Monitoring Ingress of Moisture in Structural Concrete Using a Novel Optical-Based Sensor Approach

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Abstract. The detection of moisture ingress in concrete is important for structural monitoring and in this work is realised by monitoring the shift in the characteristic wavelength of a fibre Bragg grating-based sensor. The sensor relies upon a moisture-sensitive polymer layer deposited on the fibre Bragg grating (FBG) and the strain induced on it as a result of polymer swelling is monitored. Moisture ingress experiments were carried out using two such optical fibre sensors, placed at varying distances from the edge of the face of standard concrete cubes to the inner part of the concrete sample and subjected to water at a constant temperature. Information on the properties of different types of concrete and thus potentially on the migration of dissolved salts and their effect on reinforcement bars within concrete can be obtained.

1. Introduction

Concrete structures are prone to chemical attacks which may lead to structural deterioration and instability. Moisture, one of the key elements of the degradation mechanism, and together with the contaminants that dissolve in it, can lead to the corrosion of the reinforcement bars within the concrete matrix. In the absence of routine maintenance and appropriate repair work, this will eventually bring the integrity of the structure to a potentially unsafe level. To establish the integrity of reinforced concrete structures, conventional tests which usually involve visual and intrusive inspection techniques are carried out. These tests are costly and labour intensive and may also include destructive tests in order to allow concrete samples to be taken from the structure for laboratory chemical analysis.

Structural effectiveness of concrete can be affected by the environmental conditions. Such effects on the material can be significant, and in some conditions, the concrete matrix can be completely destroyed. In the case of chloride attack which can be triggered by the penetration of chloride ions found dissolved in water, chemical compounds formed as a result of chemical reactions create an increase of the volume needed to accommodate the newly formed compound on and around the rebar. This results in cracking or spoiling of this area of the concrete and subsequent leading to the degradation of the structure. This emphasizes the value of effective monitoring of water transport and with that the contaminants which are waterborne with the material.

Various types of fibre optic sensors for both physical and chemical measurements have been reported over the years and have found a range of applications in various industries. In the field of civil engineering, use fibre optic sensors for structural health monitoring in concrete structures e.g. in measuring the effects of stress loading, has been discussed by Merzbacher et al. Most fibre optic sensors discussed in structural health monitoring application are mainly for physical measurands.
Chemical-based monitoring such as pH level in concrete is also as equally important. In healthy concrete the pH should be around 13 and since the majority of chemical attacks on concrete result in a decrease of pH, most chemical processes in concrete can be characterized by the humidity and pH level. Such pH sensors using novel optical techniques have been discussed elsewhere by some of the authors[2] but this work looks at the use of fibre optic humidity sensors to determine water, and thus contaminant, ingress issues. In this paper, we discuss the use of fibre Bragg grating (FBG) humidity sensors as an effective means of monitoring the ingress of moisture in concrete. A ‘proof-of-principle’ analysis of concrete characteristics using optical fibre humidity sensors embedded in several types concrete specimens and placed at varying distances from the surface of the material samples was carried out. Standardized concrete samples of different mixture and water-to-cement ratios (w/c) were prepared and placed in a temperature controlled water bath together with the sensors to monitor the ingress/migration of water through the cube.

2. Fibre optic humidity sensor

The sensing scheme used to monitor the humidity within the concrete specimens is based on a polymer-coated fibre Bragg grating (FBG)[3]. An FBG behaves like a notch optical filter which reflects a narrow band of the incident light signal; with a centre wavelength commonly know as the Bragg wavelength ($\lambda_B$). It is formed by UV-induced periodic refractive index modulation, which results in a series of grating planes formed along the fibre axis in the core of a photosensitive fibre. The Bragg wavelength of a FBG is dependent on the effective refractive index of the fibre core ($n_{eff}$) and the period of the grating plane ($\Lambda$) and is given by, $\lambda_B = 2n_{eff}\Lambda$. Any strain or temperature change experienced by the device will result in a change in both the refractive index value and the period of the gating plane and is reflected in the value of the Bragg wavelength. To render it responsive to moisture, a polymer coating can be deposited on the FBG and thus stressing the fibre as the polymer swell when it reacts with moisture. Detailed work on the design and testing of the sensors used has been discussed in a previous paper by some of the authors[4].

For this work, two sensors were constructed by coating the end of the optical fibre (including the FBG) with a moisture-sensitive polymer. The sensors were covered by a stainless steel sheath both to protect the optical fibre against the hazards of manually handling and also allow the moisture to be detected via the perforated bottom half of the sensor. Prior to the experiments, the sensors were calibrated at different fixed humidity levels using standard saturated chemical salt solutions, at a constant room temperature of 23°C. For each fixed humidity setting, the calibrations of the two sensors were carried out and repeated several times to ensure reproducibility. The calibration (see Figure 1) yields an estimated sensitivity of $3.0 \times 10^{-3}$ nm/%RH for Sensor A and $2.8 \times 10^{-3}$ nm/%RH for Sensor B, obtained through the linear trend line fitted to the data set. The reaction time of the in-situ sensor to an “immediate” humidity change for a typical device was obtained by subjecting the sensors which were initially stabilised in an environment of low humidity (33%RH) to another saturated with water vapour (100%RH). Typical time response shows an exponentially based function where the value of Bragg wavelength rises rapidly and then reaches a plateau. The response time can be given by a 63% change in the Bragg wavelength value and is approximately 8 minutes. Both sensors show a similar result, within experimental error, under the same conditions. Taking into account the time involved for the water ingress experiments, the time response of sensors can be considered to be rapid and sufficiently so for it to be ignored in the comparative data.
3. Experiment

3.1. Concrete samples
The concrete samples used in this work were constructed from 4 different mixes (as shown in Table 1) prepared in accordance to the guidelines from BRE (the Building Research Establishment in the UK), taking into account that the higher the cement content with a reduction in water, the less permeable are the samples and this is reflected in the time of migration of the water within the concrete.

![Figure1. Humidity response of the sensors obtained at several fixed humidity points using saturated chemical salt solutions.](image)

| Mix Number | 1      | 2      | 3      | 4      |
|------------|--------|--------|--------|--------|
| Cement Type| OPC*   | OPC*   | PFA*   | PFA*   |
| Water/Cement ratio (w/c) | 0.5    | 0.7    | 0.5    | 0.7    |
| Maximum Coarse aggregate size (mm) | 20     | 20     | 20     | 20     |
| Water (kg) | 1.62   | 1.62   | 1.44   | 1.44   |
| Cement (kg) | 3.24   | 2.31   | 2.55   | 1.88   |
| PFA (kg) | -      | -      | 1.09   | 0.77   |
| Sand (kg) | 5.78   | 6.10   | 5.79   | 6.15   |
| 10 mm aggregate (kg) | 3.58   | 3.78   | 3.58   | 3.18   |
| 20 mm aggregate (kg) | 7.16   | 7.56   | 7.16   | 7.61   |
| Total mix volume (m³) | 0.009  | 0.009  | 0.009  | 0.009  |

*Ordinary Portland Cement, *Pulverised Fuel Ash

$^a$Land based gravel aggregate (BS812 and BS882)

Table 1. Details of different concrete mixes used in this work.

The concrete specimens made from OPC and PFA were placed in a curing tank after a period of 24 hours. They were removed from curing at 7 days and 14 days respectively, where samples of different cement mixes achieved approximately 2/3 of their ultimate strength in 28 days. These samples were then dried in the oven at ~95°C for a period of 48 hours and stored in a sealed container prior to the tests. Holes with a diameter of 4mm and to a depth of 80mm were cast in the concrete cubes to allow fibre sensors to be placed in the cube and the surface of the concrete cubes were coated with a layer of bitumen, except for one face where moisture was introduced. Samples with w/c ratio of 0.7 (OPC-
Ordinary Portland Cement and PFA-Pulverised Fuel Ash) had sensors positioned at 25 mm and 75 mm (position 1 and 3) away from the uncoated face whereas for samples with a w/c ratio of 0.5, sensors were installed at 25mm and 50mm (position 1 and 2). Figure 2(a) shows the layout of the positions cast for the placement of the sensors. A photograph of a concrete cube with the sensor probes in position is shown in Figure 2(b).

3.2. Experimental set-up
To investigate the ingress of moisture using the fibre optic sensors, the experimental set-up as shown in Figure 3 was used. The set-up consists of a broadband light source to provide the incident optical signal to the humidity sensor through a fibre optic coupler and an optical spectrum analyser (OSA) controlled by a personal computer (PC) to monitor and acquire the return peak wavelength values. The two humidity sensors were installed at different positions in the concrete samples and sealed with watertight wax. The sensors were allowed to equilibrate in the sealed environment within the concrete cube before the samples were placed into a temperature-controlled water bath set to 23°C.

Figure 2. (a) Layout of the sensor placement in standard concrete cubes. (b) Photograph showing the fibre optic sensors installed in a concrete cube.

Figure 3. Experimental set-up used in this work to monitor the ingress of moisture in concrete.
4. Results

Typical responses of the fibre optic humidity sensors when placed in different positions in the concrete cube are shown in Figure 4. The responses shown were the results of moisture ingress measurements using mix 1 (OPC, w/c: 0.5), where the sensors were placed at the following positions from the cube edge: position 1 for sensor A and position 2 for sensor B. The responses from the sensors were normalized to their respective ‘plateau’ values to eliminate the effect of the differences in the wavelengths associated with the ‘dry’ and ‘saturated’ wavelength values.

Using the 5% reference point of the normalised plots for different concrete samples and the placement of the sensors, the calculation of water ingress velocity through the different sample blocks can be made. These values, together with the time response of the sensor at different positions were tabulated in Table 2. The data show, for example, a higher velocity of water ingress for w/c: 0.7 when compared to w/c: 0.5 for the OPC cube (i.e. comparing mixes 1 and 2), showing the influence of the w/c ratio.

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| Mix number, Type, w/c ratio | Sensor A – time to 5% response at 25 mm (min) | Velocity of water ingress to Sensor A (mm min⁻¹) | Sensor B – time to 5% response at various positions (min) | Velocity of water ingress to Sensor B (mm min⁻¹) |
|-----------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| Mix 1 OPC (w/c:0.5)        | 130                                           | 1.9 x 10⁻¹                                    | 590 (at 50 mm)                                  | 8.5 x 10⁻²                                    |
| Mix 2 OPC (w/c:0.7)        | 65                                            | 3.8 x 10⁻¹                                    | 625 (at 75 mm)                                  | 1.2 x 10⁻¹                                    |
| Mix 3 PFA (w/c:0.5)        | 215                                           | 1.2 x 10⁻¹                                    | >1200 (at 50 mm)                                | <4.2 x 10⁻²                                   |
| Mix 4 PFA (w/c:0.7)        | 110                                           | 2.3 x 10⁻¹                                    | 2230 (at 75 mm)                                | 3.4 x 10⁻²                                    |

Table 2. Summary of the sensor response time and the calculated velocity of water ingress for sensors A and B (at different placement points in the samples) using the 4 different concrete mixes.
both OPC and PFA (w/c: 0.7, mix 2 and 4), as shown in Figure 5 illustrates a clear difference between the time taken for the sensor to react to the moisture as it migrates through the different concrete types, due to capillary action. The only difference between the two plots is the type of cement used. When similar measurements were taken at 75 mm (position 3) from the cube face (see Figure 6), the data obtained show that the differences in the mechanisms of migration between mixes 2 and 4 become more apparent with depth into the concrete. Various factors such as density, gel and capillary change in the concrete matrix could attribute to the observation made. Data obtained also shows that the rate of water ingress reduces by a factor of ~ 2 when mix 2 (OPC) is replaced by mix 4 (PFA) for sensor A (25 mm, position 1). Further into the material (at 75 mm, and using sensor B) the PFA material shows an even slower rate of water ingress, with the calculated velocity being only ~ 30% of that for the OPC (mix 2). In the case of 0.5 w/c (mixes 1 and 3) and making a comparison at 25mm (position 1), the PFA again shows a slower velocity of water ingress, slightly under the factor of 2 seen for mixes 2 and 4 above.

**Figure 5.** Comparison of sensor response (sensor A at 25mm) obtained using OPC and PFA samples (mix 2 and 4) with 0.7 w/c.

**Figure 6.** Comparison of responses taken from sensor B positioned at 75mm from the cube face using mix 2 and 4.
5. Discussion
In this work, the use of a fibre optic humidity sensor to monitor the ingress of moisture in concrete has been demonstrated. Preliminary results from a series of experiments using standardized concrete samples of different composition have shown the effectiveness of the FBG-based sensors for the detection of moisture ingress. Data obtained allow useful comparative studies to be carried out to study the effect of the cement type and the different porosity of the concrete samples on the migration of moisture. Although the work carried out is at preliminary stage, the measurements obtained under standardized laboratory conditions shows the potential of the FBG-based humidity sensor in structural monitoring. Together with other optical chemical sensors such as pH sensors, data obtained can provide valuable information for civil engineers in assessing the condition of concrete structures.

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