboxylate-based superplasticizer was slowly added. Finally the concrete was mixed for additional 2 min.

2.2. Test details

Restrained and free shrinkage tests of sealed specimens were conducted with TSTM, which was developed based on the system suggested by Kovler [1,24], as shown in Fig. 1. The frame of TSTM was equipped with two molds, a load cell, a heating–cooling bath, displacement measurement systems, and temperature sensors. The temperature sensors were anchored in the restrained and free shrinkage specimens directly after casting to monitor temperature evolution. The molds of the sample were made of aluminum. Both groups of specimens were temperature-controlled by water circulating in the molds; hence, both isothermal tests and tests with temperature changes can be performed [26].

The restrained shrinkage test setup in TSTM is a horizontal steel frame, in which hardening concrete specimens can be loaded in compression and tension under various hardening conditions. In the restrained shrinkage specimen, one gripped end was fixed, and the other was connected to a stepper motor through a universal joint. The restraint degree δ could be adjusted and can be calculated from Eq. (1).

$$\delta = [(\varepsilon_{sh} - \varepsilon_r)/\varepsilon_{sh}] \times 100\% \tag{1}$$

where ε_{sh} was directly measured in the free autogenous shrinkage specimen, $\mu\varepsilon$; ε_r is the strain development in the restraint test obtained and monitored by a closed loop computer-controlled system. In present study, the degree of restraint (δ) was 100%; thus, ε_r was equal to 0.

This system was a computer-controlled closed loop. In the free shrinkage specimen, one end of the specimen was fixed to the setup, and the other end was free to move horizontally with an attached linear variable differential transducer to measure autogenous deformation under different temperature conditions continuously. TSTM can be used to measure not only temperature development caused by restrained deformations but also stress development in compression and tension [1,16,24].

The dog-bone specimen was characterized by a cross section equal to 150 mm × 150 mm in its center and 150 mm × 280 mm at its extremities; thus, two ends of the specimens were enlarged to ensure uniform stress distribution at the central part [7]. The straight part (center of the specimen) was 1500 mm long. Deformations were employed to control the TSTM restrained shrinkage specimen; different degrees of restraint can be obtained by allowing only a part of the free deformations to occur [27,28]. When shrinkage or expansion occurred and its level approached a strain of 1.3×10^{-6} which is relatively small (i.e., 2 μm shrinkage or expansion for a 1500 mm long specimen), the stepper motor automatically started the motion to pull or push the specimen back to the original position to keep the

Table 2
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