Construction and Building Materials 49 (2013) 635–642

Contents lists available at ScienceDirect

Construction and Building Materials

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

Early-age strain–stress relationship and cracking behavior of slag cement mixtures subject to constant uniaxial restraint

Ya Wei [a,*], Will Hansen [b]

[a] Key Laboratory of Civil Engineering Safety and Durability of China, Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Civil and Environmental Engineering, University of Michigan, 2340 Hayward, Ann Arbor, MI 48109, USA

HIGHLIGHTS

- A rig was developed to measure restrained stress starting right after casting.
- Thermal and autogenous shrinkage contributions to restrained stress were recognized.
- A constitutive relationship exists between restrained shrinkage and tensile stress.
- The cracking behaviors were described for slag cement and OPC systems.

ARTICLE INFO

Article history:
Received 25 December 2012
Received in revised form 4 August 2013
Accepted 29 August 2013
Available online 25 September 2013

Keywords:
Cracking potential
Effective modulus
Restrained shrinkage
Shrinkage rate
Slag cement
Strain–stress relationship

ABSTRACT

In this study, the early-age strain–stress development of mixtures containing slag cement was measured on uniaxially restrained specimens using a specially designed testing frame starting right after casting. It was found that thermal deformation dominates early-age stress development in low w/cm and low slag cement paste systems. While for concrete, autogenous shrinkage is the major contributing factor for tensile stress development. The early-age stress development of uniaxially restrained cementitious mixture specimens is profoundly influenced by the overt early-age relaxation effect, such that the compressive stress is significantly reduced and tensile stress develops before shrinkage begins. A linear shrinkage and tensile stress relationship is found to exist in mixtures subject to such constant restraint, regardless of w/cm and slag cement contents. Slag cement has the benefit of delaying tensile stress development and cracking time because of the reduced early-age thermal effect as compared to the ordinary Portland cement mixture. The cracking of the slag cement mixture is mainly due to the greater long-term autogenous shrinkage. The cracking time is found closely related to the shrinkage rate rather than the shrinkage magnitude, a unique relationship can be used to describe such phenomenon.

1. Introduction

Concrete structures experience volume changes as a result of thermal- and moisture-related deformations during hardening. For structures subject to external restraint from surrounding substrate or internal restraint from size effect, tensile stress develops due to the restrained shrinkage, which contributes to the premature cracking and affects the durability of newly constructed or repaired structures. Quantifying shrinkage induced stress and assessing the associated cracking potential in concrete members have been difficult due to many factors involved, such as stress relaxation, combined thermal and hygral effects. Several test methods have been proposed to assess cracking potential of concrete, including tests using restrained ring specimens [1–3] and tests using uniaxially restrained specimens [4–7]. The cracking potential of concrete has been classified as four categories of low, low to moderate, moderate to high, and high, based on time-to-cracking and stress rates obtained from the restrained ring test with specimens exposed to external drying conditions [8,9].

On the other hand, slag cement has been widely used in concrete structures due to many advantages, such as less carbon dioxide emission during the production process, lower hydration heat, lower permeability, and better resistance to sulphate attack [10]. However, cementitious mixtures containing slag cement have been observed to show a crossover effect with lower autogenous shrinkage at very early ages and greater autogenous shrinkage at later ages [11–13]. The tensile stress development and the associated cracking potential might be an uncertainty, as they are the coupled effect from both thermal contraction and shrinkage deformation.

The evaluation of cracking stress of structures requires material properties determined in a system subject to the similar restraint conditions to the field structures. For this purpose, this study measures strain–stress development in the uniaxially restrained

---

* Corresponding author. Tel.: +86 1062771646; fax: +86 1062785836.
E-mail address: yawei@tsinghua.edu.cn (Y. Wei).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.08.061

cement paste and concrete specimens, starting at very early ages using a specially designed rig. To investigate the pozzolanic effects, concretes containing slag cement are tested as well. A constitutive relationship between shrinkage and the restrained tensile stress was found for mixtures subject to constant uniaxial restraint. Mixtures containing slag cement show delayed time at cracking. The cracking potential depends on shrinkage rate. The results of this study are of significance for evaluating and mitigating early-age cracking in concrete members.

2. Experimental programs

2.1. Materials and mixture proportions

Type I ordinary Portland cement (OPC) and slag cement (Grade 120) were used as cementitious materials. The replacement levels of slag cement were 0%, 30% and 50% by mass of the total cementitious materials. The chemical composition and physical properties of each materials are listed in Table 1. The coarse aggregate was crushed limestone with a maximum size of 12.5 mm. The fine aggregate was natural sand with a fineness modulus of 2.56.

The mixture proportions of cement pastes and concretes used in this study are presented in Table 2. Cement paste was mixed in a pan mixer. For blended systems, the slag cement was first dry-mixed with Portland cement for several minutes to achieve a uniform distribution of the solid ingredients. Water was then added to the dry ingredients and mixed for another three minutes. The amount of high-range water-reducing admixture was used and adjusted to achieve adequate workability in low water–cementitious ratio concrete (w/cm = 0.35).

2.2. Autogenous shrinkage measurement

Linear autogenous shrinkage was measured on sealed-cured specimens, using a double-walled, water-cooled, stainless steel rig, as shown in Fig. 1. The specimen cross-section was 60 mm in height, 100 mm in width, and 1000 mm in length. External drying was prevented by sealing the specimens immediately after casting using two layers of polystyrene sheets. External restraint between the specimen and the stainless steel rig was kept to a minimum by placing a soft, flexible, 2 mm-thick foam rubber between the rig and the sealed specimen. The curing temperature was maintained at 23 ± 1 °C by circulating water through the double-walled chamber built-into the sides and bottom of the rig. One end of the specimen was fixed to the rig and the other end was free to move horizontally. The free end had an LVDT attached for measuring the autogenous deformation continuously. The measurement was initiated after final set and the data were recorded every 10 min.

2.3. Uniaxially restrained stress measurement

The restrained test measures stress development in the cementitious mixtures starting immediately after casting using a horizontal testing frame built for this purpose (shown in Fig. 2). Such a linear measuring system, according to Weiss and Shah [1], has the advantage of relatively straightforward data interpretation. The frame used in this study includes a load cell and an actuator with servo-hydraulic control. To provide sufficient restraint and to avoid drift over a long period of testing time, the actuator position was controlled, so that the concrete can be assumed to be under "full restraint" condition [14]. This type of frame is known as an active restraining rig for achieving a "full restraint" condition, which is independent of the restraining rigidity of the testing rig [14,15]. The 810 mm long specimen was cast directly into a mold held by the frame. Two ends of the specimen were enlarged and the central part has a cross-section of 100 mm by 100 mm. One end of the specimen was fixed to the load cell and the other end was connected to the actuator by restraint bars that are embedded in specimen. A thin vinyl sheet was placed between the specimen and the mold to reduce frictional resistance. Immediately after casting, the upper surface of the specimen was covered with a plastic sheet to prevent evaporation. The mold was equipped with copper pipes to circulate constant-temperature (23 ± 1 °C) water from a heating–cooling control bath. During the entire testing, the specimen was cured under sealed condition. The temperature distribution in the specimen was measured at three locations along the specimen depth. It was found that the specimens had a uniform temperature distributions at all times. The measurement started immediately after casting. Load was measured during the test and the data were recorded once per minute.

3. Results and discussions

3.1. Zero-stress temperature and zero-stress strain

For a restrained sealed-cured specimen, the development of early-age stress is a result of thermal and autogenous deformations. Fig. 3 shows the typical curves of temperature, autogenous deformation, free strain, and restrained stress developments measured on a sealed-cured concrete specimen. It can be seen that after casting the temperature of mixture increases from mixing temperature to the maximum due to the accelerated cement hydration, and then drops because of the slowdown of cement hydration. The temperature stabilizes eventually at the ambient temperature. The autogenous deformation starts with autogenous expansion followed by autogenous shrinkage, while the free strain shown in Fig. 3c is a combined effect from thermal and autogenous deformation. The starting point of free strain (ε_{01}) corresponds to the first zero-stress σ_{01} where the mixture reaches final set [16] and starts strength gain. After σ_{01}, the compressive stress starts to develop due to the restrained expansion deformation generated from the temperature rise and autogenous expansion. The temperature corresponding to the first zero-stress is the first zero-stress temperature ($T_{1st\text{-}zero\text{-}stress}$). The expansion deformation and the compressive stress grow continuously with the increase of temperature and autogenous expansion, and reach maximum at the maximum autogenous expansion. Then with the temperature drop or autogenous shrinkage development, the magnitude of expansion and the compressive stress reduces. At $T_{2nd\text{-}zero\text{-}stress}$, the restrained stress switches from compression to tension, indicating that after this point, any temperature drop or autogenous shrinkage deformation, if restrained, will generate tensile stress. It should be noted that $T_{1st\text{-}zero\text{-}stress}$ is not equal to $T_{2nd\text{-}zero\text{-}stress}$, and ε_{02} corresponding to the second zero stress is not necessary to be zero, because the high relaxation property of young concrete causes most of the compressive stress to be relaxed, and thus tensile stress might generate while mixture is still in expansion.

3.2. Free strain and uniaxially restrained stress developments

The free strain and restrained stress developments of cement paste and concrete were shown in Fig. 4. The free strain was calculated based on: $\varepsilon = (T_{1st\text{-}zero\text{-}stress} - T) \cdot \alpha + \varepsilon_a$, where, T is the temperature of restrained specimen; α is the coefficient of thermal expansion of cementitious mixture; ε_a is the autogenous deformation with positive value representing the autogenous shrinkage. The cementitious mixtures containing slag cement normally has lower coefficient of thermal expansion due to the less content of calcium hydroxide of which the coefficient of thermal expansion is high [17]. Therefore, α is taken as 18×10^{-6}/°C and 15×10^{-6}/°C for OPC pastes and slag cement pastes, respectively. For concrete the α value is taken as 10×10^{-6}/°C.

It is seen that the restrained stress develops following closely with the free strain development. Cement paste shows much faster strain and stress development as compared with those of concrete, and all paste specimens cracked within the first week. The free strain of concrete develops more slowly and at a lower magnitude, which allows more time for tensile stress to be relaxed. No cracking was observed during the testing period of 12 days for concrete.

Table 1
Chemical compositions and physical properties of cementitious materials.

Materials	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Blaine fineness (cm^2/g)
OPC	20.4	5.04	2.51	62.39	3.43	2.75	0.25	0.67	4290
Slag	37.49	7.77	0.43	37.99	10.69	3.21	0.28	0.46	6020