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Simultaneous measurement of shrinkage and temperature of reactive powder concrete at early-age using fibre Bragg grating sensors

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Abstract

The physical properties of reactive powder concrete (RPC) at early-age, i.e., the first 24 h from casting, and up to an age of 7 days is investigated experimentally using fibre Bragg gratings (FBGs), a type of fibre-optic sensors. A number of FBG sensors are multiplexed together and embedded directly into the RPC specimens, and the shrinkage and temperature change are measured directly and simultaneously. The final setting time and specimen size effect were also investigated. Results showed that there is an interplay between the shrinkage and temperature. The overall shrinkage for 7 days is 488 με, with the early-age shrinkage contributing about 77% of this. The temperature curve exhibits a double peak behaviour, with the first peak appears at about 7 h, which is the final setting time. There is a size effect in that smaller prisms have a higher overall shrinkage and lower temperature change than larger prisms.

Keywords: Fibre-optic sensor; Fibre Bragg grating; Reactive powder concrete; Early-age shrinkage; Temperature; Ultra-high strength concrete

1. Introduction

Reactive powder concrete (RPC) is a relatively new type of ultra-high strength concrete first introduced in 1994 [1,2]. It offers many advantages over normal strength and high performance concretes in terms of mechanical and composite properties, most notably: (i) ultra-high compressive strength (200–800 MPa); (ii) high flexural strength (up to 40 MPa); (iii) high ductility through the inclusion of short steel-fibre reinforcement; (iv) lightweight and (v) increased homogeneity because of the elimination of coarse aggregates. To date, the physical characteristics of RPC at early-age (the first 24 h from casting and may extend up to 7 days), in particular the early-age shrinkage, is still not well understood, despite the fact that it has been used in the construction of pedestrian and road bridges [3–5]. This is partly due to the relatively short history of RPC, and partly due to the practical difficulties in carrying out experiments while it is still in the plastic stage. In fact, the latter is the main problem in investigating the early-age physical properties of any type of concrete. For example, conventional methods, such as using electrical and mechanical strain gauges, of measuring the shrinkage of fresh RPC failed, mainly because no gauge-points could be established before the RPC is hardened. Indirect methods to derive and predict the early-age properties have been used. They are mainly based on calorimetric measurement [6–8], ultrasonic measurement [6–11], and hydrostatic weighing [6,7,9] of the specimen. They require complicated and delicate experimental setups, and the use of indirect quantities such as the degree of hydration, dissipated heat power, shear and compressive waves and their velocities, and weight change, in order to deduce the mechanical properties. In these methods the actual shrinkage has still not been directly measured.

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At early-age, the main types of shrinkage of RPC are autogenous, thermal and drying shrinkages. Although some other shrinkages, such as carbonation shrinkage, are also present, they contribute very little to the overall shrinkage at early-age and may be neglected. Early-age shrinkage leads to surface cracks and the formation of early-age cracks that would extend further at later stages. Since the RPC undergoes rigorous chemical reactions and phase transitions during the early-age, a knowledge of the physical characteristics at this period provides useful information and experimental data for the study of its deformation, the cause and severity of plastic shrinkage, swelling and early-age cracking. Also, it would be helpful for the improvement in the mix design and the choice of mixing materials.

Thus far, there have been only a few investigations of early-age shrinkage using fibre-optic sensors. These include the use of Fabry–Perot interferometers [12], low-coherence interferometry [13], and packaged fibre Bragg gratings (FBGs) [14] on cement paste [14] and unspecified types of concrete [12,13]. None of them were tested on RPC or on the simultaneous measurement of shrinkage and temperature. In this paper, the physical properties of RPC at early-age is being investigated experimentally using a technique based on FBGs, a type of fibre-optic sensors. The technique is capable of multiplexing a number of sensors, as well as taking all measurements automatically, continuously and remotely. The FBG sensors are embedded directly into the RPC specimens, and because of their small size, they are non-invasive to the specimens. The shrinkage and temperature change are obtained simultaneously, immediately after casting and up to an age of 7 days. In addition, the final setting time and the specimen size effect are investigated. The former is determined from the temperature characteristic, while the latter is performed by comparing specimens of two different sizes. It is hoped that by employing this technique, it would contribute to a better understanding of this ultra-high strength concrete at early-age, as well as offering a better and simpler experimental method in concrete research.

2. Measurement scheme

2.1. FBG sensing technique

An FBG is a type of fibre-optic device which consists of a periodic modulation of the core refractive index along the length of an optical fibre. The grating region can be used as a sensing element, and the typical grating length is about 5–20 mm. Thus, the FBG is considered as a point sensor similar to an electrical strain gauge. The FBG is specified by its characteristic wavelength called the Bragg wavelength, which is given by $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} is the effective refractive index and Λ is the grating period. The shift in the Bragg wavelength due to strain ε and temperature T changes is given by [15]

$$\Delta\lambda_B = (1 - p_e)\lambda_B\Delta\varepsilon + (\alpha + \xi)\lambda_B\Delta T, \qquad (1)$$

where $p_e = (n^2/2)[P_{12} - \mu(P_{11} + P_{12})] \approx 0.22$ is the effective photoelastic coefficient, P_{ij} are the Pockels coefficients of the strain-optic tensor and μ is Poisson's ratio. $\alpha = (\mathrm{d}\Lambda/\mathrm{d}T)/\Lambda$ is the coefficient of thermal expansion, and $\xi = (\mathrm{d}n_{eff}/\mathrm{d}T)/n_{eff}$ is the thermo-optic coefficient. Both p_e and ξ are wavelength dependent due to the effective index term. However, since the difference in the Bragg wavelengths between sensors are very small (about 1–1.4 nm apart in our case), this minor difference may be neglected and the two coefficients can be treated as constants.

2.2. Simultaneous measurement of shrinkage and temperature

The Bragg wavelength shift is influenced by both the physical stress and thermal change of the grating region. In order to measure the shrinkage and temperature simultaneously, these two responses need to be separated and distinguished. This can be accomplished by placing two FBG sensors under an identical situation, with one of them being free and unrestrained. As such, the latter sensor would only experience thermal change. The set of two simultaneous linear equations for these two sensors are given by

$$\begin{aligned}\Delta\lambda_{B1}/\lambda_{B1} &= k_{\varepsilon 1}\Delta\varepsilon + k_{T1}\Delta T,\\ \Delta\lambda_{B2}/\lambda_{B2} &= k_{T2}\Delta T,\end{aligned} \qquad (2)$$

where $k_\varepsilon = (1 - p_e)$, $k_T = (\alpha + \xi)$, and subscripts 1 and 2 represent the strain and temperature sensors, respectively. Eq. (2) can be expressed in a matrix form as

$$\begin{pmatrix}\Delta\lambda_{B1}/\lambda_{B1}\\ \Delta\lambda_{B2}/\lambda_{B2}\end{pmatrix} = \begin{pmatrix}k_{\varepsilon 1} & k_{T1}\\ 0 & k_{T2}\end{pmatrix}\begin{pmatrix}\Delta\varepsilon\\ \Delta T\end{pmatrix} = \mathbf{K}\begin{pmatrix}\Delta\varepsilon\\ \Delta T\end{pmatrix}, \qquad (3)$$

where $\mathbf{K}$ is the 2×2 sensitivity matrix. After solving for the measurand vector on the right hand side by inverting the sensitivity matrix, we obtain

$$\Delta\varepsilon = \frac{1}{k_{\varepsilon 1}}\left(\frac{\Delta\lambda_{B1}}{\lambda_{B1}}\right) - \frac{k_{T1}}{k_{\varepsilon 1}k_{T2}}\left(\frac{\Delta\lambda_{B2}}{\lambda_{B2}}\right), \Delta T = \frac{1}{k_{T2}}\left(\frac{\Delta\lambda_{B2}}{\lambda_{B2}}\right). \qquad (4)$$

In practice, although the two sensors are placed under the same environment, they do not necessarily have the same α, because the temperature sensor might not have direct contact with the structure under test or aligned in the direction of the strain field. However, since in optical fibres ξ is the dominant effect (~95% of the observed Bragg wavelength shift [15]) comparing to α, and that ξ is already assumed to be constant. We may assume that $k_{T1} \approx k_{T2}$, and the expression for strain in Eq. (4) becomes

$$\Delta\varepsilon = \frac{1}{k_{\varepsilon 1}}\left(\frac{\Delta\lambda_{B1}}{\lambda_{B1}} - \frac{\Delta\lambda_{B2}}{\lambda_{B2}}\right). \qquad (5)$$

This shows that the early-age shrinkage can be obtained by subtracting the fractional Bragg wavelength shift about