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Non-destructive fiber Bragg grating based sensing system: Early corrosion detection for structural health monitoring

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ABSTRACT

Steel corrosion is known as one of the major structural defects in steel structures such as pipelines. The high resolution of fiber Bragg grating (FBG) sensor and its ability to provide real-time monitoring make it a potential candidate for steel corrosion detection. Nevertheless, fiber optic sensor is now been widely used in civil engineering for structural health monitoring purpose. In this study, a non-destructive corrosion detection approach is developed using FBG sensors. The sensor comprises FBG coated with mixed pH-sensitive hydrogel and PDMS strain-sensitive coating. FBG sensors were embedded on the specimen to monitor the expansion strain caused by rebar corrosion. Specimens were placed in different environment conditions namely air, acidic and alkaline conditions, to experience different corrosion rate. The sensing principle is based on a Bragg wavelength shifts resulted from the induced strain on the FBG due to mechanical expansion and swells, in response to the changes in pH of the coating materials. A significant wavelength shift occurred at about day 20, inducing wavelength shift of 0.27 nm, 0.06 nm and 0.011 nm under acidic, air and alkaline conditions respectively. The relationship between wavelength shift, corrosion rate and strain induced is investigated and validated through this experiment. These sensors can be installed for real-time monitoring and early corrosion detection due to its non-destructive and highly sensitivity performance.

1. Introduction

Corrosion can be defined as the deterioration of a metal or an alloy caused by electrochemical reaction. The electrochemical corrosion processes are a combination of anodic oxidation and cathodic reduction. Rust from the corroded rebar is an iron oxide, which is the product of the reduction-oxidation (redox) reaction of oxygen and iron in moisture or under different environment conditions. Such reactions require one material to be oxidized (the metal), and another be reduced (the oxidizing agent). With sufficient amount of water (H_2O) and Oxygen (O_2), the iron mass will turn into rust, known as Hydrated Ferric Oxide ($Fe_2O_3H_2O$) [1,2], as per the equation below:

$$Fe + 3O_2 + 2H_2O = 2Fe_2O_3H_2O \quad (1)$$

$$(\text{Steel}) + (\text{Oxygen}) + (\text{Water}) = \text{Hydratedferricoxide(Rust)}$$

Surrounding conditions plays an important factor to accelerate the rebar corrosion as well, such as temperature, humidity and sulfuric acid attack. In addition, the interest in corrosion monitoring has been increasing because of the wastage of costly metal, risking the structural performance and inducing structural failure. Corrosion deterioration in a concrete structure over a time could cause the building to collapse and this could be a safety issue. Therefore, SHM is important because it prevents severe deterioration by detect of abnormalities in the earliest possible stage, guaranteeing the safety of reinforced concrete structures [3].

Corrosion inspection could be time consuming, costly and inaccurate since corrosion can occur at any location that cannot be inspected visually [4,5]. Weight loss coupons measurement is one of the present conventional corrosion monitoring methods. The weight loss coupon is a measurement of weight change of a coupon over some exposure time [6,7]. Furthermore, manual inspection of the structures for corrosion monitoring requires dismantling

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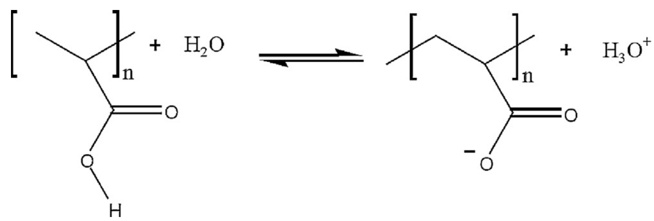

Fig. 1. Carboxylic acid groups on the polymer ionize in water.

the structures which could involve high maintenance costs and potentially cause the structural damages. Thus, to monitor and to detect the corrosion in an early stage without destructive tests, a monitoring system is designed and developed using Fiber Bragg Grating (FBG) based sensors. Monitoring via FBG sensor is a very simple method compared to the conventional methods and it is a non-destructive system. In addition, FBG provides advantages such as small size, light weight, high strain sensitivity, resistant to electromagnetic interference and most importantly, FBG sensor installation into the structure will not degrade the mechanical properties of the structural [8,9].

The monitoring of reinforced rebar in the concrete corrosion relies on the correlation between chemical parameters such as chloride concentration, carbonation from concrete and pH changes [10]. It is proposed to develop FBG pH sensors and the effectiveness of using FBG for corrosion monitoring with pH changes under different environments. The proposed sensor will be embedded in the rebar to measure the corrosion induced in different pH environment.

In this experiment, etched FBG based corrosion sensors coated with hydrogel mixed PDMS (Polydimethylsiloxane) solution were developed and monitored. The FBG sensors were embedded on the rebar for corrosion monitoring over a period of time until the rebar get corroded. This work was focused on exposed rebar structures with hot and humid weather. Hydrogels are cross-linked polymers, highly hydrophilic which absorb water and swell to an appreciable extent in water and in different pH solutions [11,12]. They have the ability to swell by absorbing water. The swelling and shrinking action of the hydrogels are readily converted to a mechanical response in the form of force and are the basis of the detection process in the present sensor. When the hydrogel absorbs water, it will swell and produce a mechanical expansion force [13]. Therefore, with the present of the hydrogel as a coating layer, the fiber would stretch and the fiber grating would expand which causes the Bragg wavelength shift. The synthesizing process of the hydrogel is simple and cost effective as there is no other chemicals need to form the hydrogel.

Hydrogels are polymers of Carboxylic acids [14,15]. Fig. 1 below shows the carboxylic acid chain when polymer ionizes in water. When these polymers interacted with water, the hydrogen atoms react and come off as positive ions. This leaves the negative ions along the length of the polymer chain [15]. Nevertheless, they tend to coil up when polymer chains are in solution, as shown in Fig. 2.

The hydrogel now has groups of negative charges down to its length, as shown in Fig. 3 [14]. If the ionic concentration of the solution is increased, whereby adding salt, the positive ions will attach themselves to the negative sites on the polymer which causes the polymer to collapse on itself. The acid ions will be removed by adding alkali and causes the position of equilibrium to move to the right; while adding acid perform the opposite effect [15]. All the hydrogels with consist of Carboxylic acid groups could expand at different pH values and ionic concentrations.

PDMS is a mineral organic silicon-based polymer, also known as Dimethicone and contains silicon, oxygen, and carbon [16]. Its physical looks as flexible clear silicone rubber. The PDMS chemical formula contains $(C_2H_6OSi)n$ and its fragmented formula is $CH_3[Si(CH_3)_2O]nSi(CH_3)_3$, where n is the number of monomers. PDMS can be in liquid or semi-solid form that depend on its monomer in the chemical formula [17]. PMDS is also a good physical resistance to mechanical damage and electrical non-conductivity. Generally, PDMS has the advantage of non-toxic, resistant to chemical, low cost, easy fabrication process and it contain a small degree of impurities which is not a suitable environment for bacteria to growth. In addition, it has its mechanical properties of strain sensitivity which were widely used in semiconductor, medicine, and automotive industries [18–20].

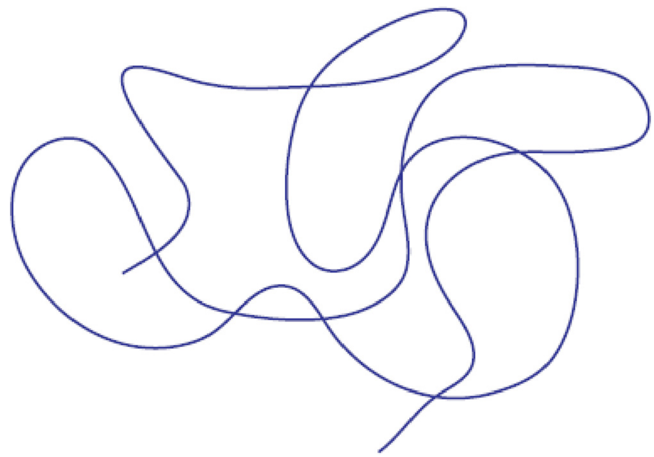

Fig. 2. A polymer chain coiled up in solution.

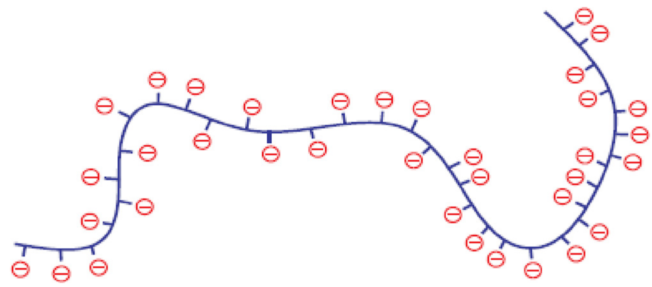

Fig. 3. A hydrogel polymer chain with lots of negative charges along its length.

2. Materials and experiment

2.1. Etching and material preparation

To enhance the sensitivity of FBG to the surrounding refractive index, the cladding around the grating region need to be reduced by wet etching process. Fig. 4 below shows the experiment setup of the wet etching process. FBG fiber was immersed in an aqueous solution of Hydrofluoric acid (HF) at 49% of concentration at room temperature of 25 °C. It comprises a broadband light source that was injected into the FBG through a 3-port circulator. The reflected spectra from the FBG was monitored through Optical Spectrum Analyzer (OSA) during the etching process. The final etched fibers were then examined and inspected via Scanning Electron Microscopy (SEM). FBG was rinsed under DI water after etching to remove remaining of HF solution and leave it for 2 min to dry before proceeding to the coating process. The total etching duration was about 19 min and 10 s, whereby the FBG thickness was etched from 125 μm to 9.7 μm.

A mixed solution of Polydimethylsiloxane (PDMS) and hydrogel were developed as a coating layer on the FBG to enhance its sensitivity as corrosion sensor. PDMS is a soft mixture with elas-