



Real-Time Humidity Monitoring Using Distributed Optical Sensor for Water Asset Condition Assessment

Christopher W. K. Chow^{1,2} · Raufdeen Rameezdeen¹ · George Y. Chen³ · Haolan Xu² · Md Mizanur Rahman^{1,2} · Xing Ma¹ · Yan Zhuge¹ · Nima Gorjian^{1,4} · Jing Gao¹

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Abstract

It is well accepted that moisture ingress in concrete reduces durability and life span of water assets. Condition assessment is an important tool to inform decision for maintenance, retrofit or replacement. However, the most significant challenge is to obtain accurate condition information, particularly when the inspection points are physically difficult to access or inaccessible. Therefore, a reliable and cost-effective monitoring (sensor) system, preferably real-time with ability to streaming online, would be a useful management tool, particularly for water utilities. This paper describes an approach to develop a distributed optical fibre humidity sensor for condition assessment and environmental monitoring both inside and outside of infrastructures, such as inside the concrete and surrounding soil. A new polyelectrolyte multilayer (PEM) coating with higher sensitive was evaluated for relative humidity measurement in soil and concrete, respectively. In this study, two simulated conditions, in concrete and soil, were conducted to evaluate the sensing concept with the development of appropriate measuring methodologies including fibre installation and protection. The optical fibre sensor setup in laboratory environment showed that optical sensor can detect and indicate voltage change with the variation of moisture contents in both soil and concrete. The test results indicate a good correlation between high levels of relative humidity/moisture and transmitted optical power. A simple relative humidity (RH) calibration can be used to convert signal to RH in percentage for soil and concrete measurements and the procedure used to imbed the fibre in both samples is effective. Nevertheless, the sensor measures soil humidity (not moisture content); therefore, further investigation is required to identify the consequence for the variation of the measured parameter.

Keywords Real-time monitoring · Distributed optical fibre sensor · Asset condition assessment · Concrete infrastructure · Soil moisture

Introduction

Asset management is now becoming part of our daily life and its importance is growing in all industries, particularly the water industry which is currently under very strict economic scrutiny and control. Water utilities are generally asset-intensive organizations and actively seeking innovative methods to become more proactive in managing their assets for better cost benefit outcomes. In situ and continuous monitoring of the surficial characteristics and structural behaviour of reinforced concrete exposed to climatic conditions is very important in estimating deterioration status and service performance of civil infrastructures [1]. Regular maintenance and repairs at the most suitable time based on exact evaluation on current conditions of the structures will reduce risks of sudden deterioration and avoid unnecessary

✉ Christopher W. K. Chow
christopher.chow@unisa.edu.au

¹ Sustainable Infrastructure and Resource Management (SIRM), UniSA STEM, University of South Australia, Mawson Lakes, SA 5095, Australia

² Future Industries Institute, University of South Australia, Mawson Lakes, South Australia, Australia

³ Guangdong and Hong Kong Joint Research Centre for Optical Fibre Sensors, Shenzhen University, Shenzhen 518060, China

⁴ South Australian Water Corporation, Adelaide, South Australia, Australia

spending. The terminology known as health monitoring is the process of observing and tracking structural integrity and of evaluating damage characteristics in structures [2]. The system relies heavily on effective monitoring of these inaccessible infrastructures, such as water/wastewater pipes and tanks, to inform the decision maker on their status. The trend in water utilities is to move away from 'time based' maintenance to 'condition based' maintenance thanks to improvements in the monitoring domain. Condition assessment becomes a very important tool for modern day asset management, particularly for critical infrastructure when aging and acidic environments are combined. Using wastewater assets to illustrate the situation, concrete often faces corrosion and damage, resulting in significant reduction in load carrying capacity and enhanced safety hazards. The environment surrounding, particularly the soil, also has a major impact on their degradation. It is essential for manager to understand the accurate structural condition of existing assets before they can make a suitable plan for maintenance, retrofitting or replacement. Although obtaining data from an integral condition assessment for improved decision making of an existing structure is essential, however, it poses numerous challenges to the water utilities. This can be achieved by using preferably an online and real-time system to monitor the performance and condition of the assets and the environment surrounding using sensing technology. However, the most significant challenge is to select and install reliable and cost-effective sensors.

Real-time sensing can provide a lot of useful information for decision making [1]. In general, sensors used at present for structural health monitoring of water tanks and pipes measure either strain, vibration, pressure, temperature or humidity. Strain sensing can give indications of structural deformations, some of which can be due to thermal expansion, but not small cracks [3]. Vibration sensing can provide a large-area coverage, but only informs the end-users when a leak is already occurring [4]. Pressure sensing is only accurate and viable in large containment structures and can be affected by temperature drifts [5]. Temperature sensing can provide alerts when there is a leak-induced change in local temperature, but it is not reliable in some cases [6]. Humidity sensing provides the most reliable information about leakage and works as an advanced warning system in most cases [7]. Sun et al. monitored moisture in a stone wall by using two types of sensors: conventional relative humidity (RH) sensors and optical fibres [8].

The humidity obtained by using the commercial RH sensors was always 100% RH, whereas the measurements with the fibre optic humidity probe indicated RH ranging from 90 to 93%. The authors recognize that, unlike most conventional RH sensors, the optical fibre RH probes were not influenced by condensation of moisture within or on the sensor itself. Hence, the optical RH sensors are the most accurate tool

which can provide a faster response and could be used in structures subjected to wet/dry cycles over several days [1]. Due to the effects of humidity on initiation and spread of reinforcement corrosion, early detection of moisture helps to protect the reinforced concrete structures from severe damage resulting from loss of structural integrity. Currently, with the development of sensor technologies, different sensors have been designed to measure the humidity in concrete [1, 9]. Some of them have multiple functions, not only measuring humidity but also recording temperature changes [10].

In this study, a proof-of-concept demonstration of a fully distributed optical humidity sensor that could be used in real-time to inform decision makers on the condition of concrete pipes was developed. The technology has evolved from the world's fastest humidity sensor [11] and a new form of ultra-sensitive and ultra-fast touchless control using humidity [12]. It consists of a laser source and a light detector, and a length of optical fibre with a functional coating which responds to environmental humidity. The sensor works by sending out light, which travels along the fibre. Upon a humidity change(s) at any point(s) along the optical fibre, the optical fibre reflects some light back to the detector. The signal processing software can determine the humidity at all positions (e.g. millimetre resolution) along the entire length of the optical fibre (e.g. hundreds of metres). The project was initialized as an industry challenge; it consists of two parts: (1) a fully distributed optical sensor development and feasibility assessment and (2) development of methodologies for asset condition assessment and evaluation of integration requirements for the two situations, (a) structural, impact of humidity on reinforced concrete infrastructures, and (b) environmental monitoring, impact of soil humidity/stability on below ground infrastructures.

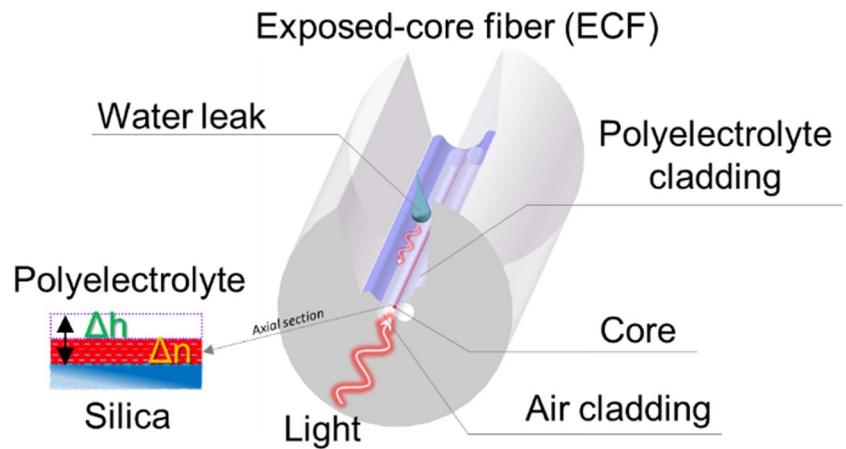
Experimental

Sensor Material Development

This section describes the development of alternative polyelectrolyte combinations (material science) and high-order mode excitation/coupling techniques (photonics) for higher sensitivity. Polyelectrolyte multilayer (PEM) coatings have been found to be humidity sensitive and, in thin-film form, very fast and able to effectively manipulate light. Among many possible pairings of electrolytes, poly(diallyldimethylammonium) (PDDA)/poly(styrenesulfonate) (PSS) showed the most promise through fast response, large optical and physical changes that works as an optical transducer along the sensing fibre (Fig. 1).

The optimum thickness was experimentally determined. High-order mode excitation was not tested at this point due

Fig. 1 Illustration of the sensing fibre. Inset: cross-section view of the polyelectrolyte multilayer coating which has reflective index (Δn) and thickness (Δh) changes upon absorption of water



to the lack of suitable optical fibres. As for coupling techniques, the existing technique of using a fibre lens to coupling large-area light into a small-area core was optimized with manual fusion-splicing settings.

Fibre-Coating Procedure

The procedure for depositing the coatings is in the following order: (i) deposit protective coatings at periodic positions, which is anticipated to spread out locally and then self-cure; (ii) deposit PDDA coating in-between protective coating segments, with overlaps being of no consequence; (iii) deposit PSS coating in a similar fashion; and repeat stages (ii) and (iii) until 10.0 bilayers are reached. Note the protective coating is deposited first to create trenches for equal-length PDDA and PSS coating segments. These two electrolytes must be of equal lengths to ensure a uniform refractive index profile and thus correct RH analysis.

Sensor System Setup

The fully distributed humidity sensor setup shown in Fig. 2 is based on coherent optical frequency-domain reflectometry (OFDR). Essentially, (i) linearly polarized coherent light is launched into the sensing fibre; (ii) changes in RH along the sensing fibre back-reflect light; (iii) returned light combines with reference light and their difference in optical frequency can be observed in the form of a low-frequency beat signal; (iv) signal processing determines the distance the light has travelled from each portion of light based on its beat frequency; (v) signal processing calculates the RH from the amplitude of the beat frequencies based on calibration data; and (vi) real-time monitoring capability over potentially longer distances (e.g. tens of metres).

To simplify the detection system, the reference interferometer was removed followed by calibration of beat frequencies to distances with physical measurements.

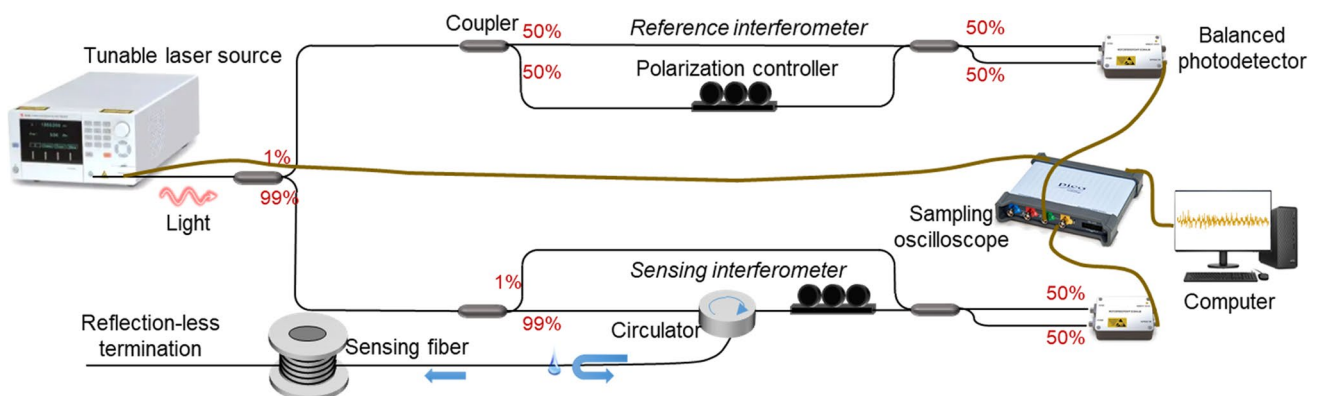


Fig. 2 Schematic of the optical frequency-domain reflectometry setup and detection system with a computer-controlled laser source, data acquisition module and waveform generator

Deployment and Testbed Setup

For deployment, a 200-cm optical fibre, fabricated using the above procedure, was connected to the separate sensor box (laser plus detector). A simulated study to assess the impact of humidity/stability on underground assets was designed with two experimental measurement procedures, measurement in (1) soil to assess the impact of soil humidity/stability on underground assets and (2) concrete to assess the impact of humidity on reinforced concrete structures. For the soil test, it was performed on a pre-wetted compressed soil cylinder (5 cm diameter) as shown in Fig. 3a, to obtain information on the distribution of moisture/RH. Although the cylinder is 5 cm in diameter, effectively, it only has 3 cm in the middle core with 1-cm loose/soft loose edge in both ends. The middle of the sensing fibre (3 cm) was in the soil with the sensing fibre which was sandwiched between two layers of paper disks to prevent contamination while permitting the ingress of moisture. Measurements were conducted in 0 min, 5 min, 10 min and 15 min.

For the concrete test, a 15 cm (diameter) \times 5 cm (depth) normal concrete disk with a compressive strength of 40 MPa was used as the test sample. The middle hole size of 1 cm (diameter) \times 1.5 cm (depth) was drilled using an electric drill prior to the insertion of the optical fibre sensor. The optical fibre was placed inside the porous protective tube by inserting through the protective tubing. The bottom surface of the concrete sample was dipped into water to measure the water penetration resistance. The end of the sensing fibre was inside the drilled concrete (Fig. 3b). The hole was padded with a longitudinally cut plastic tube to prevent direct contact. The cut allowed moisture to seep inside, and measurements were conducted in days 0, 1 and 2.

Sensor Calibration and RH Measurement

The data acquisition process analysed the electrical signal converted from the optical signal received by the

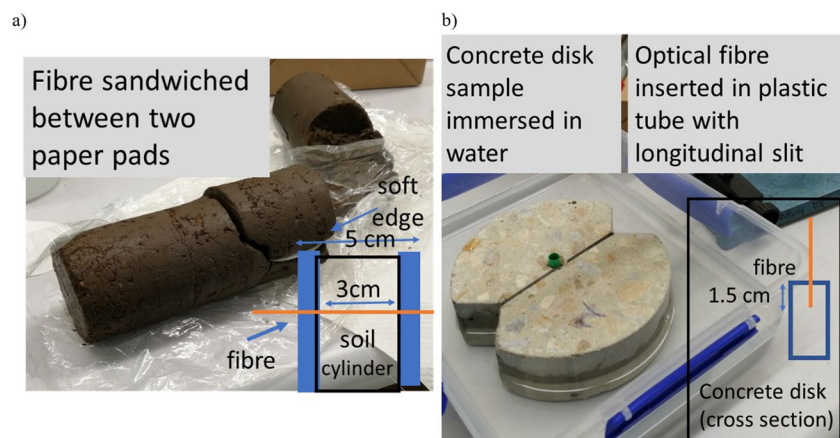
photodetectors. After signal processing in the frequency domain via the fast Fourier transform, each frequency component was converted into distance, validated by physical measurements. The frequency component amplitude upon humidity calibration can be used to determine RH at a particular location along the sensing fibre. A blank measurement was conducted in air to obtain the background signal/baseline of the optical fibre. Two repeated measurements were averaged; this averaged signal was later used as background correction to correct the imperfection of the fibre. A simple RH calibration was conducted at room RH (it was recorded as 45% RH) to convert the optical power signal (electrical voltage after conversion) into RH. Both test (soil and concrete) measurements were conducted in duplicate with average of the two recorded. Finally, a second blank in air/calibration measurement was conducted after soil and concrete measurements for comparison of signal stability before and after test measurements.

Results and Discussion

Advantages of Using the Chosen Sensor Material

Optical fibre-based designs exhibit the advantages of being immune to electromagnetic interference, can be interrogated from a single end and are inherently inert and safe to use in easily combustible environments. Furthermore, the commonly utilized sensing mechanisms of water-induced optical scattering or absorption spectroscopy are sensitive. Optical fibres are widely available at low cost and can be packaged with a small footprint. Among fibre optic sensors, the fibre Bragg grating (FBR)-based ones are the most used in structural health monitoring [1]. Although there are different technologies for measuring moisture or humidity with multiple point sensors or quasi-distributed sensors, the cost is proportional to the number of sensing points, which can be expensive for large-area or high spatial resolution coverage.

Fig. 3 The photograph and illustration of a pre-wet compressed soil cylinder with optical fibre inserted and **b** concrete disk pre-wet in water with optical fibre inserted



A fully distributed solution using a low-cost porous multi-mode fibre with reflectometry becomes increasingly unreliable over long distances (e.g. tens of metres) due to significant dispersion of light [13]. The distributed sensor design reported in this paper can potentially overcome this limitation by utilizing low-loss coatings along the optical fibre, rather than fabricating complex microstructures inside the fibre core. In this study, the optimum thickness was experimentally determined to be 10.0 bilayers, which delivers a good balance between sensitivity to humidity and response time. The key innovation of this new fully distributed humidity sensor is the unique combination of OFDR, exposed-core fibre and humidity-sensitive functional coating. Furthermore, this study also determines that the nonlinearity of the wavelength sweep to be negligible, which means resampling via the reference interferometer, is not needed for the implemented detection system. It is worth noting that a long-range version (> 10 m) of the sensor is being developed alongside an automated fibre-coating rig, which will also offer higher accuracy and reliability. The key difference is the approach to coating the sensing fibre. In this setup, the standard coherent OFDR with the availability of exposed-core fibre that provides convenient and strong interaction with the ambient environment, however, the optical propagation loss is very high and thus the current maximum sensing range is approximately 0.5 m. With the rapid development of new types of exposed-core fibres and polymer optical fibres, a significant reduction in optical loss is expected, enabling a much longer sensing distance.

Temporal Characteristics and Calibration

The moisture/humidity can be obtained via a complicated data acquisition/processing system and frequency signal can be converted to position (defined as distance) on the optical fibre and with a voltage measurement to represent the humidity at that position. The reflection from the first splice with the graded-index fibre prior to the exposed-core fibre (sensing fibre) is a stable reference for normalization. With this real-time calibration, laser intensity noise and external optical losses are effectively removed. The detail of the data processing step is described in Chen et al. [14]. Chen et al. also identified the transmitted power/voltage can be varied by the condition of the coating which a background measurement of the pristine fibre/blank in air would be necessary and it then can be used to correct and calibrate the other test measurements [14]. It is a real-time calibration process (with every data point) and thus it does not matter where the sensor is deployed. The measured voltage signals in air (blank) in duplicate are shown in Fig. 4.

Blank 1 refers to the measurement before any sample measurements (new) and Blank 2 refers to measurement after the fibre used for measurements (used). By visual

comparison of the signal, good reproducibility has been observed from the two duplicate measurements of each blank set, before (Blank 1) and after (Blank 2) experimental measurements. In fact, all four measurements (duplicate measurements before and after experimental measurements) shown are relatively similar, and after averaged, the duplicated measurements, both before and after used for experimental measure, match quite well and the minor difference would have no impact on the measurement results. From these measurements, no signal deterioration has been observed after the fibre inserted into the samples (soil and concrete) to conduct the measurement.

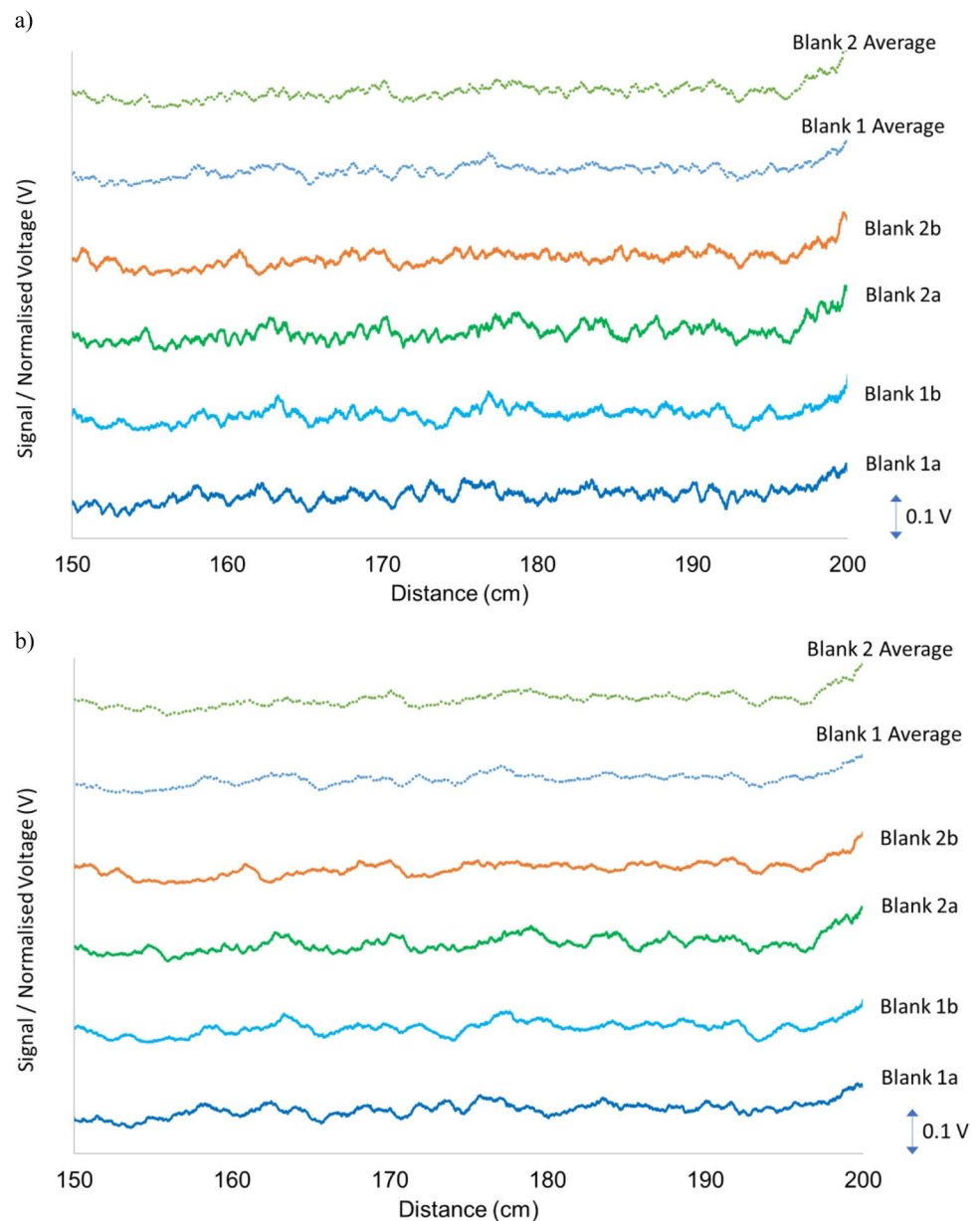
These measurements were conducted in ambient humidity which at the time was 45% (RH); the two averaged signals can be used as background correction and RH calibration for other test measurements. The frequency signal after converted into distance (cm) from the sensing interferometer (detector) has a resolution step of 0.016 cm (limited by the step of the digital and analogue convertor); to obtain a smoother and more reproducible signal for assessment, two levels, a 33-point (over the length of 0.5 cm) and a 65-point (over the length of 1 cm) moving average, have been applied and compared as shown in Fig. 4a and b; the level of smoothing is a trade-off of resolution; increasing the number of points can improve the signal with reduced distance resolution; and for a good balance, 65 points has been chosen for the rest of the study as it is about using over 1 cm of data which is sufficient in terms of distance resolution for this type of monitoring application.

Soil Measurement

Figure 5 shows similar trends of measured data at different times for a cylindrical core of natural local soil sample (Fig. 5a shows the raw signal and Fig. 5b shows the smoothed signal). In addition, the distance along the fibre is labelled in sections as inside the soil cylinder, edge of the soil cylinder and outside the cylinder indicating the signal characteristics of different sections. Soils are usually not uniform, and with some level of natural variability is expected, as observed in the recorded data, e.g. a relatively lower signal in the middle of the soil cylinder and trending towards the right side of data (end of the fibre). Outside the 3-cm contact length (1-cm edge soil cylinder sections) between the sensing fibre and the soil, there are still some correlations, but it becomes weaker with distance, due to ambient air flow affecting the local RH level. It can be shown clearer after RH calibration. The outside soil cylinder section on the right side of Fig. 5 is the end of the fibre with slight signal variation expected.

Figure 6 shows soil sample after calibrated to RH. By inspecting the signal, it can show some contrasts between the dry states and the wet states. The pre-wetted soil slowly transfers

Fig. 4 Temporal characteristic of the optical fibres in air with duplicate measurements. Blank 1—before using for experimental measurement, and Blank 2—after experimental measurement. To display clarity, the signals have been offset by 0.2 V to allow better separation of each data set, (a) 33-point and (b) 65-point moving average applied to smooth the raw signal

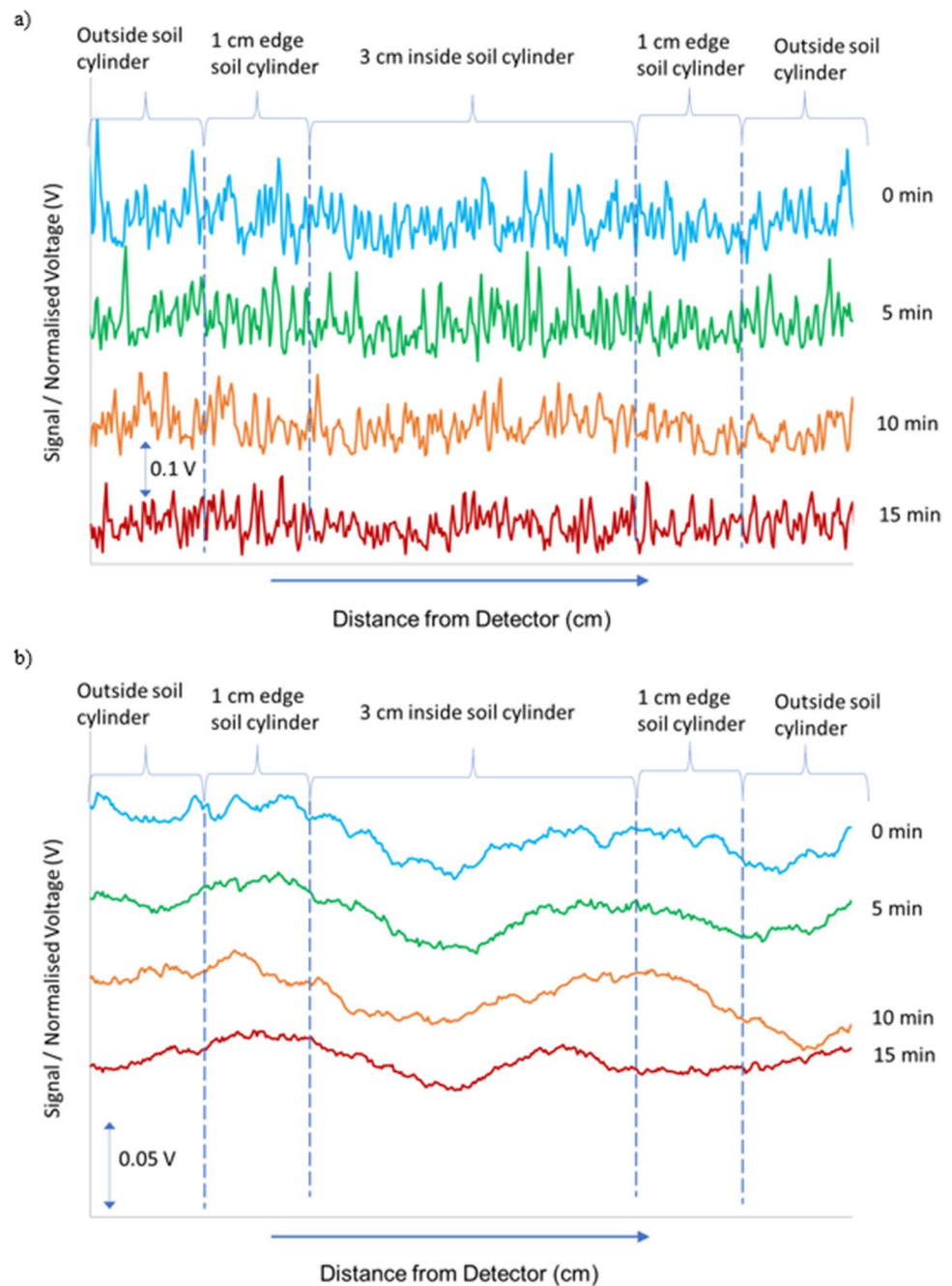


its moisture content to the paper disk and then the sensing fibre, which leads to an initial decreasing signal due to water-induced absorption of light, and this is generally a characteristic of this type of measurement. From the time measurement, it shows the soil is drying up in air overtime. Figure 6a shows the calibrated RH using Blank 1 (before test sample) measurement for the calibration of the raw signal and Fig. 6b shows the calibrated RH using Blank 2 (after test sample) measurement. Generally, both measurements are within 1% RH difference and the accuracy estimated from a previous study [14] was also about 1%RH; therefore, the sensing characteristics of the optical fibre have not affected by soil measurement (exposed to the sample); it is a positive sign of the use of the measurement for real-time monitoring by calibration of the signal to RH using the initial calibration.

Concrete Measurement

For concrete or reinforced concrete structures, especially for the ones exposed to wet conditions, moisture content in such composites can directly or indirectly contribute to deterioration of concrete. For example, the ingress of carbon dioxide or chlorides would de-passivate the reinforcements in concrete structures, and the presence of oxygen and water makes steel components to corrode. Hence, corrosion of steel reinforcement is moisture dependent [15]. Besides, chemical attacks from ingress of sulphates, acids and alkalis are also responsible for expansion, decalcification, mass loss etc., leading to chemical degradation of cement-based materials. Under freezing and thawing

Fig. 5 Optical signal from distributed fibre-optic sensor in compressed soil cylinder, before calibration. **a** Raw signal without smoothing and **b** a 65-point moving average applied to smooth the raw signal. For better clarity, the signals have been offset by 0.1 V and 0.03 V, respectively, to allow better separation

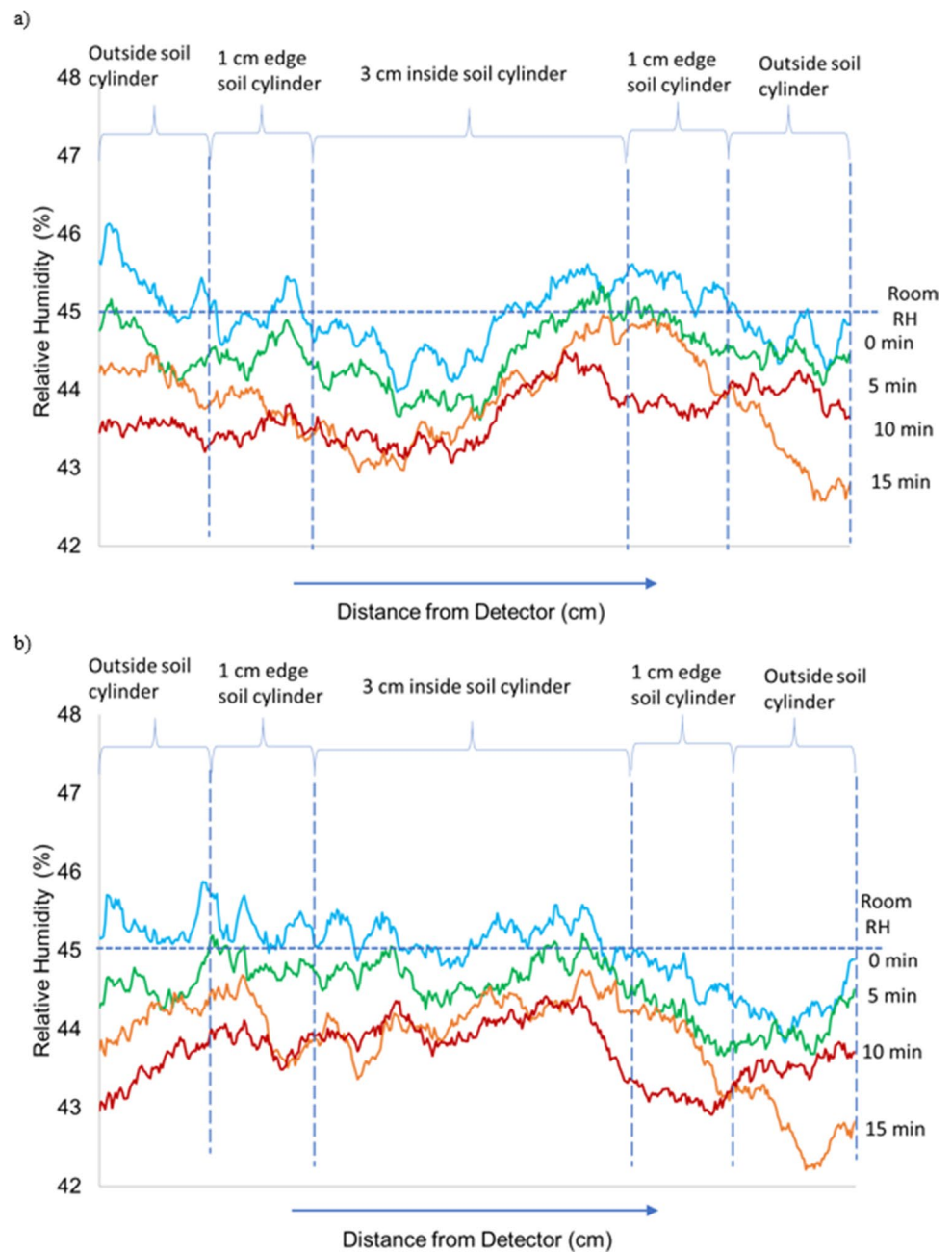


conditions, moisture movement due to energy gradient between pores in concrete also causes deterioration [16]. Other physical and durability properties of cement-based materials such as shrinkage (free dry shrinkage, plastic shrinkage, restrained shrinkage) or alkali-silica reaction can also cause cracks, the spaces for an easy penetration of above-mentioned chemicals into the cement composites. Hence, transport properties of concrete materials known as water absorption, permeation, resistance to chemical attacks etc. are now being the major concerns that compromise the structural integrity of concrete infrastructure

and make concrete infrastructures less sustainable. With regard to detrimental effects of humidity on concrete materials as mentioned earlier, it is useful to monitor changes of moisture content inside the concrete structures. In the concrete test, the fibre sensor was inserted in the middle. The bottom surface of the sample was dipped into water to measure their water penetration resistance. This allowed the simulation of an accelerated water penetration scenario to be conducted in a laboratory-controlled environment.

Two sections have been labelled as outside concrete disk and 1.5 cm inside concrete disk in Fig. 7. From the RH results

Fig. 6 Optical signal from distributed fibre-optic sensor in compressed soil cylinder, calibrated relative humidity measurement, **a** used calibration 1 and **b** used calibration 2. A 65-point moving average applied to smooth the raw signal. The dry states (below ambient/room RH) and the wet states (at ambient/room RH)



(Fig. 7), the sample after 1-day dipping into water showed a lower RH reading in day 1 indicating a lower transmitted power was recorded. It means that although moisture penetrated the concrete, the change was relatively low inside. Then after 2 days, RH increased due to moisture penetration as the water from the other end starts penetrating (the concrete was dipped in the water for this experiment). For practical application, porous protective tubing with air holes is required to strengthen the optical fibre against external effects that may otherwise break it. In addition, a specific membrane or a set of membranes (e.g. paper-based filters) must be used around the optical fibre to prevent contamination from soil or concrete particles. Although

this should not affect the measured RH, it would increase the response and recovery times. The results indicate a good correlation between high levels of RH/moisture and transmitted optical power. There are no abrupt changes in the signal as a function of distance along the sensing fibre, despite only a section of the fibre was in contact with the sample, because the moisture inside the sample emits water vapour that surrounds the sensing fibre with a gradient of changing RH. Nevertheless, the correlation suggests that if the sensing fibre was only functionalized/exposed to the local environment along the length of contact, then an abrupt change in signal should be observed across the positions of interest.

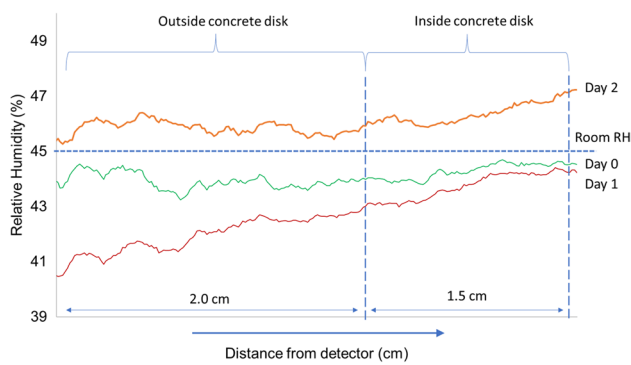


Fig. 7 Measurement in concrete disk after calibration: a 65-point moving average was applied to the raw signal

Monitoring humidity in concrete is important; Yeo et al. embedded different fibre-optic-based humidity sensors to measure the moisture absorption in concrete specimens with different water/cement ratios [17]. The fibre-optic-based sensors were coated with a layer of a moisture-sensitive polymer. The authors found that the sensors can be used to monitor humidity in cement-based materials. Compared with the sensors coated with polymer-based solutions, the ones proposed by Correia et al. using silica/di-ureasil coating exhibited enhanced durability, compatibility and adhesion with the optical fibre, especially higher sensitivity (22.2 pm/%RH) [18]. Based on humidity data obtained in concrete blocks during 1-year exposure to ambient conditions, the study confirmed the applicability of such sensors for humidity monitoring in civil engineering structures [18]. Bremer et al. installed a polymeric fibre optic sensor and an FBG-based humidity sensor along a sewerage tunnel to detect any leakages [19]. The authors pointed that both sensors were extremely resistant to high-alkaline environments. Hence, such robust and relatively low-cost sensors are suitable to be embedded in concrete structures for continuous humidity monitoring [19].

Conclusions

Moisture in reinforced concrete structures acts like a catalyst to cause carbocation phenomenon or to accelerate the ingress process of chloride into the cement composites. Such chemical reaction or attack results in reinforcement corrosion and concrete deterioration. Hence, humidity monitoring is required to partly control such detrimental effects in concrete structures. Among humidity probes, the fibre optic sensor demonstrated a suitable and durable tool to continuously monitor humidity content in concrete. The data obtained from the sensor is quicker and more accurate than from other conventional ones.

This paper reported both desktop and experimental analysis to assess the feasibility of applying this innovative concept in condition assessment of water/wastewater assets. This proposed system used real-time distributed sensors to obtain data for effective monitoring of these assets together with other existing data. The advantages of this new technology are lower cost, fewer cables, higher reliability, higher spatial resolution and potentially a longer sensing range. This will provide a leading-edge technology and a different way of thinking about asset management to support the water industry. As a preliminary study, the results of both concrete and soil moisture measurements using a distributed optical sensor system have been reported. The long-range distributed humidity sensor under development will continue to link experts across multiple areas such as photonics, soil, concrete, water and machine learning. The improvement in performance across all fronts will realize the potential to engage with many more applications. The next steps are to achieve consistency with the fibre alignment, deposited quantity, and incorporate water-rinsing stages into the system to deliver a full course of layer-by-layer assembly of polyelectrolyte coatings [20, 21].

The water industry is now positioning itself into an innovative industry; automated analytics and big data are items already on their research and development agenda. In the past, fault diagnostics of an asset by condition monitoring measurements were carried out mainly using handheld instrument for spot check. With advanced permanent online measurements implemented (only for some assets and mostly non-linear assets, such as pumps), asset condition information can be obtained real-time. The future trend in asset maintenance is by conducting fault prognostics based on forecasting the remaining operational time to end of useful asset life using artificial intelligence. This preventive maintenance approach can reduce both operational and maintenance costs which will gain support from the water industry. This paper covers a good literature collection of the application of sensors in asset management with the development of distributed optical fibre sensor, effect of humidity on concrete and soil and the commonly used monitoring techniques.

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Data Availability The data sets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Competing Interests The authors declare no competing interests.

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