Miniature fiber optic temperature sensor for concrete structural health monitoring

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ABSTRACT

This paper presents a miniature fiber optic temperature sensor and its application in concrete structural health monitoring. The temperature sensor is based on Fabry-Perot (FP) principle. The endface of the fiber was wet etched. A piece of borosilicate glass was thermally deposited into the cavity on the etched endface to form an FP cavity. Temperature calibration experiments were performed. A sensor with 30 µm microcavity length was demonstrated to have a sensitivity of 0.006 nm/℃ and linearity coefficient of 0.99. During the early-age of concreting, the sensor was embedded in the concrete structure to monitor the temperature change caused by the exothermic chemical reaction between the cement and water. The dramatically increased temperature inside the structure was directly related to its future structural health. During the concrete hydration experiment, the measured peak temperature of concrete specimens was 59.7 ℃ 12.5 hour after concrete casting.

Keywords: structural health monitoring, fiber optic temperature sensor, Fabry-Perot, concrete hydration

1. INTRODUCTION

For all concrete structures, their thermal effects during the beginning hours of concreting strictly related to their future structural health [1]. Recently, structural health monitoring using fiber optic sensors provides practical sensing capabilities in civil applications, especially for temperature detection. This is because that fiber optic temperature sensors offer unique advantages, such as good durability against harsh environments, superior stability and repeatability, high resolution, and fast response. So far wavelength-encoded temperature sensing has been achieved by using different methods including fiber Bragg gratings [2], long-period fiber gratings [3], Fabry-Perot (FP) cavities [4], and multimode interference (MMI) based fiber structures [5].

In this paper, a novel miniature fiber optic temperature sensor fabricated by using chemical etching and thermal deposition is presented. Chemical etching is widely used for fiber optic structure fabrication. Microchannel [6] and microcavity [7] can be achieved with wet etching techniques. ~~T~~Three calibration experiments and a concrete hydration experiment were performed in order to evaluate performance of the sensor. The experiments demonstrated that this fiber optic temperature sensor is an ideal candidate in the civil engineering applications.

2. SENSOR STRUCTURE AND FABRICATION

2.1 Structure of the sensor

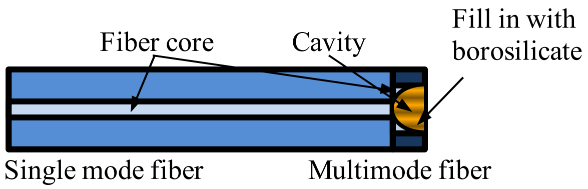

Figure 1. The structure of the temperature sensor. The sensor consists of a piece of optical fiber, a wet etched cavity and a piece of thermal deposited borosilicate glass.

Figure 1 shows the schematic of the structure of the fiber optic temperature sensor. The temperature sensor consists of a piece of single mode fiber, a cavity that is wet etched on the endface of the fiber, and a piece of thermal deposited

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borosilicate glass. Due to the different refractive index between the fused silica and borosilicate glass, the interface between the fiber core and the borosilicate glass can behave like one reflector. By polishing another side of borosilicate glass, another reflector of the FP cavity is formed. The two reflector are then joined together to form an FP interferometer. The structure can work as a temperature sensor in civil engineering applications by monitoring the changes in the reflection spectrum during the thermal expansion of the borosilicate glass. The reason we choose borosilicate glass as our sensing material is due to its higher thermal expansion coefficient compare with fused silica.

2.2 Fabrication of the sensor

A single-mode fiber (SMF) (Corning SMF-28) with core/cladding diameters of 8/125 μm was used in the fabrication of the fiber optic temperature sensor. The fiber was first cleaved using a cleaver (Fujikura CT-30B), then the well cleaved fiber was spliced with one end of multiple mode fiber (MMF) and the other end of MMF was further cleaved (Figure 2(a)). Once this was done, the fiber was dipped into a hydrofluoric solution (49% weight concentration) for 3 minutes. After being rinsed in deionized water and drying, an air cavity was formed since the etching rate of the core was higher than that of the cladding (Figure 2(b)). Finally a piece of borosilicate glass was placed on a ceramic stage (Figure 2(c)). The borosilicate was thermally filled into the wet etched cavity. The sensor was fabricated after the borosilicate surface was polished (Figure 2(d)).

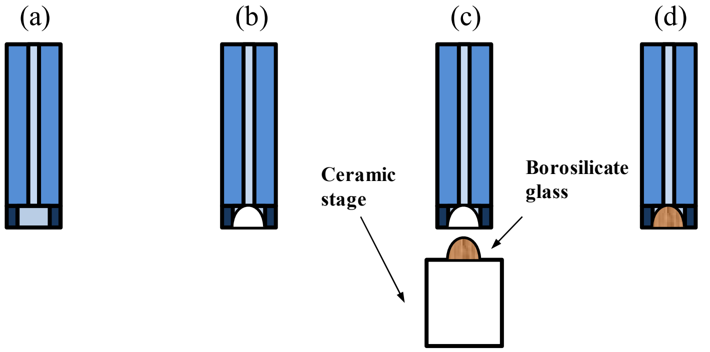


Figure 2. The sensor fabrication procedures

3. THE INTERROGATION SYSTEM AND SENSOR CALIBRATION

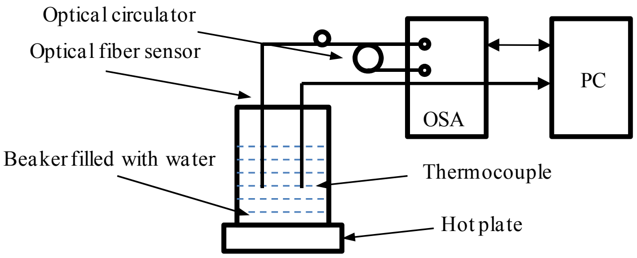


Figure 3. The interrogation scheme.

The spectrum reflection test setup was illustrated in Figure 3. An optical sensing analyzer (OSA) excited the laser signal (scan wavelength 1520 nm to 1570 nm with the 2.5 pm resolution) into fiber optic temperature sensor, while the spectrum response from the reflected light was collected and monitored through an optical circulator. The optical sensor was alongside with a commercially available thermocouple (Omega, 5TC-GG-J-30-36) in a beaker filled with water. The output of the Omega thermocouple was assumed to be the true temperature value applied to the optical fiber sensor. The reflection spectrum of the Fiber optic temperature sensor was illustrated in Figure 4. The hot plate was set up to increase the temperature from room temperature to 75 °C. The spectrum data and the output of the thermocouple were continuously collected while the water temperature was being changed. Finally, Calibrated temperature and the square errors between the sensor and the thermocouple were shown in Figure 5. The procedure was repeated for 3 cycles in order to determine the sensor's linearity, and repeatability. The sensor sensitivity was 0.006 nm/°C. The linearity was good with a correlation coefficient of 0.99.

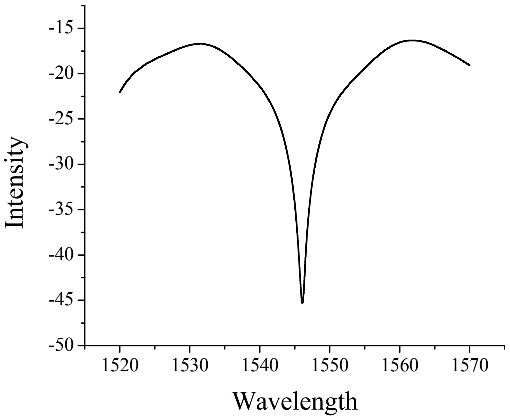


Figure 4. The reflection spectrum of the fiber optic sensor.

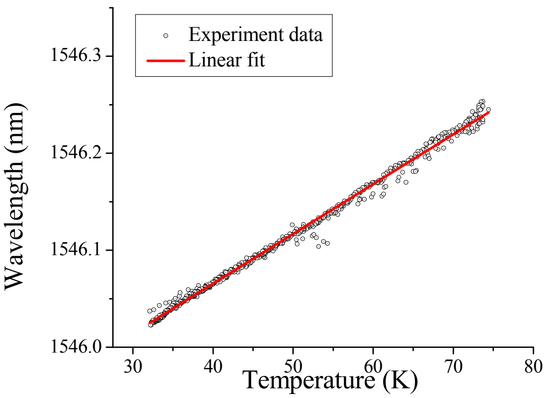


Figure 5. Linearity and sensitivity of the sensor.

4. EXPERIMENTS AND RESULTS

The detailed experimental schematic diagram is shown in Figure 6. Tests were carried out by measuring the temperature profile during the cement concreting with water-to-cement (w/c) ratios equal to 0.6.

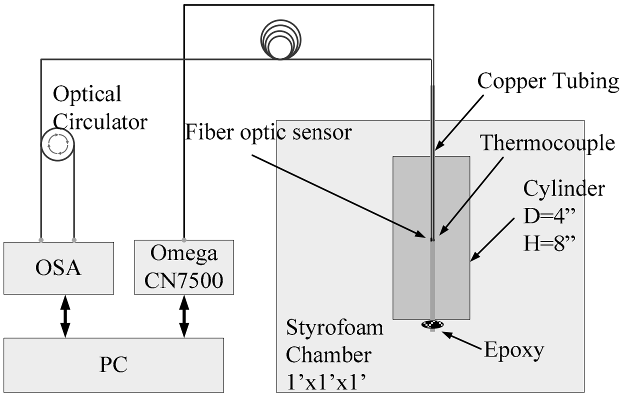


Figure 6. Experimental schematic diagram.

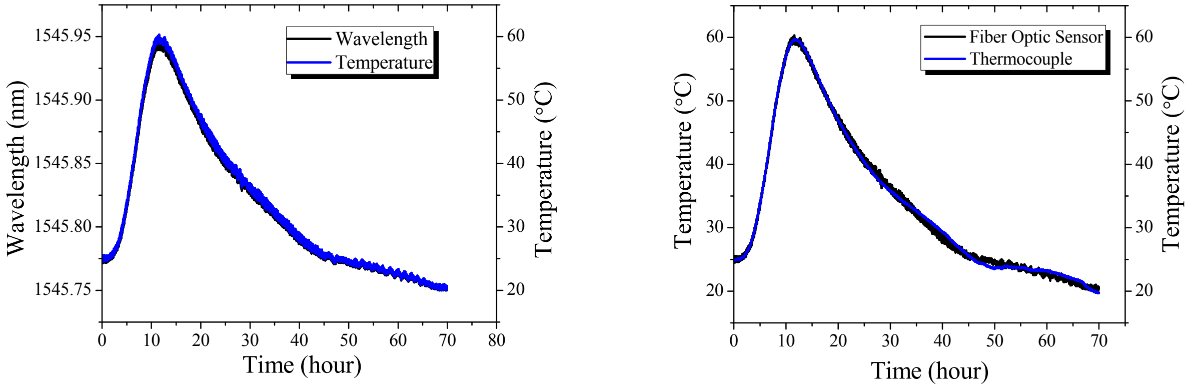
A standard concreting cylinder with 4 inches diameter and 8 inches height was selected as our specimen host. A Styrofoam chamber was built in order to isolate the heat transfer. The copper tubing in Figure 6 was applied to protect the fiber optic temperature sensor and the thermocouple from chemical corrosion, also prevent them from strain disturbances during the cement concreting. The copper tubing was properly aligned and mounted on the center of the concreting cylinder box sealed with epoxy in one side.

Table 1. Concrete Mix Design for Water-to-Cement Ratios of 0.6.

	Cement	*Sand*	*Gravel*	*Water*	*Adjusted water*
Material Dry Weight (lb)	1.510	2.562	3.408	0.870	0.913

During the cement concreting, the fiber optic sensor and the thermocouple were firstly inserted into the copper tubing and both sensor tips were guaranteed in the middle of the cylinder. By the data acquisition system the temperature data was reported during the entire process. Table 1 lists the dry weight of each material used in this research. In preparing the concrete specimens, ASTM (American Society for Testing and Materials) Type I/II Portland cement and 3/8" gravels were used. In this study, quantities of cement and sand fixed were kept at 1.51 lb and 2.562 lb, respectively. The percentage of water absorption for surface-dry sand was considered to be 0.5% (by weight) and for surface-dry gravel 1% (by weight). The amount of mixing water was adjusted in order to compensate the loss of water absorbed by surface-dry sand and surface-dry gravel.

Temperature variation of concrete specimens during the early-age of cement hydration was monitored for 70 hours immediately after mixing. When water combined with cement, hydration heat was generated, and the temperature of concrete arose. Detailed experimental results of the fiber optic temperature sensor were shown in Figures 7(a). In this figure, black curve is the valley wavelength recorded, and the blue curve is the temperature data after sensor calibration. The reference thermocouple sensor data compared with fiber optic temperature sensor calibrated data is shown in the Figure 7(b). The two curves overlap each other during the first 40 hours, which indicates that the temperature measurement by fiber optic sensor is in good agreement with the thermocouple with adjusted R-Square error equal to 0.99. In the rest of the 30 hours, there are some small variances between these two curves, the adjusted R-Square error drop to 0.92. We think that difference is attributed to the sudden environment temperature drop and different heat transfer rate between the fiber optic sensor and thermocouple.



(a) Wavelength signal recorded by fiber optic temperature sensor and the temperature data after calibration

(b) Temperature recorded by thermocouple compared with fiber optic temperature sensor calibrated data

Figure 7. Concrete hydration experiment with water to concrete ratio 0.6

5. CONCLUSIONS

This paper introduces a novel miniature fiber optic temperature sensor and its application in concrete structural health monitoring during the early-age of concrete hydration. The sensor is very easy to fabricate due to the simple FP structure. According to the calibration experiment, the sensor shows a linear response. In concrete hydration experiment, the sensor demonstrates its suitability for the civil engineering application with stable and reliable performance. The characteristic of this fiber optic temperature sensor makes it an ideal candidate in the civil engineering application.

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