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Extended study of fiber optic-based humidity sensing system performance for sewer network condition monitoring

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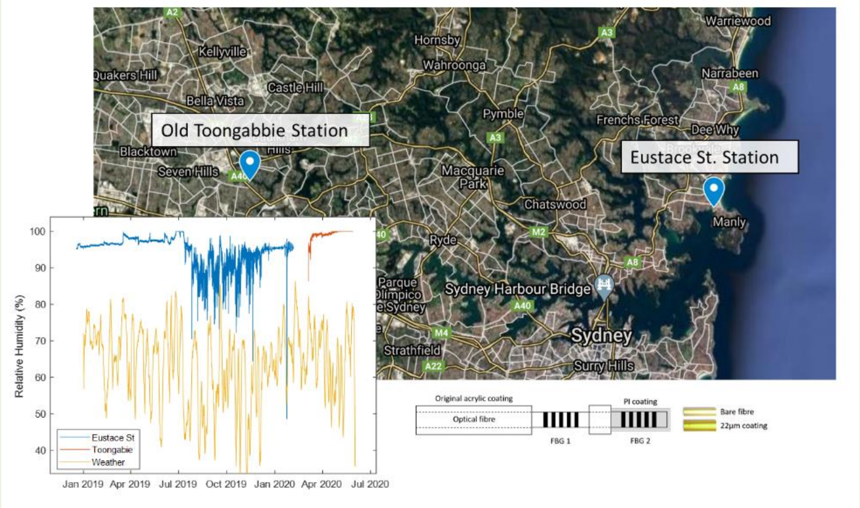
Abstract— **This paper reports on an extended (20-month) period of monitoring of humidity *in situ* at two locations in the sewer network operated by Sydney Water using a fibre optic network into which a series of Bragg Grating-based sensors had been installed. The locations (Eustace Street in Manly, Sydney and Old Toongabbie at Oakes Reserve, western Sydney, Australia) both had different operating environments and thus conditions for evaluating the sensor system. It was designed to provide a solution to enable long term, low cost and more reliable monitoring in the harsh conditions of the sewer environments in terms of high relative humidity > 95% and a broad range of hydrogen sulfide levels. The results of the study show that even after ~20 months of use, the same sensor is reliably recording humidity and temperature in the sewer environment – overcoming the problems seen with conventional electrical sensors, which typically fail within a couple of weeks of use in this continuous high acid/high humidity environment. The data, recorded constantly from the sensor system, were stable throughout the full monitoring period and further, a comparison with the changing weather conditions was made over the different seasons during the study. The sensor system developed was battery operated and had 4G connectivity for data transfer and debugging. These features have enabled the system to be installed in situations where power is not available and operate successfully with minimal human operation, thus allowing for additional systems to be integrated to the measurement system in the future.**



Index Terms— **Fibre Bragg Grating, humidity sensor, sewer corrosion, aggressive biofouling environment.**

I. Introduction

IN LIGHT of the ageing of sewers worldwide, recent attention has rightly been focused on research into actual *in situ* monitoring, allowing better simulation and thus understanding of the condition of these assets. Having a reliable flow of data on the key parameters is crucial for modeling the sewer condition and for planning active measures to allow better predictive maintenance and in particular to avoid catastrophic, and often very expensive, failure events.

Repair and refurbishment costs are closely linked to the state of the concrete-based sewers, many of which were installed decades ago (and for which the detailed structural information is often lost) but are still in continuous use: a problem is that degradation occurs within them due to the influence of natural, biogenically generated sulfuric acid (H_2SO_4), arising due to the oxidation process of hydrogen sulfide (H_2S) on the surface of the concrete sewer pipe [1]. It is well known from prior work that the presence of a humid atmosphere is important in the biogenic conversion of hydrogen sulfide into sulfuric acid. Changes – reductions – in the level of humidity can significantly influence the rate of corrosion [2].

In addition to the gaseous composition of the sewer environment being known to include high relative humidity, methane concentrations over 1%, and hydrogen sulfide concentrations up to 340 ppm [3,4] are seen.

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Previous work pioneered by the authors has shown the efficacy of the use of fiber optic sensors (by comparison to conventional electronic sensors [3]), as the highly humid environment in the sewer is not suitable for the continuous use of conventional, electronic sensors. Through this, and other published research, an important body of work has been built up on the use of different types of fiber optic sensors for monitoring in situations where conventional sensors do not offer a ready solution and where extended periods of monitoring are needed. The examples of this in the literature are diverse (and all the more interesting to engineers as a result) and include studying the long-term reliability of fiber optic current sensors [5], these being based on the difficult challenge of monitoring the polarization changes in the fiber. Further, the durability of a fiber optic corrosion sensors [6] has also been discussed in a recent paper, reporting a low cost, easy to use fiber optic corrosion sensor for practical application and applied in steel corrosion (which is a major cause of degradation in reinforced concrete structures – as result of the need for cost-effective methods to detect the initiation of corrosion in such structures). The approach uses a fiber coated with a pure thin iron film, ~200 nm thick, deposited onto the cleaved end of a bare optical fiber by sputtering as the basis of the sensor. In addition, conventional technologies underpinning strain gages, accelerometers and pressure sensors were employed in non-optical shipboard remote control and telemetry for large-scale model ship motions and loading, under realistic sea waves [7]. Again, these demonstrate the importance of long-term monitoring in extreme conditions, employing advanced sensor systems.

Fiber Bragg Grating (FBG)-based sensor systems [8] also have shown themselves to be very versatile for a number of applications to sensing in extreme or unusual environments, where the advantages of the fiber optic approach are readily exploited. Examples include monitoring of sea bed level changes in nearshore regions using fiber optic sensors [9] in a method using a sensor based on a Fiber Bragg Grating (FBG) (which is embedded in a polymeric resin block) and the increase of the pressure on the top face of the sensor due to the change of sediments layer height, results in a change of the FBG Bragg wavelength. This use of a polymer block creates a very durable sensor, but unfortunately this is an approach that cannot be used in many cases as the measurand under study needs to interact more intimately with the FBG forming the basis of the sensor. Research using FBG-based sensors and their extended use has further been seen in optical fiber intrusion detection systems, for example for railway security [10]. Here the FBG-based systems employed are monitoring entry points such as windows and doors or in fence perimeter systems, allowing the deployment of a cost-effective interrogation strategy as part of a complete fiber optic technology-based security system. These, and other examples that could be cited, demonstrate the value of optical fiber-based technologies for monitoring in challenging environments.

The work reported here addresses one further challenging environment and to the knowledge of the authors is the first report of long term testing and evaluation of a fiber optic-based humidity sensor system in an extreme environment, and operated successfully over a very long period of testing and evaluation. Here the environment is the corrosive atmosphere of the sewer, which also rapidly damages the metallic parts of conventional sensors (such as the wiring, contacts and electronics), making it impossible for this type of technology to be employed effectively in the long term. By contrast, optical fiber sensors (and here FBG-based sensors have proved to be the best choice) are inherently better suited to applications such as this, taking advantage of their light weight, robustness, chemical inertness and multiplexing capability. This application takes full advantage of their having been used successfully in many different applications, with successes now widely seen in structural health monitoring – creating smart asset monitoring systems – and including both humidity and temperature sensing as key elements of the overall monitoring [4 and the references therein]. Such well-established technologies are reliable, cost effective and have been widely used internationally, over the last decade in particular, being preferred even over other fiber sensing methods such as Fabry-Perot interferometry [11-13] in light of its ease of use and ready integration into industrial processes.

As indicated this work builds on that approach reported in a previous paper, research into the installation and use of a system comprising a series of humidity and temperature sensors using fiber optic technology deployed in a gravity sewer in Manly, Sydney has been reported. The conclusions of that study showed that, in operation and monitoring over an initial period of ~6 months, measurements in such a harsh environment where conventional sensors could not survive typically longer than one week, were possible [14]. This paper now presents an extension of that study to report on the longer term application of the Fiber Bragg Grating (FBG)-based optical fiber-based system, when employed in the monitoring of both humidity and temperature changes that occur. Such an extension of the evaluation period is not merely incremental – it represents the sort of period where equipment of this type would be used by industry and thus creating a better understanding of the performance – and any weaknesses which would show up after that time – are important. In addition, by comparison to the previous short study that was undertaken, this is done across (and indeed beyond) a full annual cycle, thereby allowing the sensor system to experience the climate changes seen across the full four seasons where not only different temperatures, but different levels of rainfall and thus use of the sewer capacity are seen, occurring during this long-term monitoring. To create further diversity in the evaluation of the sensor system done, (and building on this prior evaluation and the short term study carried out at that time), in addition to the extended measurement period chosen, two separate and different sewer locations were monitored, this being done to demonstrate greater evidence of the reliability and robustness of the fiber optic-based system – essential for the deployment of such systems more widely in the water industry, not just in Australia but globally.

II. SENSOR DESIGN AND INSTRUMENTATION

In the underpinning research undertaken to develop sensor systems, a dual fibre optic-based humidity and temperature sensor was created and, as discussed, this work builds on that foundation [15]. As discussed there, the 'packaging' – that is the specific design of the containment and protection of the essential fiber optic sensor elements – of the sensor system is critically important for it better to be used in the environment for which it has been designed, and in the very long term. In summary, the sensor system was based on two FBGs written into a piece of germanium-doped photosensitive fibre (Fiber Core SM1500(4.2/125)), where the gratings were of length, 5 mm and an excimer laser/phase mask technique was employed [16]. The grating centre wavelengths used were set ~5 nm apart, to allow the signal obtained from each grating to be readily distinguished, the one from the other. Here, ~1550 nm and ~1557 nm (at 20°C) were then chosen as the grating centre wavelengths used and one of these, the humidity-sensitive grating was coated with polyimide, which is the hygroscopic material used to create that sensitivity. When experiencing a change in humidity, the FBG was exposed to a consequent excess strain and through a knowledge of the relationship between humidity and strain (achieved through careful calibration in a text chamber environment) the *humidity sensitivity* could be calibrated. Equally, through changes in the temperature (at constant humidity) the *temperature sensitivity* of the FBGs is determined and then individually calibrated: thus temperature-corrected strain measurements were possible from the sensor system.

Fig. 1 illustrates this set up and to achieve the humidity sensitivity through the use of a hydroscopic coating, one of the FBGs – here FBG2 – was dip-coated with polyimide as the humidity sensitive material (PI, HD Microsystems PI-2525). In prior work, the number of layers used in the sensor had been optimized to provide a suitable 'trade-off' between sensitivity and the time-response, carefully engineered for this specific application. Based on that, in this work, ~20 layers of the hygroscopic material were individually applied (drying in an oven between applications) and creating a coating thickness of ~22 μm – found to be stable and robust. Achieving stable bonding of the PI layers to the bare fibre is critically important and so the fibre was first treated with 3-APTS (3-Aminopropyltrietoxysilane) to provide a foundation to ensure that happened.

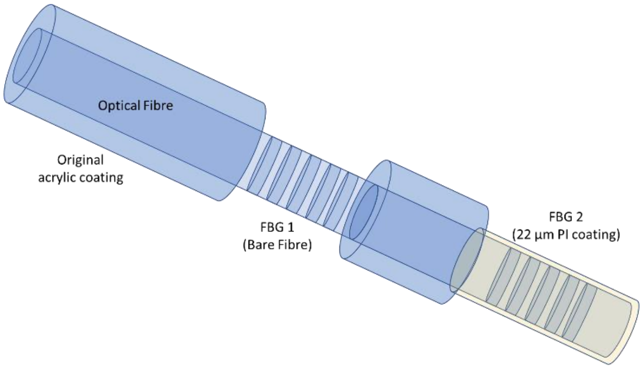

Fig. 1. Sensor design showing one bare FBG (for temperature-only measurement) and a second FBG coated with a hygroscopic material (for temperature and humidity measurement) as described above.

The equations which describe the response of the grating-based sensors are shown below. Here grating FBG2 is sensitive both to humidity *and* temperature changes and the uncoated grating, FBG1, has been designed to achieve temperature compensation, as discusssed. FBG1 thus has been designed to show *no sensitivity* to humidity while FBG2 shows a different strain response to changing humidity levels. The relationships given below thus can be used:

$$\boldsymbol{T = \frac{1}{C_{T1}}\left(\lambda_1 - \lambda_{1(0)}\right)} \qquad (1)$$

$$\boldsymbol{RH = \frac{1}{C_{RH2}}\left(\lambda_2 - \lambda_{2(0)} - C_{T2}\ T\right)} \qquad (2)$$

where λ_i are the Bragg wavelengths (in nm) of FBG1 and FBG2 ($i = 1$ or 2), $\lambda_{i(0)}$ their Bragg wavelengths at 20 °C, C_{Ti} the temperature coefficients or sensitivities (nm/°C), and C_{RHi} the moisture sensitivities (nm/%RH). The relationships can be described, simply in matrix form, as:

$$\boldsymbol{\Lambda = CX}$$

with:

$$\boldsymbol{\Lambda = \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} C = \begin{bmatrix} C_{T1} & C_{RH1} \\ C_{T2} & C_{RH2} \end{bmatrix} \quad X = \begin{bmatrix} \Delta T \\ \Delta RH \end{bmatrix}}$$

where C_{RH1} equals zero as FBG1 has no humidity sensitivity.

As mentioned above, successful 'packaging' of the optical fibers to create an effective probe is critical and to do so, the fibers themselves were carefully installed inside a perforated PEEK (polyether ether ketone) tube – this material being chosen as it shows excellent mechanical and chemical resistance. The probe outer diameter is illustrated in Fig. 2 and is a compact 8 mm, where in the design, an inner and outer tube with a PTFE (polytetrafluoroethylene) layer between is used. This approach has been created to prevent detritus, including water droplets, from entering the sensor through the holes in the PEEK which can be seen in Fig. 2 – thus preventing damage to the key sensor elements underneath.

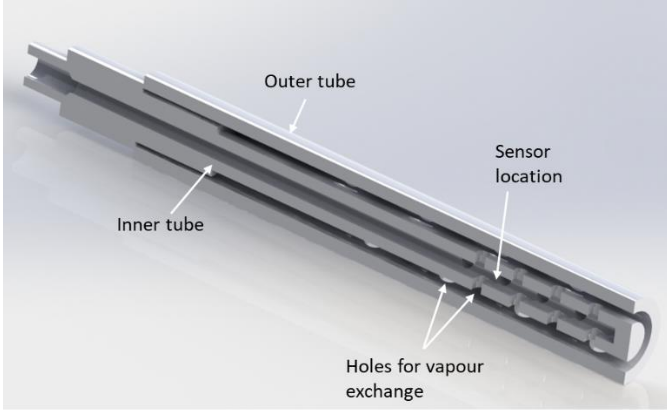

Fig. 2. Sensor system design for this work – illustrating the perforated peek outer tube and smaller inner tube design used.

Calibration of the sensor was undertaken in an environmental chamber (Binder KBF115), as indicated above, and the results obtained are shown in Fig. 3. Prior to calibration, the sensors were subjected to multiple cycles of high and low humidity in the same controlled humidity chamber in the laboratory, to ensure that stability of performance was achieved. In that way, the sensors were then readied for installation 'in-the-field' where through the diurnal cycle of humidity changes over the 20 month test period, the sensor experienced approximately 500 such cycles.

What is noticeable is the linearity of the sensors across the full operating range (as noted previously by Alwis et al [3]). The temperature range studied was derived from the expected operational conditions: 25 – 45 °C, calibrated in steps of 5 °C and a linear relationship was seen. The humidity calibration was carried out over a humidity range of 35 – 75 % RH, in steps of 10% RH and again a linear relationship was observed. The calibration involved using 200 points for each step, then fitting to obtain the required coefficients and reference peak wavelengths for equations (1) and (2).

Fig. 3 illustrates clearly that both FBGs are sensitive to temperature and as expected, only the coated FBG responds to changes in RH. The linearity is good, as R2 values > 0.999 are seen. The sensitivity achieved for the humidity determination from the sensors used in this work ranged from 2 to 5 pm/%RH. As shown in Fig. 4, analysis of the noise levels (at a controlled environment of 80% RH) gives a standard deviation of ~0.3% and the mean deviates from the actual value in ~0.4%, reaching a resolution of 0.1%RH with 1%RH accuracy, after noise reduction treatment such as averaging being applied. This meets the requirements for this industry, as they seek to distinguish variation as low as 1%RH.

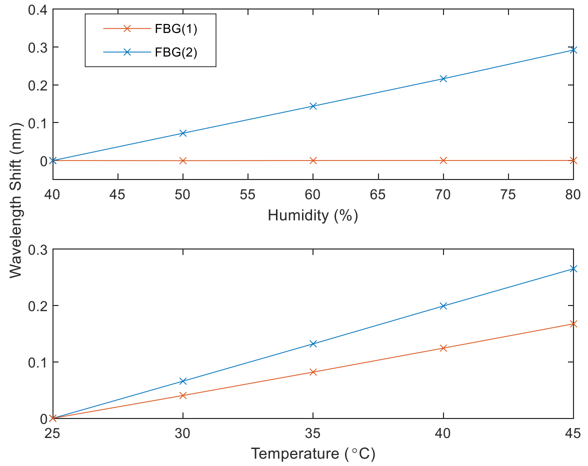

Fig. 3. Sensor calibration graphs used showing (a) humidity and (b) temperature responses of the gratings (FBG1 and FBG2 as defined in the text) forming the basis of the sensor system.

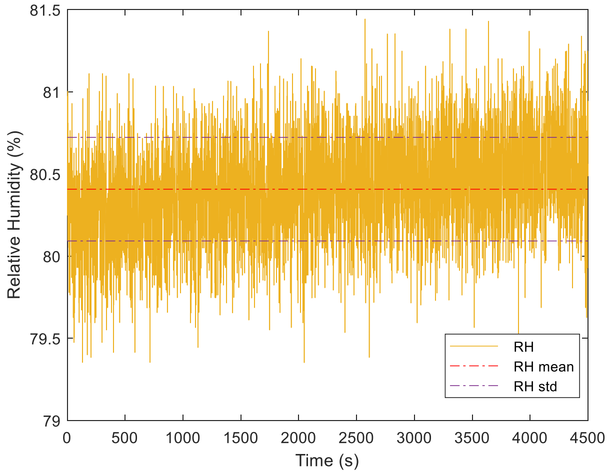

Fig. 4. Noise levels, mean and standard deviation at a controlled relative humidity of 80%.

In order to interrogate the responses of the FBGs used, a commercial 'Micron Optics type si155' system was used. An important consideration in the system design was that the planned installation was a remote one: one where there was no access to mains electricity, and thus long-term battery-operation was required. Thus a key consideration for the system was power conservation: this meant allowing for the unit to 'hibernate' between measurements, and thus to conserve energy. In this way it was possible to extend the available measurement period achieved between battery recharge. To do so, careful consideration was given to the design of the data collection and transfer: a Raspberry Pi 3 (Model B) module was used, providing the required 4G connectivity which permitted the remote data transfer desired by the client. Thus the processor module was disconnected from the power supply between measurements – a Sleepy-Pi 2 module was used for that purpose. Fig. 5 shows a schematic of the system: chosen to provide protection against the environment, it was mounted in a type IP65 enclosure to provide the protection needed (ingress protection 65, dust tight and protected against water projected from a nozzle), for field operation, as discussed in the next section.

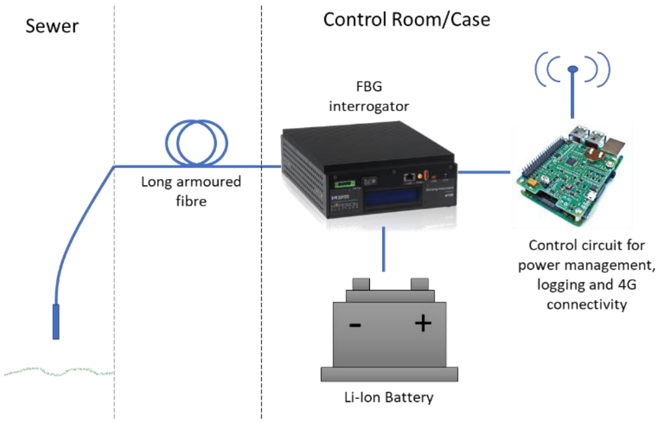

Fig. 5. Hardware setup for the system used in this work, illustrating the sensor interrogation and data transfer approach used.

III. FIELD APPLICATION AND VENUES

Two operational sewer sites were chosen by Sydney Water, for the evaluation of the sensor system, to allow humidity and temperature monitoring as a key part of the maintenance regime, to be undertaken. The evaluation here was designed to establish the feasibility of achieving a long term goal of establishing a vaible sensor network for monitoring of the infrastucture conditions across the sewer for an extended period. Fig. 6 illustrates the relative position of the two chosen sites for this long term pilot study in the city of Sydney.

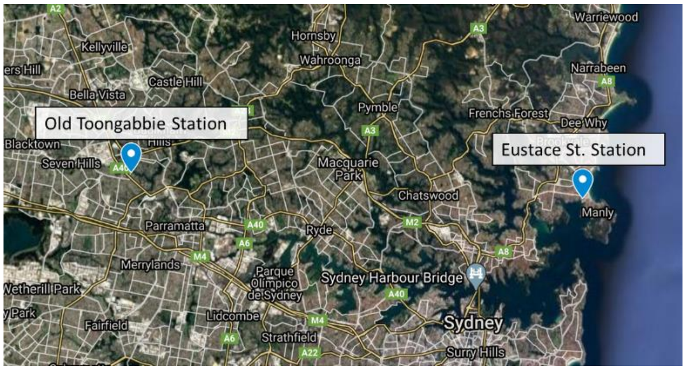

Fig. 6. Sites used for deployment of the sensor system in Sydney.

The installation sites chosen were ~30 km apart, both being in the Sydney metropolitan region, as illustrated. Fig. 7 (a) and (b) respectively show the set up of the sensor system, above ground for two stations – these being Manly's Eustace St, on the coast. and Old Toongabbie (30 km west of Sydney). These two environments experienced broadly similar humidity and temperature conditions but differed in that the Eustace St site has high airflow due to a scrubber downstream of the site and the way the system was installed. Fig. 8 illustrates how the sensors are deployed, as they were both placed in a position where they were hanging *above* the sewerage surface, yet avoiding any possible change to the sewer level or spillage. There is also a constant flow of air which keeps the sewer atmosphere renewed and thus avoids the accumulation of gases.

Fig. 7. Photographs of the installation of the system located at (a) Eustace Street Station and (b) Old Toongabbie Station.

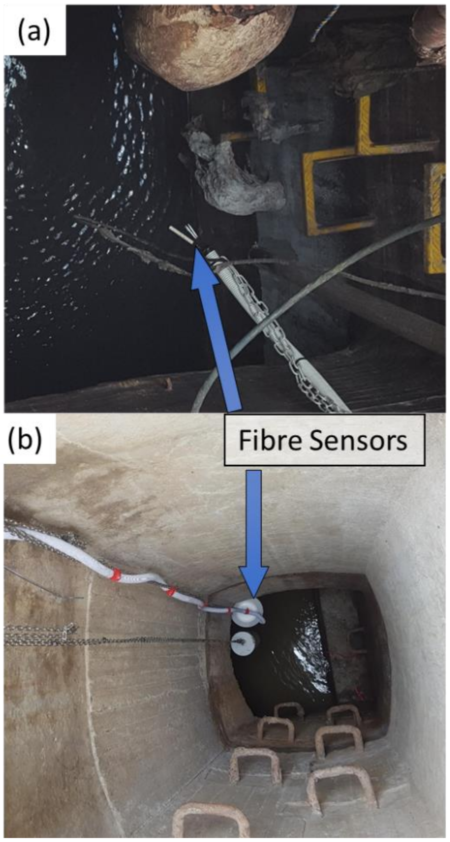

Fig. 8. Sensor installation locations at the two sites chosen (a) Eustace Street Station and (b) Old Toongabbie Station.

IV. RESULTS OF THE CONTINUED MONITORING

As highlighted in the previous section, the sensors were placed in a way which meant that they were in the same environment as the air flow in the sewer. In that way, the key aim of the tests was to show that reliable data could be obtained, in particular showing that the system could be used successfully over a long period, using the instrumentation developed for this application, and the results given below confirm that. All the data collected through the use of the sensor system, described earlier, were plotted as a function of time. Additionally, these measurements are shown together with data from a weather station for the corresponding period to provide a comparison, especially given that data were collected over at least the full four seasons (in the Southern Hemisphere). This meant that creating a correlation of the sensor data with external data could be possible – in that way to see the relationship between the measured data from the photonic sensors and what would be expected for a specific weather condition at that time of the year. A long term evaluation of the system had thus been designed, recognizing that the sensor system had been designed to survive the harsh environment to maximize its utility for monitoring purposes. As it turned out, a truly extended study was possible as, in total, data were acquired from a total of 20 months of measurement (from December 2018 to July 2020).

This is illustrated below and Fig. 9 and Fig. 10 show the key measurements obtained over that period of monitoring from the gravity sewers, with data from Eustace St in blue and Toongabie in orange. Close examination of the results show that there is a gap between the two sets of data, which results from the time lost for measurement between the removal of the system from Eustace Street and its subsequent installation in Old Toongabie. Looking first at Fig. 9 showing *temperature* data, both sets of data (from Eustance St. and Toongabie) follow each other very closely, as would be expected with data collected from the external weather information [17]. This arises as these sites are well ventilated – in that way showing the close correlation with the outside weather conditions (also shown on the figure). As also would be expected, the temperature data collected inside the sewers show a smaller daily deviation (the graphs are 'smoother') than is seen in the data from the weather station which monitor the external temperature.

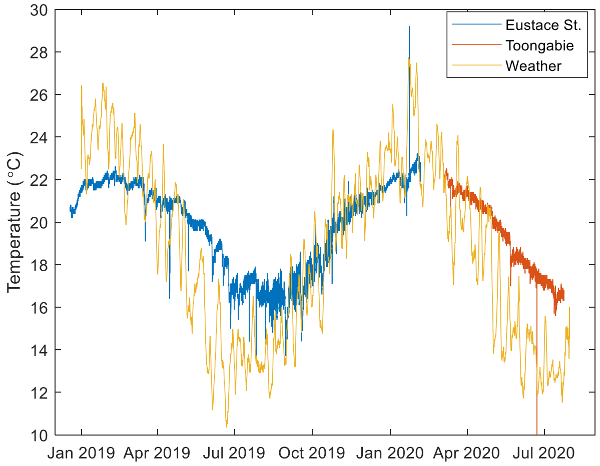

Fig. 9. Temperature data from the sensor system located on two different sites in the Sydney Water sewer and weather data for comparison.

Fig. 10 shows humidity data collected over the same period and using the same sensor system (which then had been transfered from Eustace Street to Old Toongabbie). From this extensive set of data, it became clear that the relative humidity measured inside the sewer is much higher than that measured by metereological stations in the Old Toongabbie area, as would be expected. It also shows that the external weather data show a much more unstable pattern – thus the humidity is both high and relatively stable *inside* the sewer. The data obtained there show high levels of humidity: the data range from 90% to saturation (~100%) for most of the period of study, which illustrates the key point of the study: that on-going high humidity conditions were the point of concern in light of the on-going corrosion of the concrete sewer in the presence of the biogenically generated sulfuric acid (H_2SO_4). Although these high values of humidity are seen, there is a period between July and December 2019 when the data show a higher variation in the humidity values. This can be attributed to a period of maintenance when the hatch was constantly open. This also shows the possibility to add, in the future, some event detection to the software, which then could be part of the maintenance service arrangements for the sewer network and triggered by this change in humidity.

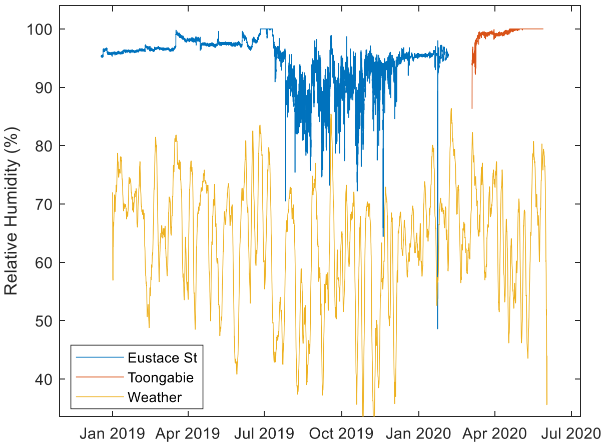

Fig. 10. Humidity data from the system 1 located on two different sites in the Sydney Water sewer with weather data for comparison.

In the last week of May 2020, in the end of our study, the sensor was reaching saturation of the humidity measurement and the cause for this was then the subject of investigation. The sensor was taken out and some water droplet condensation could be seen inside the sensor packaging. This phenomenon is the subject of on-going investigation: however it is conjectured that with the sensors being already ~18 months in operation in Eustace St followed by Toongabbie, in such a harsh environment, this could be the first sign of deterioration of the polymer, causing the sensor calibration to drift after the ‘drying out’ process. A positive outcome of the measurements made is that it is noticeable that the sensor *does continue to provide a stable reading*, albeit one that has deviated from the series of measurements taken previously. Further investigation of this is being carried out to evaluate the polymer condition (through the use of electron microscopy) to assess the situation with the sensor and thus to recommend a suitable shelf-life, or period between calibration events, for the sensor and suitable for future measurement cycles.

V. DISCUSSION

The work undertaken represented a successful contination of research measurements previously undertaken and of *in situ* sewer monitoring [10]. The results here build on, and are consistent prior monitoring, but considerably extend those previously obtained and show the feasibility of an integrated system for long term health monitoring at several points in Sydney Water’s concrete sewer infrastructure. This shows its value in the design, remote implementation and reliable use of a sensing network to support the better deployment of resources for preventative maintenance.

The stability and accuracy of the presented data have shown the reliability of the fibre sensor system in continuous operation for periods approaching 2 years and thus the applicability of that system in such an environment to create a robust sensor network. With the deployment of such sensor systems, there is the real opportunity for gathering important data from a number of sites within the sewer network. In this way, coupled with appropriate models, it will also be possible to identify patterns in the deterioration of the sewers, as well as serve as input for creating more reliable models of the concrete condition in a system like this.

Future work will, in addition to investigating the long term performance of the humidity sensor at Old Toongable, aim to monitor an even wider range parameters to tackle better the broad condition monitoring issue, such as the inclusion of strain sensors to monitor possible concrete cracking failures and to determine the changing concentrations of problematic corrosive gases, such as hydrogen sulfide in the presence of humidity. Work is on-going to investigate the conditions of the sensor components at the end of this test and to investgate the hygroscopic film (an SEM analysis will be carried out) in an effort to assess if any significant polymer degradation due to the continuous exposure to the sewer environment has occurred and the impact that this might have for even longer duration testing and evaluation.

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