Construction and Building Materials 191 (2018) 1–12

Contents lists available at ScienceDirect

Construction and Building Materials

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

Restrained early-age shrinkage cracking properties of high-performance concrete containing fly ash and ground granulated blast-furnace slag

Lina Ma, Yanhua Zhao *, Jinxin Gong

State Key Laboratory of Costal and Offshore Engineering, Dalian Univ. of Technology, No. 2 Linggong Road, Ganjingzi District, Dalian 116024, China

HIGHLIGHTS

- Concrete slab test is a practicable method to study early-age shrinkage cracking.
- Fly ash and slag are useful in controlling early-age shrinkage cracking.
- Larger water/binder delays initial cracking, but increases cracking width and area.
- Restrained condition has inverse effects on early-age shrinkage cracking property.

ARTICLE INFO

Article history:
Received 8 April 2018
Received in revised form 8 September 2018
Accepted 20 September 2018

Keywords:
Shrinkage cracking
Shrinkage strain
Cracking area
Maximum crack width
Restrained slab test

ABSTRACT

The investigation was carried out to study the effects of water/binder (*w*/*b*) ratio, replacement level of supplementary cementitious materials (SCM), and restrained condition on early-age shrinkage cracking of high-performance concrete (HPC). To this end, concrete slabs with threaded rods placed peripherally providing restraints were used. Four *w*/*b* ratios were considered, namely, 0.25, 0.30, 0.35, and 0.40. For each *w*/*b* ratio, five replacement levels of cement with SCM (fly ash/slag = 1:1) were adopted: 0%, 20%, 30%, 40% and 50% by weight of total binder content. Furthermore, for each replacement level, unrestrained, two-side restrained and four-side restrained conditions were imposed to study cracking area, maximum crack width, cracking time, and shrinkage strain development for early-age HPC. The test results show that partially replacing cement by SCM led to a better crack resistance behavior of HPC. As the replacement level increased, cracking area and maximum crack width decreased, and the initial cracking time was delayed. While for a higher *w*/*b* ratio, cracking area and maximum crack width increased and it took much longer time to initiate cracking. But for very low *w*/*b* = 0.25 and two-side restrained condition, no crack was observed due to the enhanced structure of concrete. No crack appeared for unrestrained HPC slabs. More restraints, however, increased cracking area and maximum crack width and at the same time initiated cracking earlier. Statistical analysis showed that the crack width was well fitted using lognormal probabilistic model. Shrinkage strain was larger in the middle part of concrete slab edges by comparing to that at the corner. Shrinkage strain was smaller for a higher SCM volume, a higher *w*/*b* ratio and less restraints and they could be used to account for the cracking potential of concrete at early age.

1. Introduction

High-performance concrete (HPC) nowadays has found wide applications due to its excellent workability, low permeability and improved durability comparing to traditional concrete. HPC is often obtained by keeping a low water to cement (*w*/*c*) ratio and adding supplementary cementitious materials (SCM), such as fly ash, silica fume or slag. As a result, early-age shrinkage of HPC may be considerable. The shrinkage that causes cracking may be from plastic shrinkage, autogenous shrinkage, drying shrinkage or thermal gradient. Plastic shrinkage is a volume change of concrete while the concrete is still in a plastic state. Fast evaporation of moisture can be responsible for plastic shrinkage. Autogenous shrinkage is a volume change without moisture transfer to the environment, and it is a result of chemical reactions during cement hydration process. Autogenous shrinkage is most prominent in HPC. Drying shrinkage is the volume decrease in concrete with moisture exchange with the environment. Drying shrinkage and autogenous shrinkage are the two main contribu-

* Corresponding author.
E-mail addresses: yanhuazh@dlut.edu.cn (Y. Zhao), gongjx@dlut.edu.cn (J. Gong).

https://doi.org/10.1016/j.conbuildmat.2018.09.154
0950-0618/

tions to the total shrinkage of concrete. Shrinkage per se cannot produce cracking, but concrete members often receive restraints from reinforcement, foundation or adjoining structure members which may prevent this movement resulting in residual tensile stresses in concrete that may be sufficient to cause cracking. It is generally agreed that HPC has a high potential of early-age shrinkage cracking that may cause a significant degradation of strength and durability of HPC. These restraints can be grouped into external restraining and internal restraining [1,2]. External restraint is imposed by components that are not part of the concrete member, such as supports or adjacent parts. Internal restraint is achieved by elements that are part of the concrete such as aggregate. The restrained extent from aggregates was found to be associated with aggregate type, size, volume, and absorption rate [3–5]. In mass concrete, internal restraint is mainly the restraint arising from different volume changes (thermal gradient). Even so, when it comes to restraint, most researches focus on external restraining condition [6,7]. At present, there are no standard testing methods to assess restrained shrinkage cracking, and various specimen geometries have been used to simulate restrained conditions, such as axially or linearly restrained condition for concrete or reinforced concrete [8], plate/slab-shaped geometries [1,9–12] or restrained circular or elliptical rings [3,6,13]. What's more, molds with steel inserts to initiate cracking was updated to measure plastic shrinkage [14]. Geometries have been chosen for different purposes of research. Axially restrained geometry, restrained circular and elliptical geometry are often used to detect cracking caused by shrinkage from autogenous shrinkage and drying shrinkage. The restrained ring-test is economical, easy to perform and does not pose difficulties in providing sufficient end restraint. Up to now the restrained ring or elliptical-ring has been widely used to assess the shrinkage cracking potential of cement-based materials. Dong et al. used elliptical ring specimens to assess the likelihood of cracking and cracking age of concrete subject to restrained shrinkage [7]. Nguyen et al. studied the early-age shrinkage cracking of HPC for two mixes using restrained ring tests and found the early-age cracking potential increased with the decrease of *w/b* ratio [15]. A similar trend was found in the literature where uniaxially restrained dog-bone geometry was used [16]. This linear specimen geometry belongs to a quantitative test method, which can measure the early shrinkage stress, elastic modulus and other parameters of concrete. But it is not popular because of high cost of frames and difficulties associated with providing sufficient end restraint [13]. Slab-like geometry is often aimed at cracking problems due to plastic shrinkage that occurs within the first few hours after concrete has been placed. Also, restrained and unrestrained slabs were used to assess cracks induced from drying shrinkage [1,12]. Concrete slab undergoes external restraint from threaded rods peripherally placed around the slab mold which is more suitable for simulating highway pavements and bridge decks which are characterized by large surface to volume ratio. High strength concrete slabs restrained at the end were found to crack considerably earlier than normal strength concrete when silica fume slurry was added in high strength concrete and no SCM was used in normal strength concrete [11]. Concrete panels were used to evaluate plastic shrinkage cracking when subjected to varying exposure conditions [17], where cracking initiation time, cracked area, and crack width were monitored.

2. Research significance and objective

Despite growing concerns on the early-age shrinkage of HPC, very incomplete information is available regarding the restrained shrinkage-cracking of HPC slabs that can be used to simulate highway pavement or bridge decks. As such, the main focus of this paper is on characterizing the early-age shrinkage cracking of HPC slabs, including cracking pattern, cracking area, cracking width, cracking potential and shrinkage strain development. Among them, cracking pattern, cracking area, and cracking width were recorded at the 3rd day of testing, and strain development were monitored until 2 d of testing, thus the shrinkage that caused cracking may be the combination result of plastic shrinkage, drying shrinkage and autogenous shrinkage. Three variables were considered in the experimental design: *w/b* ratio, cement replacement level by SCM and restrained condition. Therefore, the influences of *w/b* ratio, SCM volume and restrained condition were studied for better understanding the cracking resistance of early-age HPC.

3. Experimental programs

3.1. Materials

Ternary binding materials used in this study comprised cement, fly ash and ground granulated blast-furnace slag, and they were all manufactured in China. The cement used was Portland cement P·II42.5R fulfilling the requirements of the Chinese standard GB 175-2007 *Common Portland Cement*. The compressive strength of the cement at 3 d and 28 d were 28.3 MPa and 53.9 MPa, respectively, and its specific area was 331 m^2/kg. Class I fly ash was selected in accordance with the Chinese standard GB/T1596-2005 *Fly Ash Used for Cement and Concrete* which had a specific surface area larger than 400 m^2/kg. S95 ground-granulated blast-furnace slag that had a density of 2.87 g/cm^3 and specific surface area 417 m^2/kg was used conforming to the Chinese standard GB/T 18046-2008 *Ground Granulated Blast Furnace Slag Used for Cement and Concrete*. The chemical compositions of the cement, fly ash and slag used in the study are shown in Table 1.

For fine aggregates, a natural river sand was used whose fineness modulus was 2.40 and whose gradation zone was II as specified by the Chinese code JGJ52-2006 *Standard for Technical Requirements and Test Method of Sand and Stone (or Gravel) for Ordinary Concrete*. Graded crushed gravel with a maximum size of 25 mm was used as coarse aggregate. For the sake of workability of concrete, a polycarboxylate-based superplasticizer (water-reducing rate larger than 25%) was used, and its dosage was properly adjusted to maintain a similar slump of about 200 mm for all mixtures. In addition, mixing water was local fresh tap water.

3.2. Mixing proportions

In this study, four different *w/b* ratios of 0.25, 0.30, 0.35 and 0.40 were included. For each *w/b* ratio, five concrete mixtures were designed according to the amount of SCM, i.e., 0, 20%, 30%, 40% and 50% meaning the total mass percentage of fly ash and slag to the binder where the fly ash and slag were of the same mass. As one of the purposes of this study goes to investigate restrained shrinkage, three restrained conditions were arranged including one control concrete without any restraint and two restrained conditions (two-side restrained and four-restrained). Table 2 presents the proportions and details of all mixtures.

3.3. Experimental methods

The slab for shrinkage testing had dimensions of 600 mm × 600 mm × 63 mm, and three different restrained conditions were applied as shown in Fig. 1. For restrained slabs, M10 × 100 mm threaded rods were placed staggeringly along the mold periphery (two sides for two-side restrained condition and four sides for four-side restrained condition), which could restrain concrete when shrinkage happens; while for unrestrained slabs, no bolts were arranged and they could be regarded as control slabs. For restrained slabs, strain gauges were mounted at the root of the upper bolts, and then connected to a data acquisition system logged on a computer for shrinkage strain measurement, as shown in Fig. 2. The bottom surface of each wood mold was covered with a polyethylene film to prevent the loss of cement paste and water as well as minimize the frictional restraint during HPC shrinkage. After casting, the specimens in mold were exposed to a laboratory-controlled air at temperature of (20 ± 5) °C and (50 ± 5%)RH, and concrete samples were placed under a light bulb and an electric fan producing a constant wind speed of 4.8 m/s for accelerating drying of concrete (see Fig. 3). Only one specimen per condition was tested. The slabs were checked visually for sign of cracking every 30 min and the test was ended at 3d when the recorded restrained strain nearly unchanged. In addition, cubic specimens 150 mm × 150 mm × 150 mm exposed to the same condition as slabs were used for compressive strength at 28 d of HPC, and results are illustrated in Table 2. It can be concluded that the addition of SCM up to 50% replacement shows little adverse impact by comparing to HPC without any SCM.

Here, total cracking area, crack width and initial cracking time were adopted to evaluate the early-age cracking resistance of HPC. The term "crack" in this paper means a macrocrack that can be visually detected. Hereinto, the cracking initiation time of each specimen was determined visually by inspecting the specimen top sur-