Sewerage tunnel leakage detection using a fibre optic moisture-detecting sensor system

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A B S T R A C T

The design and development of a new fibre optic sensor system for the optical detection of leakages in sewerage tunnels is reported. The system developed overcomes the disadvantages of the usually employed camera based inspection systems which are relatively complex and, in addition, require cleaning of the structures to be monitored beforehand. The sensor concept created combines a Fibre Bragg Grating (FBG)-based humidity sensor and a swellable polymeric fibre optic sensor. Both sensors are located along the sewerage tunnel so that they can response immediately to any leakages that may occur. The swellable polymeric fibre optic sensor shows a response of 34.2 dB in the presence of water, a performance which is superior to that seen form other swellable polymeric fibre optic sensors reported so far. Furthermore, the resistance of both sensors to highly alkaline environments (pH 13.4), an important feature of such sensors was verified. Consequently, when compared to the use of conventional inspection techniques, the novel fibre optic sensor system provides a robust, relatively low-cost and continuous monitoring system well suited to use in sewerage tunnels.

1. Introduction

Approximately 20% of the public owned and more than 40% of the privately owned sewerage tunnels in Germany are damaged [1] and similar problems are seen across the developed world, due to the age of current infrastructure. The reasons for experiencing damage to these structures are various and are due, for instance, to excessive loading caused by obstructions, or corrosion, displacement, mechanical pressure or the penetration of roots, all of which can damage sewerage tunnels. The effect of this is often to cause flooding and landslides as well as the contamination of groundwater and ground soil and, hence, the outcome of such events can be long-lasting and the effects profound. It is clear that, as a consequence, efforts to achieve a better form of structural health monitoring of sewerage tunnels are essential to be able to predict such events before they occur and take mitigating action at an early stage, minimizing economic losses as a result.

To date, no sensor system or inspection technique has been reported that detects leakages in sewerage tunnels rapidly and simple. The most common technique to monitor the structural health of sewerage tunnels is a remote inspection using a video camera-based system. However, this technique only allows for an assessment of the sewerage tunnel at regular intervals, due to the complex nature of the inspection process, as well as the necessity for the cleaning of the sewerage tunnel beforehand, which is expensive and time-consuming.

It has been observed that leakages in sewerage tunnels, which are based on linings using water-impermeable concrete, occur mostly at the interface between sewerage pipes, followed by leakages along the sewerage pipes due to the formation of cracks [2]. The cracks occur first at the bottom of the sewerage pipe and propagate from the inside surface to the outside due to mechanical pressure.[1] Therefore, a more efficient approach to the detection of leakage can be obtained from the observation of moisture along a sewerage tunnel, as well as at the interfaces between any two sewerage pipes.

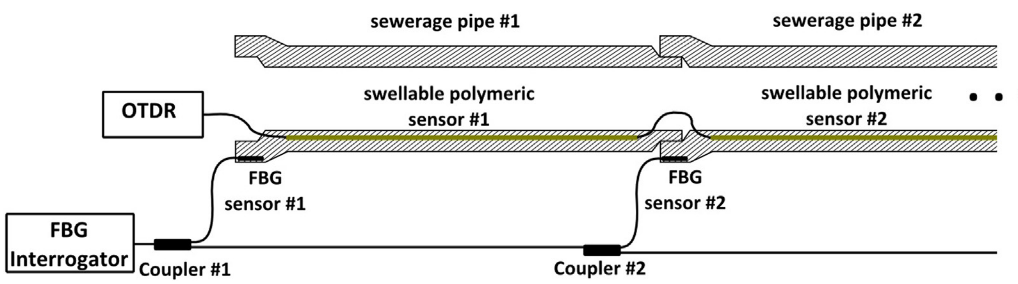

Fig. 1. Schematic of a fibre optic sensor system to detect leakages in sewerage tunnels. FBG-based humidity sensors are applied at the interface between two sewerage pipes. Fibre optic swellable polymeric sensors are applied to detect leakages along the sewerage tunnel.

Fibre optic sensors have the inherent advantage of being robust, electrically passive, easy to multiplex as well as the capability to be operated remotely. In the past, several different approaches to the design of fibre optic moisture sensors have been reported [3,4]. In terms of single-point fibre optic sensors a considerable level of research has been performed on the development and evaluation of fibre optic humidity sensors based on Fibre Bragg Gratings (FBGs) [e.g. 5,6] under a range of different conditions. In this approach, a hygroscopic coating such as using polyimide is applied to the FBG that swells in the presence of moisture, the result of which is an axial and radial strain in the fibre and, thus, to the FBG and this can readily be detected. Compared to the use of Long-Period Gratings (LPG) [7], and evanescent field [8]-based humidity sensors, FBG-based humidity sensors have the advantage of a linear response to humidity and they are easy to multiplex. In terms of distributed moisture sensing, a fibre optic based swellable polymeric system has been reported in previous work [9]. Such a fibre optic swellable polymer sensor consists essentially of a water-swellable hydrogel, which attenuates the light propagating in an optical fibre in the presence of water. Different approaches have been reported for the design of such fibre optic swellable polymeric systems of this type. For instance, a hydrogel coated central rod [9,10] or a hydrogel only [11,12] have been configured with an optical fibre by, for example creating a helically twisted thread with a winding pitch of several millimetres. The helically twisted thread acts to create microbends in the fibre so that, in the presence of water, the hydrogel swells and causes an attenuation of the light within the optical fibre. In this case the fibre optic swellable polymeric system, in combination with Optical Time-Domain Reflectometry (OTDR), can be used to locate any water leakages which may be distributed over a distance of several hundred metres [10].

The work reported in this paper focuses on the design and development of a detection system based on a suite of fibre optic sensors to detect and identify leakages in sewerage tunnels, with a fast response time. The main objectives of the work have been the identification and evaluation of damage events to sewerage tunnels using an optimized design of appropriate fibre optic sensors developed in this work.

2. Leakage detection of sewerage tunnels using fibre optic moisture sensors

A schematic of the novel fibre optic-based sewerage leakage detection sensor system is illustrated in Fig. 1. FBG humidity sensors are expected to be placed at each joint in order to detect leakages at the interfaces between sewerage pipes. As FBG-based humidity sensors are only single-point sensors, a fibre optic-based swellable polymeric sensor is used additionally, in order to detect leakages along the sewerage tunnel. Furthermore, in order to simplify the installation and use of the sensor system, both types of fibre optic sensors are integrated in each pipe of the sewerage tunnel. However, this requires that the moisture transport properties in concrete needs to be considered carefully as well.

If a concrete element is exposed to water unidirectionally, the unsaturated water flow is initially described by a combination of permeation and capillary suction [13]. Above capillary suction or if a concrete element is exposed to water vapour only, the moisture transport mechanism is characterized by diffusion caused by a partial water vapour pressure gradient. The development of moisture build-up in the concrete pores due to the diffusion of water molecules can be specified as due to adsorption of water molecules against the pore-walls for low relative humidity (RH) and as arising from capillary condensation on the water menisci formed in the pores by the adsorbed water molecule layers for high RH [13]. The dependence of the moisture content on the RH is known as the sorption isotherm. In the past, RH has been measured inside concrete in order to determine the moisture level [14]. While the measured RH is not a direct measure of the moisture content, it still can be correlated to deleterious effects such as shrinkage, thermal strain and diffusivity of the concrete sample [15].

According to the moisture transport properties in concrete, an appropriate location of both fibre optic moisture sensors is important for the proper detection of leakage. As shown in Fig. 1, the FBG-based humidity sensor should optimally be located at the bottom of each sewerage pipe interface in order to measure the ingress of moisture due to permeation and capillary suction of the ambient water caused by a leakage. By contrast, the swellable polymeric fibre optic sensor should be located near the inner surface of the sewerage pipe. However, determining this distance from the inner surface is critical where the distance has to be higher than the maximum capillary suction height of the applied concrete so that the swellable polymeric fibre optic sensor is only exposed to water in the case of a crack.

3. Design of the fibre optic-based moisture sensors used in this work

3.1. FBG based humidity sensor

A detailed description of the operation and packaging of the FBG based humidity sensor can be found elsewhere [16]. The FBG based humidity sensor employed consists of a bare and a polyimide (PI)-coated FBG, with both FBGs multiplexed in series along the fibre. The PI acts as a hygroscopic coating that swells in the presence of water vapour due to the adsorption of the water molecules and, hence, this effect causes strains on the FBG. The level of the strain experienced depends linearly on the applied RH and, thus, the ambient RH value can be easily determined by monitoring the shifts in the characteristic Bragg wavelength and comparing against a prior calibration using known values of RH. In order to measure accurately the value of the RH, the temperature cross-sensitivity of the PI coated FBG has to be compensated. Therefore temperature

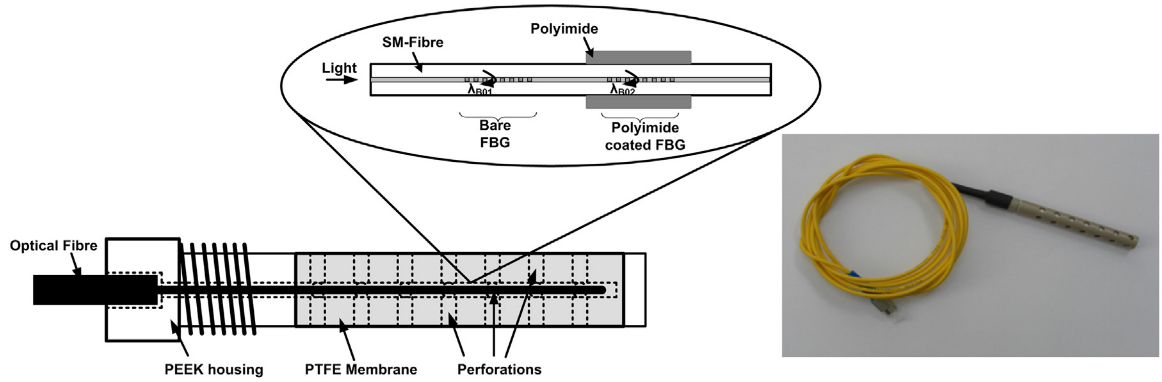

Fig. 2. Schematic and photograph of the FBG based humidity sensor developed in this work [16].

data from a bare (uncoated) FBG are used to determine any temperature changes and thus compensate for any temperature drifts that may be experienced by the PI-coated FBG [6]. However, as the FBG based humidity sensor will be applied below ground, the temperature environment will be relatively stable and thus changes experienced by the sensor due to any temperature effects will be minimal.

In this work, both FBGs were inscribed into a Fibercore™ PS1250/1500 optical SM fibre using light from a KrF excimer laser and using the phase mask technique. Following this, the fibercore optical fibre was tempered at 200 °C for 3 h to avoid any subsequent thermal drifts from the FBGs used to create the sensors. Subsequently, one FBG was coated with polyimide (Pyralin PI 2525) using the dip coating technique [5] to create a humidity sensor. In order to enhance the bonding between the polyimide coating layer and the optical fibre, a second FBG fibre was first treated with 3-aminopropyltriethoxysilane (3-APTS) solution (0.1%) diluted with deionized water [5]. In order to protect the FBG based humidity sensor from other deleterious environmental effects, sensor packaging appropriate to this application was developed an employed. At first, the optical fibre into which both FBGs were written was embedded into a tube made of PEEK and this was perforated at the tip. This perforated tip ensures that water vapour reaches the PI-coated FBG to monitor moisture effectively. The perforated tip was then covered with a permeable PTFE membrane to protect the sensor against dirt and chemicals [17]. Finally the PTFE membrane and the PEEK tube were further covered using a perforated PEEK rod with a centrically bore hole. The packaged FBG based humidity sensor thus developed is shown in Fig. 2.

3.2. Fibre optic swellable polymeric sensor

The fibre optic swellable polymeric sensor developed for this application consists of a hydrogel rod, an optical fibre and a device to cause micro bending of the fibre. Hydrogels swell in water without dissolution and thus in this work, poly (vinyl alcohol) (PVA) was used as it is resistant to oil, grease and solvents, very important and appropriate for this application to sewerage tunnels. The ‘micro bender’ developed is thus realized by using a helically twisted thread, which covers both the PVA hydrogel and the optical Single-Mode (SM) fibre. In the presence of water, the PVA swells and thus presses the SM optical fibre against the helically twisted thread and causes an attenuation of the light transmitted through the fibre. Initially, the hydrogel rod was fabricated from PVA by dissolving 21.6 g of PVA granulate (Kuraray Exceval HR 300) in 108 ml of deionized water. Following that a cylindrical tube of diameter of 17 mm and length of 510 mm was filled with liquid PVA and the PVA rod was then polymerized by a freeze–thaw cycle of 24 h duration. Following the polymerization, the PVA rod was dried at room temperature and known RH (40% RH and 20 °C) for one week. The shrinkage of the PVA rod due to the evaporation of water was measured to be ~41%. Thus depending on the length required, the PVA rod was cut accordingly. Subsequently an optical Single-Mode (SM) fibre (SMF-28e+) was helically twisted around the PVA rod with a winding pitch of 100 mm. Both the PVA rod and the optical SM fibre were then tied together by use of a helically twisted thread. The optimum performance of the device, in terms of response time and attenuation, was observed when using a winding pitch of between 8 mm and 15 mm [11] for the helically twisted thread. Finally the swellable polymeric fibre optic sensor thus created was covered using a felt wick where this felt wick acts as a protective cover, as well as extending the water-exposure area of the PVA rod due to its water transport capabilities. Important characteristics for the water transport capability of the felt wick are the wettability of the felt fibre surfaces as well as the capillary structure of the felt which contributes to this. The packaged fibre optic swellable polymeric sensor is illustrated both schematically and in a photograph in Fig. 3.

4. Experimental evaluation of the system

4.1. Evaluation of FBG based humidity sensor

The packaged FBG based humidity sensor system developed in this work was evaluated using a FBG interrogator consisting of a broadband light source (BBS) (Opto-Link ASE light source), a 3 dB coupler and a spectrometer (Ibsen I-Mon E). At the beginning of the evaluation, the humidity response of the FBG-based humidity sensor was determined. Different and known levels of humidity were obtained for the calibration by using different saturated salt solutions. In Fig. 4, the response of the sensor is shown at several of these: 11% RH (LiCl), 33% RH (MgCl2), 75% RH (NaCl), 85% RH (KCl) and 99% RH (saturated air). Furthermore, the response was also measured when the sensor was immersed directly in water (100% RH). As shown in Fig. 4, the response of the sensor depends linearly on relative humidity which is an important characteristic feature. However, when the sensor was immersed in water directly, the response reads a value which appears to be slightly above 100% relative humidity. The reason for this experimental error would appear to be a lower vapour pressure within the packaging of the FBG based humidity sensor. The temperature and humidity sensitivity of the sensor evaluated in Fig. 4 were measured to be as follows: 4.7 pm/%RH and 12 pm/°C for the PI coated FBG and as 8.3 pm/°C for the bare FBG. The higher temperature sensitivity of the coated FBG can be explained by the induced thermal strain and the thermo optic effect due to the PI coating which was investigated in previous work by some of the authors [18]. Furthermore, in Fig. 4 the response time of the FBG based humidity sensor to different

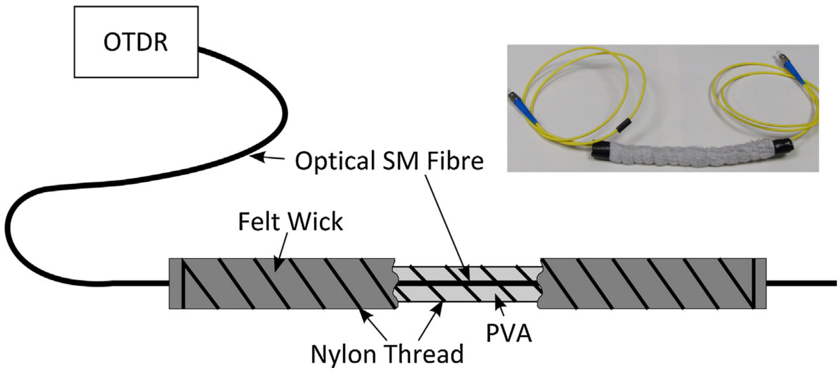

Fig. 3. Schematic and photograph of the fibre optic swellable polymeric sensor developed in this work.

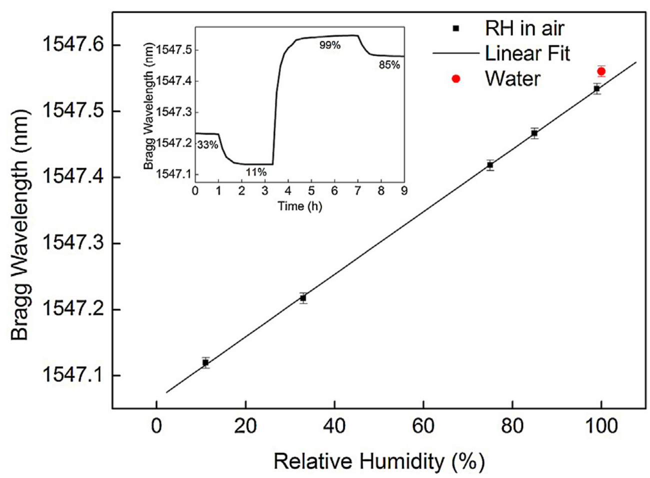

Fig. 4. Response of the PI-coated FBG to various applied RH levels. These known RH levels were obtained by using different saturated salt solutions.

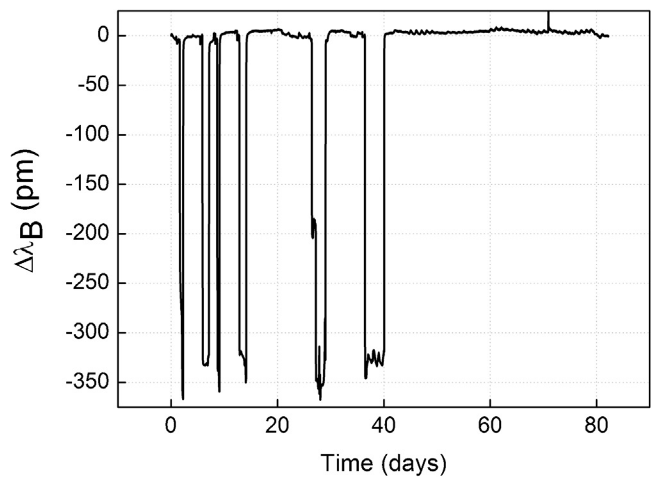

Fig. 5. Evaluation of the long-term response of the FBG-based humidity sensor. The relative change of the Bragg wavelength, $\Delta\lambda_B$, is referenced to the Bragg wavelength measured when the sensor was immersed in water.

saturated salt solution is illustrated (inset). The response time of the sensor evaluated in Fig. 4 was determined to be 30 min (t90, where the sensor reaches 90% of its final value). Although not measured directly, based on prior work and a knowledge of how the characteristics of these devices change with coating thickness, the humidity sensitivity and response time, the thickness of the PI coating was estimated to be approximately 35 µm [18]. As the packaging of the FBG based humidity sensor has no direct influence on the sensor response [16], the response time and sensitivity can be optimized by changing the coating thickness [18]. However, in terms of detecting leakages in sewerage tunnels the response time and sensitivity of the current device were designed to be well suited to this specific application. Following this, the long-term response of the packaged FBG-based humidity sensor was evaluated. For this calibration, the sensor was immersed in water and dried at ambient relative humidity, at random intervals. Fig. 5 illustrates the long-term evaluation of the sensor used over 82 days. The Bragg wavelength shift shown in Fig. 5 refers to the Bragg wavelength measured with reference to the situation when the sensor is immersed in water. It is evident from Fig. 5, that the FBG-based humidity sensor system designed in this work provides a long-term, stable measurement of the humidity.

4.2. Evaluation of the fibre optic swellable polymeric sensor

Initially, the response time and light attenuation characteristic of the fibre optic swellable polymeric sensor, without the use of the felt wick was evaluated. An 8 cm sensor element with a diameter of 8 mm and a winding pitch of 8 mm was immersed on two occasions in water and the light attenuation resulting, as well as the response time achieved were measured. The light attenuation was measured using a powermeter (FiboTec dB-Meter) and the result of that measurement is illustrated in Fig. 6. The standard deviation of the FiboTec dB-meter has been specified as 0.02 dB and this is reflected in the error shown in the measurement. The sensor shows a small level of hysteresis in terms of the maximum attenuation and

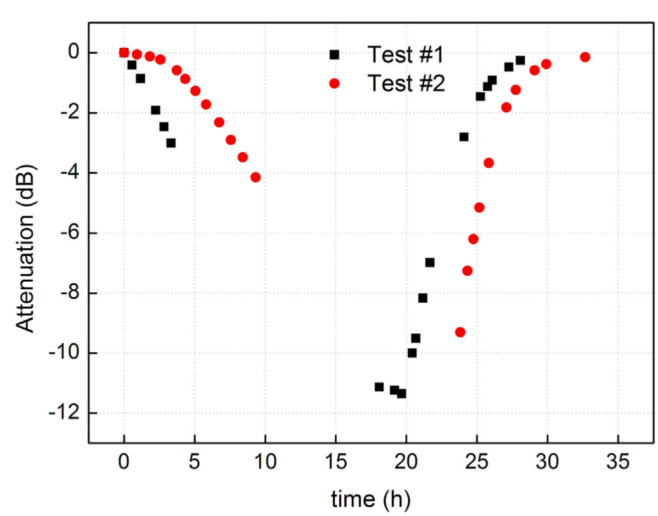

Fig. 6. Response of the fibre optic swellable polymeric sensor to immersion in water. Two tests were conducted (shown as Test 1 and Test 2) to determine the hysteresis in the measurement.

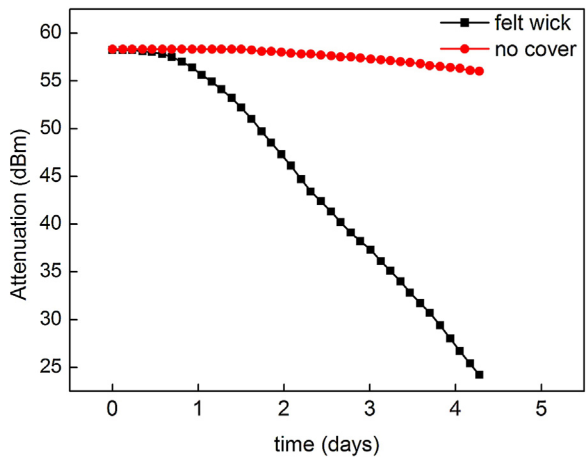

Fig. 7. Enhanced response of the fibre optic swellable polymeric sensor when the sensor is covered with a felt wick.

the response time. However, the maximum attenuation for both experiments is sufficient to allow the detection of the moisture ingress in the concrete of a sewerage pipe using an OTDR system. Furthermore, the sensitivity of the fibre optic swellable polymeric sensor to RH was evaluated in this experiment. For this purpose, the sensor was kept in a climate chamber (Memmert CTC256) which allowed the fixing of the RH at 99% and the temperature at 20 °C for 19 days. However, no light attenuation caused by this level of RH was observed.

Following this initial evaluation, the performance of the sensor when subsequently covered with the felt wick was evaluated. To verify whether the use of the felt wick leads to an advantage in terms of performance seen through a change in the light attenuation, water was dripped onto a 40 cm long sensor with and without the felt wick. The drip rates used were 11 ml/min and 23 ml/min, this depending on whether the sensor was covered with or used without the felt wick. As illustrated in Fig. 7, the fibre optic sensor with the felt wick cover shows a much higher attenuation, measured to be 34.2 dB. The reasons for the enhanced level of light attenuation and thus greater sensitivity of the device are due to the water storage and the water transfer capabilities of the felt wick employed.

4.3. *Resistance to alkaline pore water*

The highly alkaline nature of the pore water of concrete is of critical importance when considering embedding fibre optical sensors, because it can degrade the performance and the lifetime of the sensors used. Therefore, the alkali resistance of both sensors developed for this application was investigated. An alkaline solution which was representative of what would be experienced in practical use was obtained by using 0.75 M KOH and 0.75 M NaOH in a 10% CaOH solution [17]. The pH value of this solution was measured to be 13.4 in the laboratory, this being measured using a laboratory pH-meter (Hach HQ40d). In order to evaluate the resistance of the FBG-based humidity sensor to alkaline pore water (which has a similar value of pH to the laboratory solution), a packaged sensor was immersed in this alkaline solution for 22 h. In Fig. 8, the responses of the packaged FBG-based humidity sensor with the sensitivities of 7.1 pm/%RH, 14.6 pm/°C (PI coated FBG) and 8.3 pm/°C (bare FBG), monitored before and after immersion in the alkaline solution are shown. The RH levels used in Fig. 8 were controlled by making the measurements in a climate chamber (Memmert CTC256). Fig. 8 indicates that the sensor packaging should withstand operation in high pH situations and therefore the packaging has been effective in protecting the FBG-based humidity sensor against the effects of

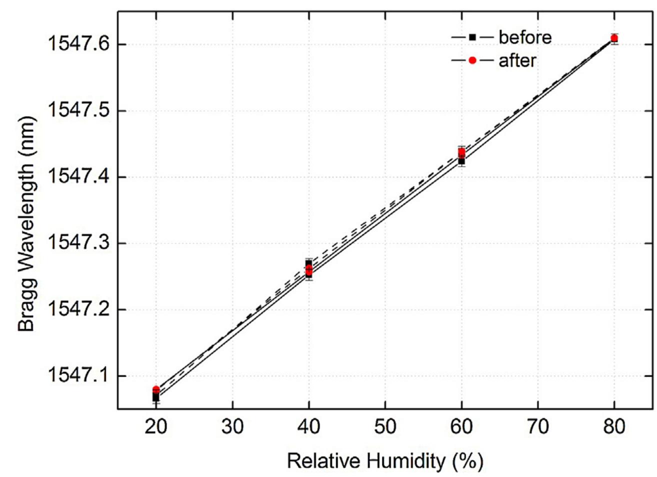

Fig. 8. Resistance of the FBG based humidity sensor to the presence of the alkaline pore water. RH measurements were performed using the climate chamber (Memmert CTC256) for increasing and decreasing humidity levels and the measurement of the Bragg wavelength of the PI-coated FBG before and after immersion in the prepared alkaline solution [16].

alkaline pore water. Furthermore, the packaged FBG-based humidity sensor displays no hysteresis in its performance. Following this, the resistance of the PVA material used to alkaline pore water was evaluated by immersing two identical samples of PVA, separately in both deionized water and the alkaline solution prepared and then measuring the weight of each sample over a three month evaluation period, as shown in Fig. 9. After the system had saturated and the swelling of both samples was complete, the weights of both PVA samples remained constant over the measurement period and hence no degradation of performance due to the effects of water or the prepared alkaline solution was observed.

4.4. *Moisture transport in concrete sewerage pipes*

In light of the discussion in Section 2, the positioning of both of the sensors developed in the sewerage pipe environment is very important, to guarantee the proper operation of the sensors and thus of the leakage detection system. From the evaluation undertaken, the report of which follows below, it is important that the fibre optic swellable polymeric sensor is only sensitive to water. Hence this sensor should be located above the permeation and

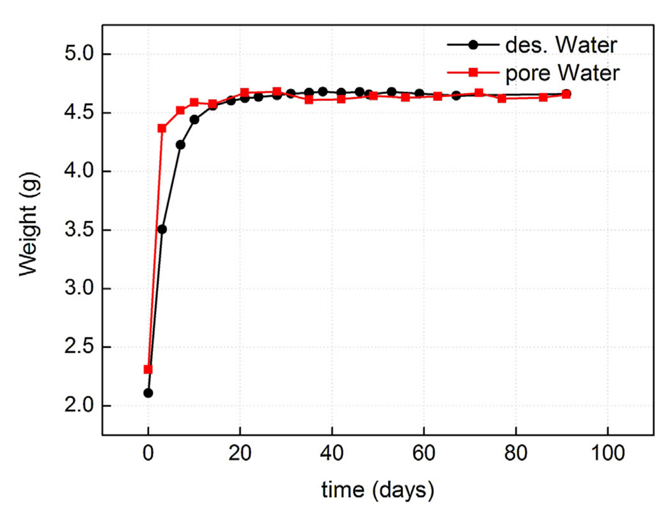

Fig. 9. Evaluation of the resistance of the fibre optic swellable polymeric sensor to the alkaline pore water obtained by immersion of a PVA rod in both distilled and then the alkaline pore water.

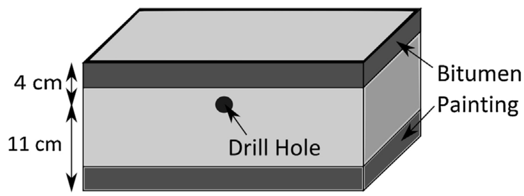

Fig. 10. Front view of a 150 mm × 150 mm × 240 mm concrete block used to simulate the moisture transport in a concrete sewerage pipe.

capillary suction height of the concrete so that the sensor only responses to the case where there is a damaged sewerage pipe. Furthermore, as the FBG based humidity sensor responses linear to the applied RH, the sensor should be located very close to the outer surface so that the waste water inside the sewerage pipe has almost no impact on the response of the FBG based humidity sensor.

In order to determine the optimal location of the two fibre optic sensors within the concrete sewerage pipe, the moisture ingress into the concrete sewerage pipe was evaluated for different positions and heights in the pipe. For this purpose, a 150 mm × 150 mm × 240 mm concrete block was fabricated using C40/50 concrete, a type which is commonly used to manufacture sewerage pipes. After the concrete was cured, a hole was drilled into the block at a height of 11 cm from the bottom and 4 cm from the top, as is shown in Fig. 10. Furthermore, in order to simulate the moisture ingress at the inner surface of the sewerage pipe due to both waste water and moisture ingress at the outer surface due to a leakage, the sides of the concrete block were covered with bitumen paint so that water could penetrate only into the concrete from the bottom or the top. Finally, the FBG-based humidity sensor was integrated into the drilled hole and protected by being covered with a sealant.

At the beginning of the evaluation, the presence of moisture at the outer surface of the concrete sewerage pipe, due to waste water being inside the sewerage tunnel, was simulated. Therefore the bottom of the concrete block was immersed in water and the humidity level at a height of 110 mm was measured over a period of 14 days. After the humidity measurement at that height of 110 mm was saturated, the concrete block was turned around to measure the moisture at a height of 40 mm, in that way to simulate the moisture ingress into the sewerage pipe due to the presence of waste

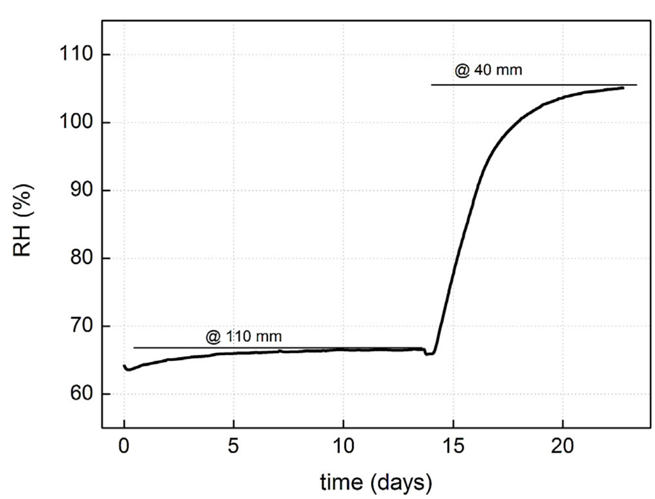

Fig. 11. Measurement of the moisture transport in a concrete sewerage pipe. Measurement at a height of 40 mm simulates the moisture ingress due to a leakage, whereas the moisture ingress at 110 mm is due to waste water within the sewerage pipe.

water or ambient water. The results of these measurements are shown in Fig. 11.

From Fig. 11, it follows that the humidity level inside the concrete sewerage pipe depends on the height of the sensor system when the pipe is exposed unidirectionally to the presence of water. Furthermore, the FBG-based humidity sensor measures a RH value of above which is determined to be 100% at a sensing height of 40 mm. From the data in Fig. 4, this indicates that the FBG-based humidity sensor was surrounded by water due to capillary suction of the concrete pore holes. Therefore, the results indicate that the location of the fibre optic swellable polymeric sensor should be above 40 mm, so that the sensor is only in contact with water in the case of a crack in the concrete structure. Furthermore, the FBG-based humidity sensor should thus be located very close to the outer surface of the pipe.

5. Summary

In this work a fibre optic humidity sensor system has been designed and evaluated to detect and measure leakages in sewerage tunnels. The sensor system discussed comprises, in essence, a FBG-based humidity sensor and a fibre optic swellable polymeric sensor. The FBG-based humidity sensor is used to detect leakage at the interface between two sewerage pipes. Experiments undertaken have verified a very satisfactory performance of the FBG-based humidity sensor in terms of its sensitivity, hysteresis and long-term stability. The fibre optic swellable polymeric sensor has been shown to be capable of detection of leakages along the sewerage tunnel caused by cracks at the bottom of the sewerage pipes. The sensor developed shows a light attenuation of 34.2 dB in the presence of water, a performance which is superior to that seen from swellable polymeric fibre optic sensors reported to date. In addition, both sensors have also proved their resistance to highly alkaline pore water (evaluated at pH 13.4) and thus their capability to be integrated in concrete structures where such a pH value of the water is experienced. Consequently, compared to the conventional use of camera-based inspection techniques for leakages in sewerage tunnels, the novel fibre optic sensor system developed and reported here provides a robust, relatively low-cost and continuous monitoring system. Currently, field trials are running in order to determine the sensor performance in operative conditions and the results of such trials will be published in due course.

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