Construction and Building Materials 119 (2016) 241–250

Contents lists available at ScienceDirect

Construction and Building Materials

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

Damage behaviors of self-compacting concrete and prediction model under coupling effect of salt freeze-thaw and flexural load

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HIGHLIGHTS

- The damage behaviors of self-compacting concrete under coupling effect of salt freeze-thaw and flexural load were studied.
- Higher stress levels always caused earlier and more occurrences of brittle fracture.
- A prediction model of damage degree of self-compacting concrete was proposed.

ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form 4 May 2016
Accepted 9 May 2016
Available online 17 May 2016

Keywords:
Self-compacting concrete
Salt freeze-thaw
Flexural load
Damage behavior
Prediction model

ABSTRACT

In this paper, the workability, mechanical properties and damage behaviors of self-compacting concrete (SCC) under coupling effect of salt freeze-thaw and flexural load were experimentally investigated. The results showed that the workability of fresh SCC and mechanical properties could be influenced by fly ash, blast furnace slag and silica fume added in the mixture. Salt freeze-thaw had small influences on the surface erosion and relative dynamic elastic modulus of the SCC used in this study. Under coupling effect of salt freeze-thaw and flexural load, different levels of flexural load were applied on the SCC specimens. The results showed that with increasing salt freeze-thaw cycles, the weight loss increased and the relative dynamic elastic modulus declined. The coupling effect had a slight influence on the surface erosion, while it had a significant influence on the occurrence of brittle fracture. Higher stress levels always caused earlier and more occurrences of brittle fracture. A prediction model of the damage degree of SCC was proposed by incorporating the test results achieved in the paper. The comparison results showed that the prediction values had good consistencies with the experimental values. The model is expected to be used to predict the damage degree of SCC under coupling effect of salt freeze-thaw and flexural load.

1. Introduction

The damage of concrete structure is easily caused by flexural load, which provides channels for salt solution to enter the concrete. In this case, the damage propagation in concrete is easily intensified by salt freeze-thaw cycles. That is, the coupling effect of flexural load and salt freeze-thaw cycle can accelerate the damage of concrete [1–3]. Especially in cold regions, concrete damage under coupling effect of salt freeze-thaw and flexural load is one of the main durability problems for in-service concrete structures [4].

The damage behaviors of concrete under the single effect of salt freeze-thaw cycle or flexural load have been studied by many researchers. For example, the damage behaviors of plain concrete and self-compacting concrete (SCC) under coupling effect of salt freeze-thaw and other factors (e.g., water flow [5], carbonation [6] and wet-dry cycle [7]) have been performed. Besides, the damage behaviors of plain concrete under the coupling effect of flexural load and other factors (e.g., chemical attack [8,9], chemical attack and carbonation [10], water freeze-thaw [1,2,11], high concentrated bitterns and freeze-thaw [12], mixed corrosion and freeze-thaw [13], seawater and freeze-thaw [14], mixed corrosion, carbonation and freeze-thaw [15]) were also performed. By far, only Sun et al. have studied the damage behaviors of plain concrete, high-strength concrete and steel fiber reinforced concrete under coupling effect of salt freeze-thaw and flexural load [4,16–18].

Besides the experimental investigations on the damage behaviors of concrete, many researchers also proposed some damage prediction models for plain concrete under the single effect of freeze-thaw cycle [19–23], the coupling effect of freeze-thaw cycle and other factors (e.g., salts attack [19,24], carbonation [25], and

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http://dx.doi.org/10.1016/j.conbuildmat.2016.05.073
0950-0618/

salts attack and water flow [5]), and the coupling effect of flexural load and other factors (e.g., chemical attack [26] and water freeze-thaw [27]).

SCC has many advantages, such as high fluidity [28], low noise during casting [29] and high pouring efficiency [30]. Nowadays, it has been widely applied in many kinds of structures [31]. However, the internal microscopic pore structure and material composition of SCC are different from those of plain concrete, high-strength concrete and steel fiber reinforced concrete, which determines the significant durability differences of these four concretes [32]. Unfortunately, there are no studies on the damage behaviors of SCC and prediction model under coupling effect of salt freeze-thaw and flexural load, which is the main purpose of this study.

As a result, a SCC mixture that had better workability, better mechanical properties and higher salt freeze-thaw resistance was selected to experimentally study the influences of the coupling effect of salt freeze-thaw and flexural load on its damage behaviors through the workability, mechanical properties and salt freeze-thaw tests. Based on the experimental results of achieved in the paper, a regression model was proposed to predict the damage degree of SCC under coupling effect of salt freeze-thaw and flexural load.

2. Materials and test methods

2.1. Materials

It was revealed that the concrete mixed with fly ash, blast furnace slag, silica fume or air-entrainment agent had higher salt freeze-thaw resistance [33–36]. To achieve this purpose, fly ash, blast furnace slag and silica fume were added in the SCC mixtures. Accordingly, the water-binder ratio was used to design the mixtures, of which the binder included cement, fly ash, blast furnace slag and silica fume. The water-binder ratio (by weight) of the SCC mixtures was set to be 0.35, and the binder content was kept at 460 kg/m^3. Ordinary Portland cement (CEM I 42.5 N) was used. The fine aggregate was natural sand with sizes below 0.67 mm, and the coarse aggregate was crushed limestone with sizes between 2.5 mm and 8 mm. The polycarboxylic based water-reducing agent and polycarboxylic based air-entraining agent were used to obtain good workability and appropriate air content, respectively. The detailed mixture proportions of five SCC mixtures prepared by adding different dosages of fly ash, blast furnace slag and silica fume are shown in Table 1.

2.2. Description of specimens

For each mixture, a total of seven groups of specimens (150 mm × 150 mm × 150 mm) were prepared. Four groups of specimens were used to measure the 3-day, 7-day, 28-day and 56-day compressive strengths, respectively. The other three groups were used to measure the 28-day and 56-day tensile strength and the 56-day tensile strength after 50 salt freeze-thaw cycles.

One group of specimens (150 mm × 150 mm × 300 mm) of each mixture was prepared to measure elastic modulus. And one group of specimens (40 mm × 40 mm × 160 mm) of each mixture was prepared for salt freeze-thaw test.

A total of five groups of specimens (40 mm × 40 mm × 160 mm) of the SSF mixture were prepared. One group of specimens was used to measure the 28-day flexural strength. The other four groups were used to experimentally study the damage behaviors under coupling effect of salt freeze-thaw and flexural load. Four load levels of 0, 10%, 30% and 50% of flexural strength were applied to the four groups of specimens (i.e., SSF-0, SSF-10, SSF-30 and SSF-50), respectively.

The details, including geometric dimensions, numbers of specimens, load levels of flexural strength and test parameters, of all specimens used in different tests are shown in Table 2. Before test all the specimens were cured under the temperature of 20 ± 2 °C and humidity of 95%.

Table 2
Details of all specimens.

Mixture type	Geometric dimensions (mm)	Numbers of specimens (group × number)	Load levels of flexural strength	Test parameters
Control	150 × 150 × 150	4 × 3	–	3-day, 7-day, 28-day and 56-day compressive strength
SF	150 × 150 × 150	4 × 3	–	
SSF	150 × 150 × 150	4 × 3	–	
FSF	150 × 150 × 150	4 × 3	–	
FSSF	150 × 150 × 150	4 × 3	–	
Control	150 × 150 × 150	3 × 3	–	28-day and 56-day tensile strength and 56-day tensile strength after 50 salt freeze-thaw cycles
SF	150 × 150 × 150	3 × 3	–	
SSF	150 × 150 × 150	3 × 3	–	
FSF	150 × 150 × 150	3 × 3	–	
FSSF	150 × 150 × 150	3 × 3	–	
Control	150 × 150 × 300	1 × 6	–	Elastic modulus
SF	150 × 150 × 300	1 × 6	–	
SSF	150 × 150 × 300	1 × 6	–	
FSF	150 × 150 × 300	1 × 6	–	
FSSF	150 × 150 × 300	1 × 6	–	
Control	40 × 40 × 160	1 × 3	–	Weight loss and relative dynamic elastic modulus
SF	40 × 40 × 160	1 × 3	–	
SSF	40 × 40 × 160	1 × 3	–	
FSF	40 × 40 × 160	1 × 3	–	
FSSF	40 × 40 × 160	1 × 3	–	
SSF	40 × 40 × 160	1 × 3	–	Flexural strength
SSF-0	40 × 40 × 160	1 × 3	0	Weight loss, relative dynamic elastic modulus and damage mode
SSF-10	40 × 40 × 160	1 × 3	10%	
SSF-30	40 × 40 × 160	1 × 3	30%	
SSF-50	40 × 40 × 160	1 × 3	50%	

2.3. Test methods

2.3.1. Workability of fresh SCC mixtures

The slump flow diameter (SFD), slump flow time to reach a 500 mm-diameter spread circle (T_{500} time), slump flow diameter of J-Ring test (JRD) and separation ratio of fresh SCC mixture were measured to evaluate the filling, passing and anti-separation abilities, respectively, according to the methods reported in JGJ/T 283-2012 [37].

2.3.2. Compressive strength test and elastic modulus test

The compressive strength at ages of 3 days, 7 days, 28 days and 56 days, and elastic modulus at age of 28 days were measured according to the methods reported in GB/T 50081-2002 [38].

2.3.3. Splitting tensile strength test

The 28-day, 56-day splitting tensile strength and 56-day splitting tensile strength after 50 salt freeze-thaw cycles were measured according to the method reported in GB/T 50081-2002 [38].

2.3.4. Salt freeze-thaw test

All the specimens were immersed in the 3.5 wt.% NaCl solution for 4 days at a constant temperature of 20 °C before salt freeze-thaw test. The 3.5 wt.% NaCl solution was also used in the salt freeze-thaw test, which was conducted according to the method reported in ASTM C666 Procedure A [39]. The 28-day specimens (40 mm × 40 mm × 160 mm) and 56-day specimens (150 mm × 150 mm × 150 mm) were salt frozen and thawed for 300 and 50 cycles in the salt solution with

Table 1
Mixture proportions of SCC (kg/m^3).

Mixture type	Water	Cement	Fly ash	Blast furnace slag	Silica fume	Fine aggregate	Coarse aggregate	Water-reducing agent	Air-entraining agent
Control	160	460	–	–	–	688	1099	5.98	0.032
SF	160	305	66	89	0	688	1099	5.98	0.032
SSF	160	327	0	111	22	688	1099	5.98	0.032
FSF	160	327	111	0	22	688	1099	5.98	0.032
FSSF	160	283	66	89	22	688	1099	5.98	0.032