Application of two types of embedded fiber-optic sensors for process-induced strain measurement in cement mixture

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Abstract. Two types of fiber-optic sensors applied to process-induced strain measurements of cement mixture are compared in this study. Point fiber-optic strain sensors based on the Bragg grating and distributed fiber-optic strain sensors were embedded into cement sample at the manufacturing stage. Embedded optical fibers did not have any additional protective coating except standard one (polyimide or acrylate). Both systems remain their integrity and operability after casting and hardening of the studied material and show the good agreement in strain measurements at the period taken into consideration.

1. Introduction

Structural health monitoring of various engineering structures is a complex and important task. Timely maintenance and safe operation of existing structures, as well as increased requirements for monitoring of the state of new buildings, have led to a growing demand for cost-effective and reliable measurement and control systems. Currently, a large number of different sensors (accelerometers, extensometers, etc.) are actively used to monitor the structures state. In particular, to assess the mechanical state of structures made of concrete and cement compositions, it is promising to use fiber-optic sensors (FOSs) embedded into the material [1–4]. The possibility of embedding the FOSs into the material allows to assess the strain state not only during the operation of the structure, but also during manufacturing stage. The use of optical fiber as a sensing element offers numerous advantages over traditional sensors. Fiber-optics sensors can be divided into two types: point FOSs and distributed FOS. FOSs can be multiplexed and immune to electromagnetic interference; are dielectrics, and also have high reliability and relatively small dimensions [5–7]. There is a big amount of studies, when various types of protective structures are used in the area of the fiber Bragg grating (FBG) during optical fiber embedment. Metallic, silicone, composite and other protective coatings are of great practical importance [8] since an optical fiber itself, even with a polymer coating (polyimide, acrylate), is prone to rupture during pouring of the material. One of the good solutions is to protect the optical fiber in the cable sheaths and use of additional protective coatings in the area of the sensitive element (FBG) [9,10]. However, the cost of using protective coatings is the incomplete strain transfer from the host material (concrete, cement) to the optical fiber and therefore the inconsistency of the mechanical behavior of the material in the grating area and in the host material in which the optical fiber is embedded. To restore the real picture of the mechanical state, it is necessary to use the recalculation of the values obtained with the FOSs [11]. The correction factors must be established in laboratory conditions and require knowledge of the strain distribution of the host material at the points, where the embedded sensors are located.

The possibility of using point and distributed fiber-optic sensors to monitor the mechanical state of a cement sample during the formation of the material was investigated in this paper. The optical fiber used for embedding has no additional protective coatings other than polyimide or acrylate. Despite the fact that this variant of optical fiber embedment has significant limitations for practical use in construction, the use of an unprotected optical fiber in laboratory conditions makes it possible to obtain a more reliable picture of the mechanical state of cement samples at the early stages of formation.
2. Sample description and sensors used in the experiment

In the course of the work, the registration of internal strains arising in the cement mixture, poured into a cylindrical mold was carried out with the help of two types of fiber-optic sensors (FOSs). The strain along the length of the sample was measured at the stage of material formation and is limited in this work to the first 72 hours after material casting. The cement mixture was poured into a polypropylene mold, in which the sample was subsequently formed and hardened. Before casting, two types of FOSs were placed in the empty mold: point FOSs based on the fiber Bragg gratings (FBG) and distributed FOS. Optical fiber with Bragg gratings was suspended in the center of the mold, passing through the free top surface and bottom surface of the cylindrical polypropylene mold. The distributed fiber-optic sensor was placed at a distance of 37 mm from the FBG sensors. After placing the fiber-optic sensors, layer-by-layer (with compaction and vibration) filling of the mold with a cement mixture to the level of the free surface was performed so that both lines of fiber-optic sensors remained immersed in the cement mixture. The vertical positioning and centering of the optical fibers were performed by attaching the weight. Figure 1 shows a scheme of a sample with embedded fiber-optic sensors based on FBG (s1−s6) and distributed fiber-optic sensor which utilizes the optical backscatter reflectometry (OBR) for measurements.

![Figure 1. The scheme of fiber-optic sensors location in the sample.](image)

The first fiber-optic line located inside the cement sample contains six FBGs and was designed in such a way that the FBGs were evenly distributed over the entire length of the sample. FBG represents the periodically changing refractive index of the fiber core over a certain length of an optical fiber [12]. Such a change in the refractive index profile makes it possible to filter the introduced broadband optical signal, reflecting only its narrow part with a central wavelength $\lambda_B$, which depends on the effective refractive index $n$ of the optical fiber core and the grating period $\Lambda$ [13]:

$$\lambda_B = 2n\Lambda$$  \hspace{1cm} (1)

Under external action on the Bragg grating (strain or temperature change), the central wavelength of the reflected optical spectrum shifts. Such relationship between the shift of the Bragg wavelength, the longitudinal strain component along the fiber and temperature change can be written in the form [14]:

$$\frac{\Delta\lambda}{\lambda_B} = k\varepsilon_x + S_T\Delta T$$  \hspace{1cm} (2)
where $\varepsilon_3$ – longitudinal strain component along the fiber, $\Delta \lambda = \lambda - \lambda_b$ – central wavelength shifts in the current $\lambda$ and initial $\lambda_b$ moments of time, $k$ and $S_T$ – strain and temperature sensitivities, $\Delta T$ – temperature change. In case, when the optical fiber in the region of the Bragg grating is in, or close to uniaxial stress state, the strain sensitivity $k$ can be calculated by the given expression:

$$ k = 1 - \frac{n^2}{2} \left( p_{12} - \nu (p_{11} + p_{12}) \right) $$

(3)

where $p_{11}, p_{12}$ – strain-optic coefficients. For silica glass fiber $p_{11} = 0.113$, $p_{12} = 0.252$, $n = 1.458$, $\nu = 0.17$. Thus, under the uniaxial stress state of the Bragg grating, the coefficient $k \approx 0.78$ [15].

In contrast to a point FOSs based on FBG, where only a small region of the optical fiber is sensitive to strain and temperature change, in a distributed FOS the entire length of the optical fiber is used as a sensitive element. Thus, no preliminary action on the optical fiber is required in order to change the refractive index. The distributed strain measurement method used in this work is based on measuring Rayleigh backscatter as a function of length by optical frequency-domain reflectometry (OFDR) technique [16]. The refractive index of any optical fiber along its length undergoes minor changes due to the small imperfections of the material. For different optical fibers, the change in refractive index along the length will be different, but will remain from measurement to measurement (in the absence of external influences) for a single optical fiber. Thus, a reference profile of the reflected signal can be formed for an optical fiber under test. Under an external influence on an optical fiber (strain, temperature), the signal shifts in the frequency domain. To calculate the strain or temperature change, the signal shift relative to the reference signal is estimated on a certain window and this shift is multiplied by the coefficient of strain or temperature sensitivity of the optical fiber. In this way distributed FOS is similar to weak Bragg grating so the relation (2) is valid. Distributed FOSs based on Rayleigh backscatter allows to obtain the distribution of the measured value with a very high resolution, however, it is associated with complex calculations and, as a consequence, the use of expensive equipment. In this work, an OBR 4600 backscatter reflectometer by Luna Innovations was used to carry out distributed measurements. Another limitations of distributed sensing are the short maximum length and low sampling frequencies compared to point sensors based on Bragg gratings.

In this study fiber-optic sensors which were embedded in the sample didn’t have any additional protective coating, apart from the polyimide coating with thickness 12 $\mu$m for the optical fiber with Bragg gratings and acrylate coating with thickness 60 $\mu$m for optical fiber used for distributed sensing. After pouring the sample, measurements made by point FOSs were recorded with a frequency of 1 measurement per second and a distributed FOS with a frequency of 1 measurement per minute. The length of the used Bragg gratings was 5 mm. Each measurement point recorded with a distributed FOS was calculated on a 5 mm base.

3. Results and Discussion

The Figure 2 shows the strain values for a cement sample as red lines, obtained using point sensors based on FBG, within 72 hours from the moment of sample pouring. Also the strain values in a cylindrical sample, recorded using a distributed fiber-optic sensor are shown on the figure. These readings are displayed as a surface in the same time period. This figure clearly shows the difference between the two measuring systems based on fiber optics. Whereas FBG point sensors allow to obtain strain values only at certain points, the distributed fiber-optic sensor allows data to be obtained along the entire length of the sample.
Figure 2. The strain values recorded by FBG and distributed fiber-optic sensor.

To compare the readings obtained from two different fiber-optic measuring systems, a graph (Figure 3) is given of the averaged values for all FBG sensors and the values obtained by distributed fiber-optic sensor averaged over the same fiber-optic sections where the FBG point sensors are located. It can be noted that in this case the difference between the averaged readings of the two types of sensors does not exceed 4% in the area of maximum strain and 6 $\mu$ε in the absolute value during the whole measurement period.

Figure 3. Averaged readings of the two types of sensors.

Figure 4 shows the strain distribution along the sample length, obtained at the time when the strains in the sample reached their maximum value. For clarity, an additional diagram of the sample is presented, where the position of the point sensors corresponds to the position of the red dots on the graph.
Figure 4. Strain distribution along the sample length.

The strain values obtained from point sensors correlates well with the strain values obtained from distributed fiber-optic strain sensors. Application of embedded fiber-optic sensors gives great opportunity to measure strain distribution inside studied structure with resolution which strongly depends on the type of sensing system.

4. Conclusions
The paper presents a study of the possibility of using two types of fiber-optic sensors: point, based on the Bragg grating, and distributed, based on measuring Rayleigh backscatter, for investigating processes and monitoring the mechanical state of a cement sample. For better understanding the process-induced strain formation process, the embedded fiber-optic strain sensors collected data from the moment the cement sample was poured. Using two systems, the history of process-induced strains arisen in the process of sample manufacture was recorded and stored. The work shows the results of measurements for the first 72 hours after sample pouring.

Both optical measuring systems have shown their good performance, despite the absence of additional protective coatings, apart from the standard ones. Analysis of the obtained data shows a good agreement of the measurement results of the two optical systems. It can be noted that the combined use of both systems can significantly improve the quality of the obtained data. However, the special features of each measuring system should be taken into account when using these measuring systems separately.

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