Construction and Building Materials 146 (2017) 410–418

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Tensile creep and cracking resistance of concrete with different water-to-cement ratios at early age

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HIGHLIGHTS

- The tensile creep and cracking potential considering w/c ratio was studied by TSTM.
- The tensile stress rate of concrete increased with the decrease of w/c ratio.
- The early-age specific basic tensile creep increased with the decrease of w/c ratio.
- The early-age basic tensile creep/shrinkage increased with the decrease of w/c ratio.
- The early-age cracking potential increased with the decrease of w/c ratio.

ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 6 April 2017
Accepted 8 April 2017

Keywords:
High-performance concrete
Cracking resistance
Early-age
Tensile creep
Restrained stress
Autogenous shrinkage
Water-to-cement ratio
Temperature Stress Test Machine

ABSTRACT

With the widely use of high-performance concrete, the lower and lower water-to-cement (w/c) ratio is applied in practice. This low w/c ratio can offer high strength and low permeability, however, coming with other drawbacks, such as high self-desiccation and high temperature rise, both of which can increase the early-age cracking potential of concrete. Creep is important to evaluate the early-age cracking resistance of concrete. Although studies on the influence of w/c ratio on the creep of mature concrete have been conducted, investigations on the influence of w/c ratio on the early-age tensile creep remain lacking. Therefore, investigations on the influence of w/c ratio on the tensile creep and cracking resistance of early-age concrete must be conducted. Experimental studies on the influence of w/c ratio (0.33, 0.40, and 0.50) on the temperature change, autogenous shrinkage, restrained stress, tensile creep, and cracking resistance of early-age concrete under adiabatic condition and at full restraint degree were conducted using Temperature Stress Test Machine. The test results indicate that (1) the temperature rise under adiabatic condition increased by 32.6%, and 74.2% when w/c ratio decreased from 0.50 to 0.40, and 0.33, respectively; (2) the restrained tensile stress rate under adiabatic condition and at full restraint degree increased by 16.7%, and 33.3% when w/c ratio decreased from 0.50 to 0.40, and 0.33, respectively; (3) the early-age specific basic tensile creep and basic tensile creep/shrinkage under adiabatic condition and at full restraint degree increased with the decrease of w/c ratio; (4) the early-age cracking potential under adiabatic condition and at full restraint degree increased with the decrease of w/c ratio according to the integrated criterion.

1. Introduction

Concrete has undergone significant changes for the past decades, with the increasing promoted use of high-performance concrete (HPC), decreasing water-to-cement (w/c) ratio is being applied in practice [1–5]. HPC can offer high strength and low permeability [6,7], this low w/c ratio comes with other drawbacks, including high self-desiccation [8,9] and high temperature rise [10], both of which can increase the cracking potential of early-age concrete [11]. Autogenous shrinkage which is a consequence of self-desiccation of concrete leads to cracking and even failure at early age if restrained internally by aggregate skeleton and externally by the hyperstaticity of the structure [12].

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http://dx.doi.org/10.1016/j.conbuildmat.2017.04.056
0950-0618/

Creep is extremely important in estimating the cracking resistance of concrete due to shrinkage and thermal stress at early age [13]. Creep of concrete is the viscoelastic deformation of the cement hydration products under applied stress. Some mechanisms are considered to be responsible for creep: redistribution of capillary water or interlayer water movement, plastic flow, viscous flow, permanent plastic deformation caused by microcracking, and diffusion of solid materials. And early-age concrete creep is influenced by material properties, such as restraint degree, cement type, w/c ratio, aggregate type and content, temperature and humidity, and so on [14,15]. A better understanding of creep is essential for a rational analysis and a more appropriate solution of many practical projects, such as water-retaining structures or pre-stressed elements [16]. Early-age creep occurs in the hardening concrete due to the restrained stress of concrete under restrained condition. More than 50% stresses induced by shrinkage can be relaxed due to tensile creep [17]. However, the creep of concrete at early age is difficult to be obtained because physical and chemical properties change at the same time [17]. Although the creep behaviors of mature concrete have been investigated [14], the creep of concrete at early age under tensile condition is different from that under compressive condition [18]. There is no consensus concerning the tensile creep of concrete at early age with different w/c ratios. For example, the specific tensile creep of concrete at early age decreases with the decrease of w/c ratio in [19,20], while the observations in [21,22] are quite opposite and the specific tensile creep of concrete at early age increases with the decrease of w/c ratio. The investigations of w/c ratio on the effect of tensile creep of early-age concrete including HPC are still lacking [14]. Therefore, the influence of w/c ratio on tensile creep of concrete including HPC at early age needs to be further investigated.

The adiabatic temperature rise profile should be adopted to study the deformation, stress development, tensile creep, and cracking resistance. In reality, the temperature of concrete during early stage increases because of hydration heat, and the temperature decreases thereafter until it reaches environmental condition [23]. The interior concrete of the mass concrete is insulated well, and temperature decrease occurs over long period of time [10,24], this behavior is characterized as being close to that of adiabatic temperature rise profile, in which no heat is lost from the material to its surrounding [10,25]. However, most measurements of early-age behavior of concrete are normally performed at constant temperature [17,26–28]. Up to now, only a few authors have estimated the cracking potential of HPC under adiabatic condition. Investigation of cracking resistance of concrete with different w/c ratios under adiabatic condition is still lacking. Therefore, the effect of w/c ratio on the cracking resistance of early-age concrete including HPC under adiabatic condition should be investigated.

Knowledge of the mechanical properties (relaxation or creep, restrained stress and modulus), restraint degree, and the autogenous shrinkage are essential for quantifying the cracking resistance of concrete at early age. Therefore, some test machines are often used to study the cracking resistance of concrete, such as the ring and doubly restrained plate. However, the results in the doubly restrained plate test depend on specimen geometry, and this test cannot be used for shrinkage stress calculation [29]. The tensile creep of concrete has been investigated by the dual ring test [26]. The restraint degree cannot be kept constant and the restraint degree strongly depends on the geometry and the rigidity of the materials in the ring test [19,30]. The creep of concrete is closely related to the restraint degree [14]. Test results show that the creep of early-age concrete under constant and varying restraint degree is different, and the stress development of concrete is also affected by the creep. The development of microcracking of concrete is also affected by the restraint degree [31]. Therefore, the cracking resistance of concrete is influenced by restraint degree. The restraint degree of Temperature Stress Test Machine (TSTM) could be adjusted and set as constant, even 100% (full restraint degree). The creep could be determined once the restrained stress appears by using TSTM. Therefore, TSTM is often used to study the cracking resistance of early-age concrete [29,32,33]. Therefore, investigations on the cracking resistance of concrete including HPC with different w/c ratios at early age under adiabatic condition and at full restraint degree by using TSTM are necessary to better understand the tensile creep and other properties.

The majority of available studies concerning the cracking resistance of early-age concrete with different w/c ratios do not simultaneously consider temperature history, autogenous shrinkage, restrained stress, and tensile creep under adiabatic condition and at full restraint degree. The influence of all relevant parameters must be studied and quantified to investigate the cracking resistance of concrete at early age with different w/c ratios more accurately [34]. Therefore, the influences of w/c ratio on temperature history, autogenous shrinkage, restrained stress, and tensile creep under adiabatic condition and at full restraint degree need to be further studied by using TSTM to better understand the cracking resistance of early-age concrete.

2. Experimental program

2.1. Mixture proportions and materials

Three concrete mixtures with different w/c ratios were used in present study. The mixture proportions, designated as S33, S40, and S50, are shown in Table 1. For mixtures S33, S40, and S50, the w/c ratio was 0.33, 0.40, and 0.50, respectively.

Ordinary Portland Cement (Cement II 52.5R) with a Blaine fineness of 375 m^2/kg and a loss on ignition of 3.11% was employed in accordance with China National Standard GB 175-2009. The chemical compositions of the cement are shown in Table 2. The strength characteristics of the cement were as following, the initial setting time was 167 min, the final setting time was 221 min, the compressive strength in 3 d was 35.5 MPa, and in 28 d was 66.9 MPa, respectively. Normal weight river sand with a fineness modulus of 2.05 and a maximum size of 1.8 mm was used. Crushed limestone with a maximum size of 26 mm was employed as coarse aggregate. The apparent density was 2660 kg/m^3. A liquid polycarboxylate-based superplasticizer was added to mixtures S33 and S40 in the amount ensuring flow ability similar to the mixture S50. Tap water was used as mixing water. The concrete was mixed for about 2 min.

2.2. Test details

Restrained and free shrinkage tests of sealed specimens were conducted with TSTM, which was developed combining the principles of Kovler [1,29] as uniaxial restrained shrinkage closed-loop computer-controlled setup, and of Springenschmid [35] as TSTM machine, as shown in Fig. 1. The frame of TSTM was equipped with

Table 1
Concrete mixture proportions.

Mixture composition	Concrete mixtures		
	S33	S40	S50
Water (kg/m^3)	171	180	200
Cement (kg/m^3)	512	450	400
Fine aggregate (sand) (kg/m^3)	636	655	666
Coarse aggregate (kg/m^3)	1131	1165	1184
Superplasticizer (%)	0.6	0.4	0