Measurement 46 (2013) 4313–4320

Contents lists available at ScienceDirect

Measurement

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

Added advantages in using a fiber Bragg grating sensor in the determination of early age setting time for cement pastes

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ARTICLE INFO

Article history:
Received 30 August 2012
Received in revised form 5 April 2013
Accepted 24 June 2013
Available online 3 July 2013

Keywords:
Cement paste
Early age curing
Curing period
Portland cement
FBG sensor

ABSTRACT

A fiber Bragg grating (FBG) sensor was used to monitor the early age curing temperatures of cement paste. Additional advantages in using the sensor were highlighted. The FBG was inscribed by a Continuous Wave 244 nm argon ion laser in the photosensitivity fiber. The fabricated FBG was calibrated from room temperature to 105 °C. In this temperature range, the FBG was found to be good in terms of both the sensitivity and linearity which were around 9 pm/°C and 99.9%, respectively. A host specimen with ratio of Portland cement, sand and water of 800, 500, and 275 ml by volume was used in the experiment. Results showed that the FBG could determine the initial and the final early age setting times. The initial early age setting time for the cement paste was about 5 h and the final early age setting time was about 14 h after casting.

1. Introduction

Early-age cracking can be a significant problem in concrete. Cracks can develop when the tensile stress due to the volume changes in concrete exceeds the tensile strength, which is generally only 10% of the compressive strength as stated by Lothenbach et al. [1]. At early age, this strength is still developing while stresses are generated by volume changes. The volume of concrete begins to change shortly after it is cast and the early volume changes within 24 h can influence tensile stress and crack formation in hardened concrete. Escalante-Garcia and Sharp [2] showed that the early-age volume change is related to the chemical shrinkage, auto-genous shrinkage, creep, swelling, and thermal expansion. The increasing curing temperature can promote the hydration process leading to high early strength. As cement hydrates, the reaction is exothermic and provides a significant amount of heat. In large elements, this heat is trapped and can induce significant expansion. When thermal changes are superimposed upon auto-genous shrinkage at early age, cracking can occur. Several researchers like Escalante-Garcia and Sharp [3], Komonen and Penttala [4] and Price [5] have shown that the differential thermal stress can occur due to rapid cooling of large volumes of concrete elements. As such, the temperature monitoring and control are most important during the casting of concrete structures. Generally, a thermocouple can provide temperature measurement with an acceptable accuracy, however, it is a typical local sensor, which only provides the temperature measurement at a certain location.

Conventionally, the temperature monitoring for concrete structures can be carried out by the use of thermocouples embedded in the cement paste as pointed out by Bushnell-Watson and Sharp [6] and Bushnell-Watson and Sharp [7,8]. Glisic and Simon [9] and Hampshire and Adeli [10] showed that in the last few decades, optical fiber sensors have been utilized in composite material field popularly for their predominating advantages such as small size, low cost, and capability of avoiding electromagnetic influence. In the late 1980s, FBG sensor attracted considerable attentions to the applications in aerospace, structural, medical and chemical spheres as exemplified by work by Okabe et al. [11], Slowik et al. [12] and Wong et al. [13]. Since then, the FBG have received more research attentions

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0263-2241/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.measurement.2013.06.036

in optical communication and sensing applications, especially in the sensing of temperature and strain.

Laboratory equipment has been designed to investigate curing and other properties of cement and concrete using the above instrumentation by researchers like Wilson and Gupta [14]. Xie et al. [15] demonstrated a novel system to investigate the Bragg wavelengths shift of an array of in-FBGs by a digitizing method. A grating scale was employed to read out the output of the system.

The application of optical fiber to monitor the cement curing process has been conducted by several workers like André et al. [16]. A method was proposed which is based on the scattering of the propagated optical signal in grooves imposed to the fiber. By monitoring the intensity of the transmitted light signal with time the cement setting rate along all the curing period was determined. The system had enough sensitivity to analyze a curing period of 28 days, where the received optical power was 5% of the initial value. Curing monitoring of composite material was also conducted by Chiang [17]. Early age curing of Portand cement paste, with a 0.50 water cement ratio (w/c) was conducted by Câmara et al. [18]. The temperature variations during the early age period were characterized.

The FBG sensor has been utilized to assist in describing the process of drying and evaporation of cement pastes. A fluid mechanics approach for water evaporation based on the boundary layer theory, mass transfer, diffusion, and convection was described by Bakhshi et al. [19]. A parametric study was conducted on the effect of boundary layer temperature, wind speed, relative humidity, and evaporation characteristic length on the calculated evaporation rates was conducted. Results show that given appropriate environmental parameters, evaporation rates can be predicted with a good degree of accuracy. Discrete modeling of plastic cement paste subjected to drying was also conducted by Slowik and Ju [20].

A sensor embedded in the composite laminate can act as a temperature transducer during the composite cure mechanism. Once the composite is cured, the same sensor can be used to provide information on the mechanical changes that influence the performance of the material. Afromowitz [21], Glisic and Simon [9], Murukeshan et al. [22] used the FBG sensor for monitoring the composite curing process. Afromowitz and Lam [23] proposed that polymer fiber be embedded into composite materials to monitor the refractive index changes in the composite materials during the curing process. Dunphy et al. [24] presented a Fiber Optic Fresnel Reflection Technique for monitoring the curing process. In the late 1980s, FBG sensors attracted considerable attention and were employed in aerospace and structural engineering. FBG sensors are small and compatible with common polymeric materials, and thereby are easily embedded close to the internal sensing site in a composite structure without introducing significant defects. In 1990, Giordano et al. [25], Okabe et al.[10], Ren et al. [26], Xu et al. [27] and Wang et al. [28] used sensors embedded into composite materials to monitor the curing process, to measure strain and residual stress after curing, to monitor the epoxy curing, and to find the glass transition temperature with intensity changes. To make FBG sensors less susceptible to local damage, such as cracks that widely exist in existing civil infrastructures, the gauge length of a FBG sensor can be extended from several millimeters to centimeters or even meters for macro-strain measurements as proposed by Gu et al.[29], Moaveni et al. [30], Park et al. [31], Xia et al. [32] and Xu et al. [33]. Currently, one of the most practical approaches for distributed strain and temperature monitoring is the optic fiber sensing technique based on the Optical Time Domain Reflectometry (OTDR) technique, which was originally developed for telecommunication systems. Ansari et al. [34] developed a distributed optical fiber sensor based on the intensity of the optical power. Results were obtained with an associated FBG sensor system for the cure monitoring of smart composites. The performance of the embedded FBG sensor smart composite specimens under 3- and 4-point bending conditions were also investigated.

Zou et al. [35] used the Fabry–Perot (FP) fiber optic temperature sensor to investigate the effects of concrete hydration process. The FP temperature sensor was fabricated by controllable chemical etching and adjustable fusion splicing. Detailed optical properties of the sensor were theoretically analyzed and temperature calibration experiments were performed. A sensor with a 90 μm cavity length was demonstrated to have a temperature sensitivity of 0.01 nm/°C and the linearity coefficient of 0.99. The FP sensor was embedded in the concrete structure for sensing the temperature change during the early age of hydration. The final setting times of 13.52 h (w/c = 0.4), 14.16 h (w/c = 0.5) and 15.2 h (w/c = 0.6) after concrete casting were found.

The interior shrinkage deformation and temperature change of high-strength concrete (HSC) at very early age, i.e., the first 24 h from casting, and up to an age of 72 h was investigated experimentally using optic fiber sensors (SOFO) and thermally sensitive resistors. The initial and the final setting times of HSC were also investigated. Results show that two turning points (I and II) on the development curve of deformation,both represent the onsets of the variation of rigidity in fresh HSC, can be recognized as the initial and the final setting times, which are evaluated around 4.5 h to 5.7 h and 9.0 h to 11.8 h, respectively. Also, the higher the fly-ash or silica fume replacement ratio, the longer the setting times. The setting times of HSC evaluated from the curve of temperature development are quite close to those measured from the deformation curve. In addition, the HSC setting times determined by penetration resistance method (ASTM C403) demonstrate unusually large values. This method is therefore not advised to be used to measure the setting times of HSC as pointed out by Liu et al. [36].

There are good prospects for development of ultrasonic excitation-fiber Bragg gratings (UE-FBG) damage detection techniques in the field of nondestructive testing (NDT). However, corresponding strain sensing theories are few and only applicable to the embedded FBG sensors in composite structures. Tan et al. [37] followed the following procedure. First, a four-cylinder sensing model for both the embedded and glued FBG sensors is established by introducing a surface-bonded effect coefficient obtained from simulation analysis in this paper. According to the