Feasibility Study: Embedded Sensors

Final Report

CRC-P: Smart Linings for Pipe and Infrastructure
Sub-project 3: Smart Sensing and Application

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Nu Flow Technologies
Parchem Construction Supplies
Sanexen Environmental Services
SA Water Corporation
South East Water Corporation
Sydney Water Corporation
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Note: This report is an extract from the full sub-project 3 report.

5 Milestone 4 – Collaboration with Liner Manufacturers to Incorporate Sensors into Liners

Incorporating sensors into liners involves either placing them in the pipe prior to lining, or embedding sensors into the liner itself. Such placement may allow for non-destructive measurements of key attributes relater to performance both in the short and long term. This would provide utilities with an evidence based means of knowing when a liner or coating needs replacement without performing costly destructive testing. In order to assess the possibility of embedding sensors into liners in the future a feasibility study was undertaken with input from manufacturers.

Sensors for wastewater liners generally focus on measuring pH and moisture as a proxy for acid penetration. The University of London has developed fibre optic in-pipe sensors to measure humidity and model expected corrosion, though these are not embedded. Macquarie University is currently working on embedding similar fibre optic sensors into concrete pipe that will measure relative humidity, again to measure expected corrosion levels. Radio frequency identification (RFID) tags can be used as a sensor by integrating them to smart materials that exhibit electrical changes when exposed to variations in pH. RFID sensors are promising as they do not require a power supply, however the corrosive environment of sewers is a challenging place to keep sensors in the long term.

Sensors for water liners include fibre optics installed prior to CIPP liner installation that can detect temperature. This is useful to ensure curing temperatures are met during liner installation and can provide evidence of water between the host pipe and the liner over the long-term. RFID sensors may also be able to be either embedded in liners or installed before lining and used to measure temperature and humidity, though only some initial testing as UTS has been completed at this stage.

5.1 Embedded Sensing Technologies for Wastewater Pipe Infrastructure

Currently, there are no non-destructive sensing technologies available in the literature that can directly measure the levels of acid permeation inside sewer pipe coatings. The measurement of pH levels at different depths is used as a proxy parameter to estimate the penetration of acids inside the coatings. Therefore, this section focusses on reviewing embedded sensors relevant to acid permeation (pH, moisture) for condition assessment of CAC and geopolymer coatings.

The expression "strength of hydrogen" or "potential of hydrogen" is abbreviated as pH. It is a scale that shows whether a solution is acidic or alkaline. The scale range from 0 to 14, with 7 indicating neutral (distilled water), above 7 indicating alkaline solution, and below 7 indicating acidic solution. The pH scale is depicted in Fig. 14.

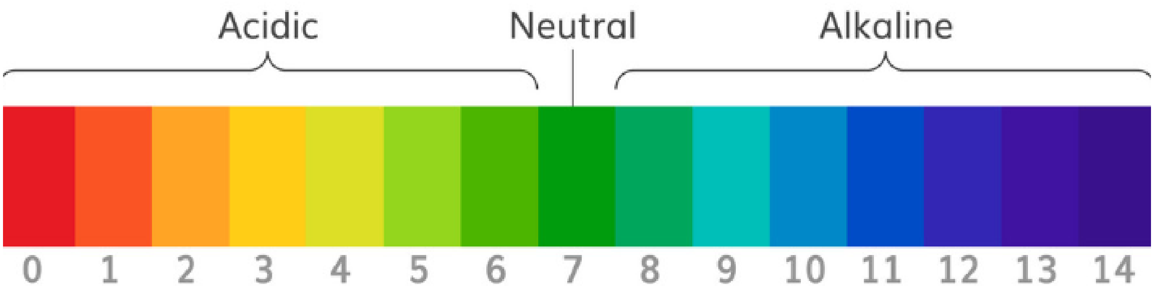


Fig. 14: pH scale.

5.1.1 Fibre optic technology

Fiber optic sensing technology can be combined with an azo-dye based pH indicator to detect pH conditions in concrete structures as described in [16]. The optical fibres absorbance varies as the azo dye changes colour. The measurement setup is shown in Fig. 15 and the sensor prototype is shown in Fig. 16. Fig. 17 depicts the variations in absorption spectra due to pH changes. This fibre optic sensing technology is known to be performing well for pH levels greater than 10.

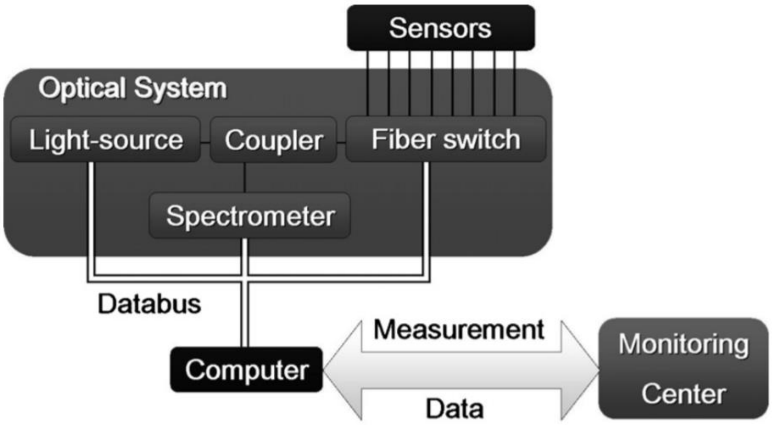


Fig. 15: Fiber optic pH sensor measurement system. [16]

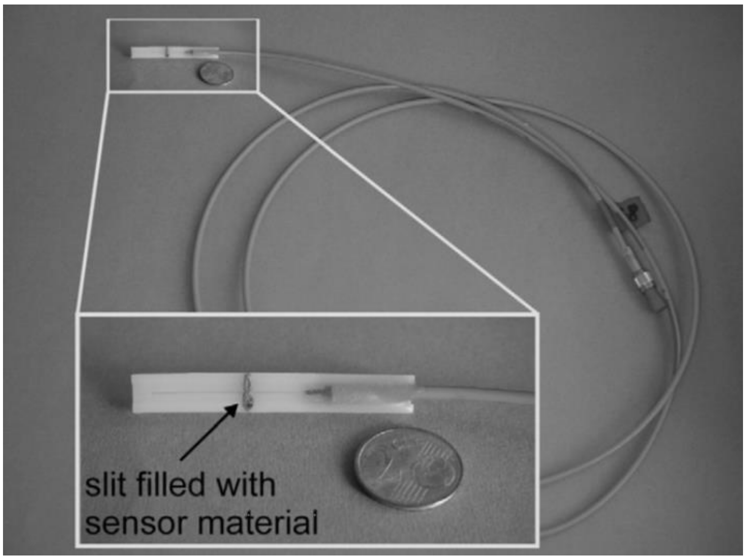


Fig. 16: Fiber optic pH sensor. [16]

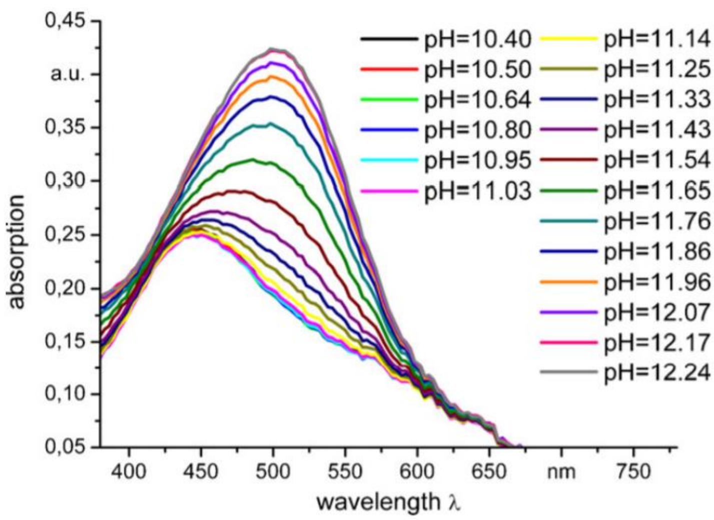


Fig. 17: Fiber optic pH sensor wavelength and absorption behaviour. [16]

As certain dyes are exposed to alkaline pH variations, they change colour. Alizarine Yellow R and indigo carmine dyes [17] are examples of dyes that change colour. The colour differences for the dyes are shown in Fig. 18.

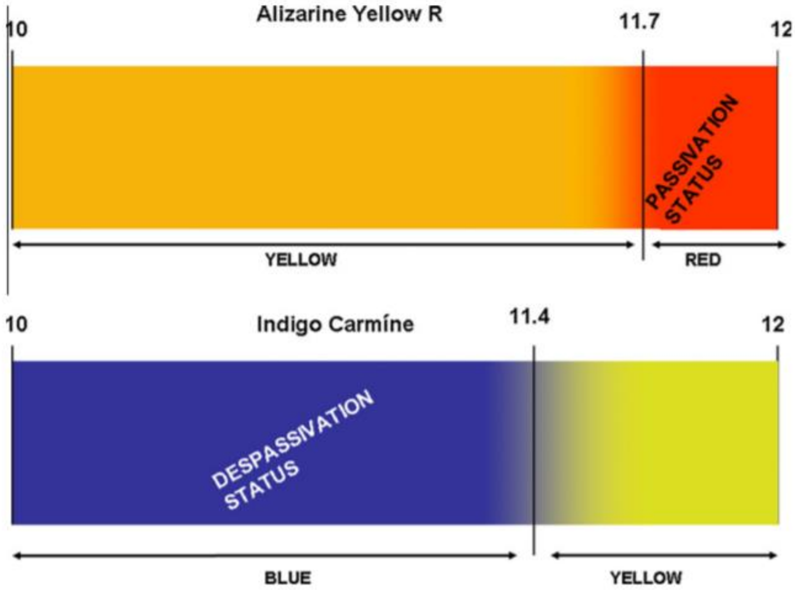


Fig. 18: Alkalinity in concrete is monitored using Alizarine Yellow R and indigo carmine dyes. [17]

Sol-gel is another form of dye that changes colour when the pH is between 8 and 12. They can be applied to a fibre optic sensor to monitor colour changes and interpret concrete pH levels.

Researchers from the University of London (UoL) have created an optical fiber-based sensor system for monitoring humidity levels in concrete sewer pipes in collaboration with Sydney Water Corporation [18]. The fibre Bragg grating (FBG) technique is used in this sensor, which is used within sewer infrastructure with aggressive corrosion conditions. The predictive analytic model uses data from this FBG fibre-optic sensor to estimate concrete sewage pipe corrosion. Fig. 19 shows the sensor and Fig. 20 shows the hardware setup for real-time monitoring.

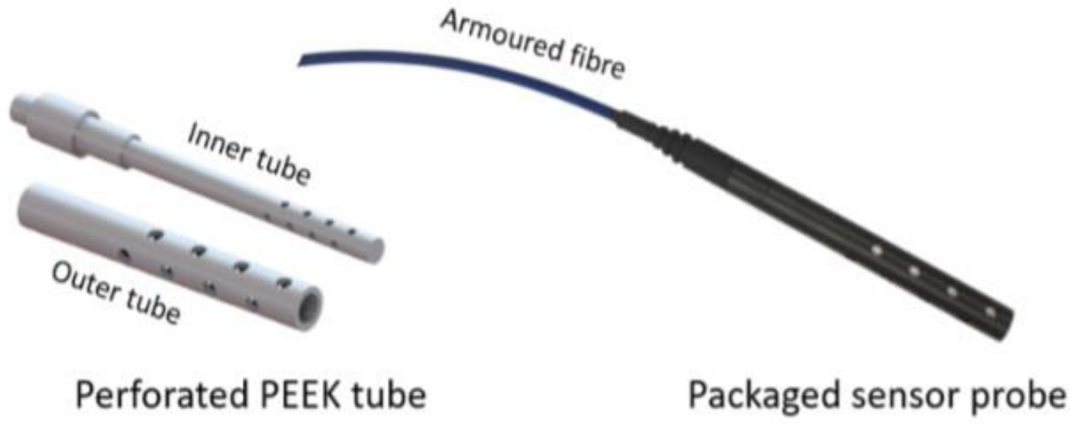


Fig. 19: Sensor packaging components showing outer and inner tubes. [18]

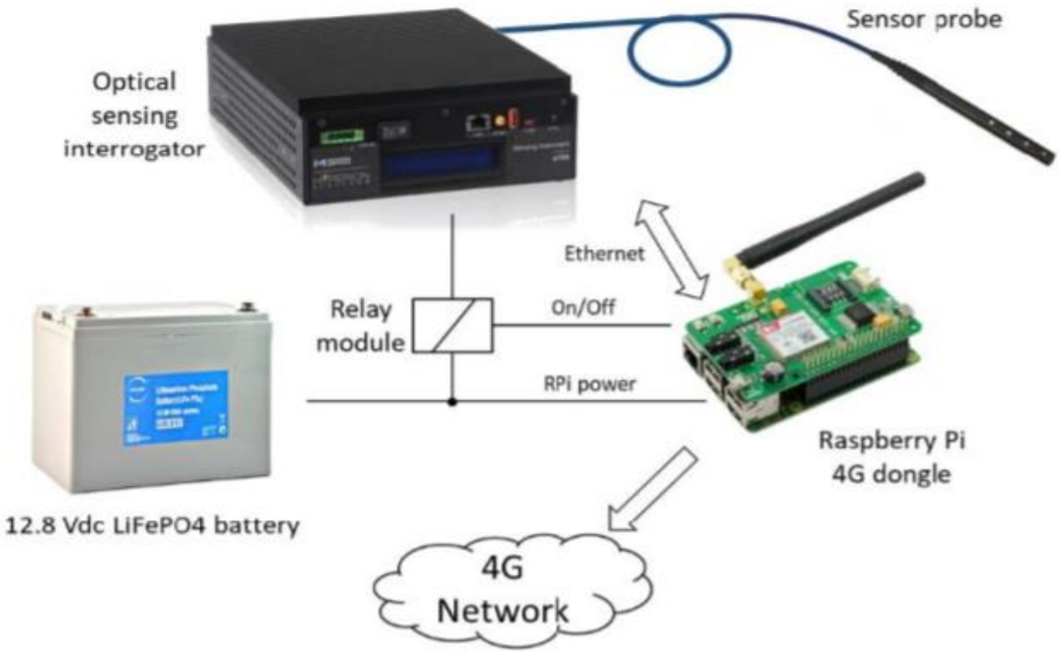


Fig. 20: Hardware setup for sensor monitoring and data collection. [18]

The University of London's research team has recently developed pH-sensitive fluorescent probes based on coumarin [19]. With aqueous solutions of various pH levels, their fluorescent behaviour was evaluated. The developed material can be used to determine pH in alkaline media using optical fibres. However, developing a sensor that can withstand the acidic conditions of concrete sewer pipe coatings is difficult.

Macquarie University from Australia is developing embedded fibre-optic sensing technology to determine relative humidity conditions within the concrete sewer host pipe for estimating corrosion [20], similar to the University of London's fibre-optic humidity sensor. This sensor's suitability to measure pH at different levels is yet to be proven. Nuron, a Sheffield-based company from United Kingdom, has created a next-generation fiber-optic sensing technology that can monitor multiple flow parameters in the sewer network in real time. Such sensing systems can be used to monitor blockages in sewage pipes, such as fatbergs. The transmission of sonic waves is used by the University of Sheffield to track changes in pipe walls, valves, joints, and lateral connections. This project is only in its early stages, and there isn't much public information available.

In [21], the apparent pH of Geo-polymer concrete is measured using a commercially available glass electrode in this work. Two pH probes make up this pH sensor. The sensor system is shown in Fig. 21. After casting, the sensor was immersed in concrete geopolymer. The pH monitoring setup is depicted in Fig. 22. In geopolymer, the pH sensor survived 9 months of pH monitoring.

Fig. 21: pH Sensor System. [21]

Fig. 22: pH Sensor monitoring in geopolymer sample. [21]

5.1.2 RFID technology

The radio frequency identification (RFID) tags can be used as a sensor by integrating them to smart materials that exhibit electrical changes when exposed to variations in pH. The following are some pH-sensitive materials that can be used with RFID-based sensors:

- PEDOT
- Graphene oxide
- Polyaniline (PANI)
- Carbon nano tubes

PEDOT is a robust conducting polymer that can be used in combination with an RFID sensor to measure pH levels. This material comes in the form of a film that can be applied to a substrate. Fig. 23 displays a 1μm thick PEDOT film fabricated on a flexible Kapton substrate. The PEDOT film has a conductivity of 5×10^4 S/m. Variations in PEDOT film alter the conductivity of the film. Low pH values are indicated by higher conductivities.

Fig. 24 demonstrates how the conductivity of the PEDOT film varies as the pH changes. The pH transition is reversible, making it ideal for RFID-based sensing.

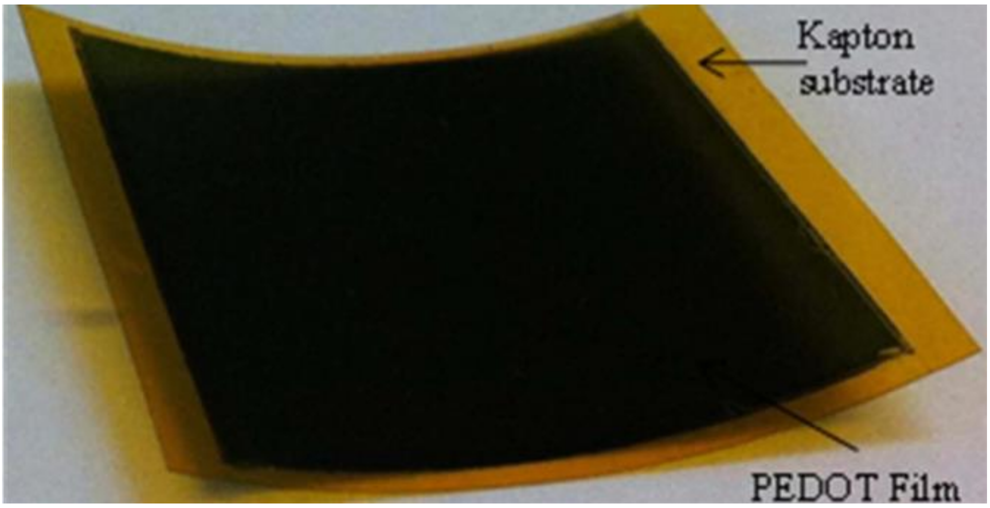


Fig. 23: PEDOT film on a Kapton substrate.

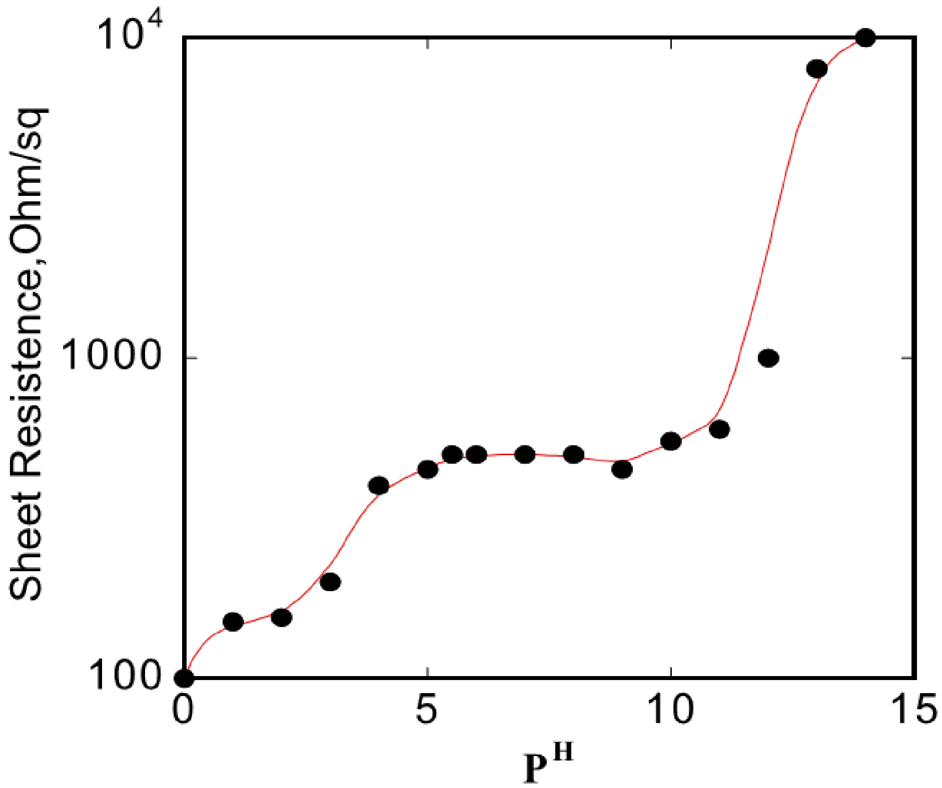


Fig. 24: pH versus conductivity of PEDOT film.

A pH sensor made of graphene oxide was used to monitor the pH levels of wounds [22]. Fig. 25 shows the graphene oxide based pH sensor that has a sensitivity of 31.8 mV/pH, where the voltage decreases when the pH increases. The graphene oxide-based pH sensor's voltage and pH activity is shown in Fig. 26.

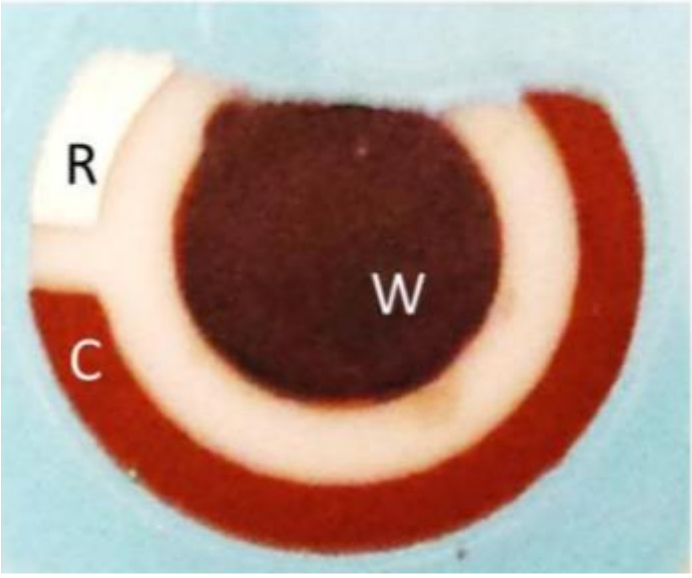


Fig. 25: pH Sensors, where 'W' represents the graphene oxide coated sensing electrode, 'R' represents the silver or silver chloride reference electrode, and 'C' represents the gold substrate content. [22]

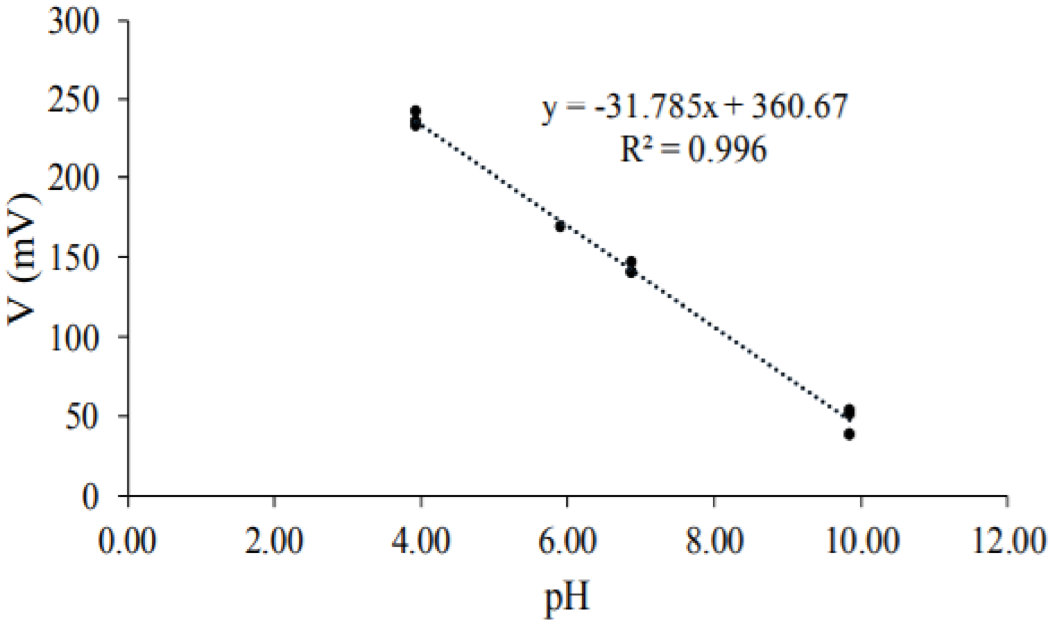


Fig. 26: The behavior of voltage signals for changes in pH. [22]

Another conducting polymer that is susceptible to pH changes is polyaniline (PANI) [23]. As shown in Fig. 27, this material can be turned into a film and applied to radio frequency tags. The PANI material is doped with polystyrene sulfonate (PSS) and deposited on an

RFID tag with a frequency that varies based on pH changes. The pH resonant frequency (fp) shifts corresponding to the pH levels are shown in Fig. 28.

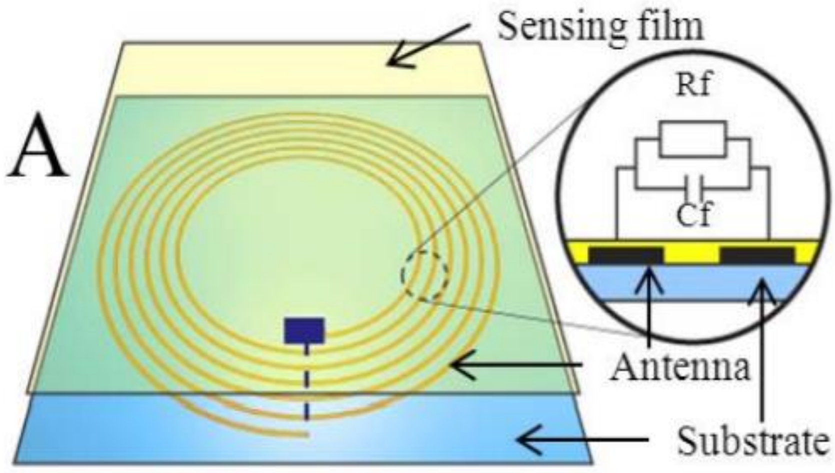


Fig. 27: PANI sensing film. [23]

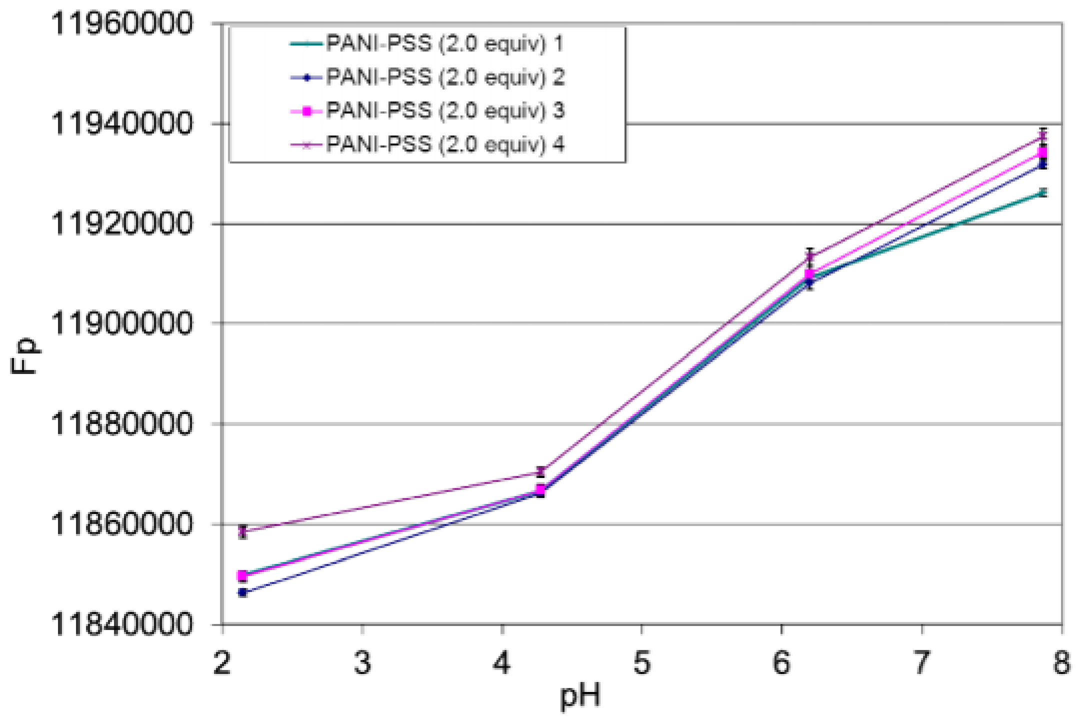


Fig. 28: PANI sensing film showing resonant frequency changes to pH changes. [23]

Single-walled Carbon nanotubes (ox-SWNTs) functionalised with the conductive polymer poly(1-aminoanthracene) (PAA) can be used as a sensing element for pH monitoring via radio frequency signals [24]. Fig 29 depicts the RFID-based pH sensor that was created. Fig 30 shows how the conductivity of the sensor changed to pH changes.

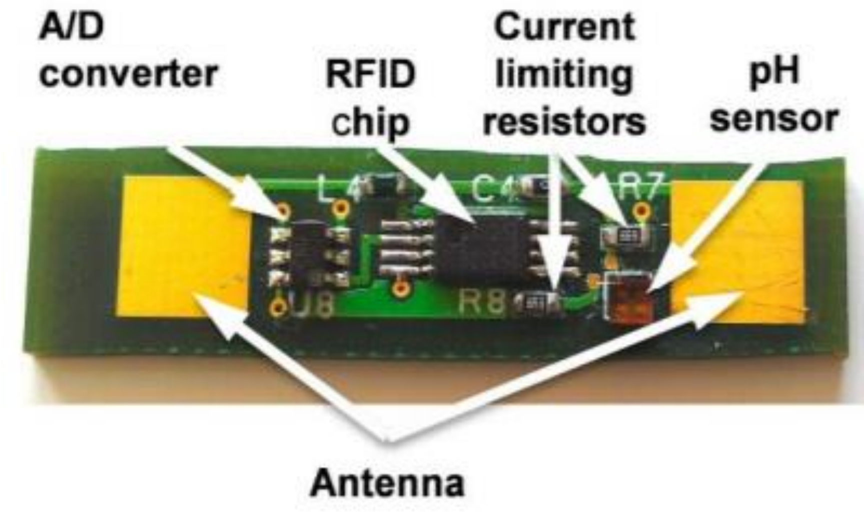


Fig. 29: RFID pH Sensor. [24]

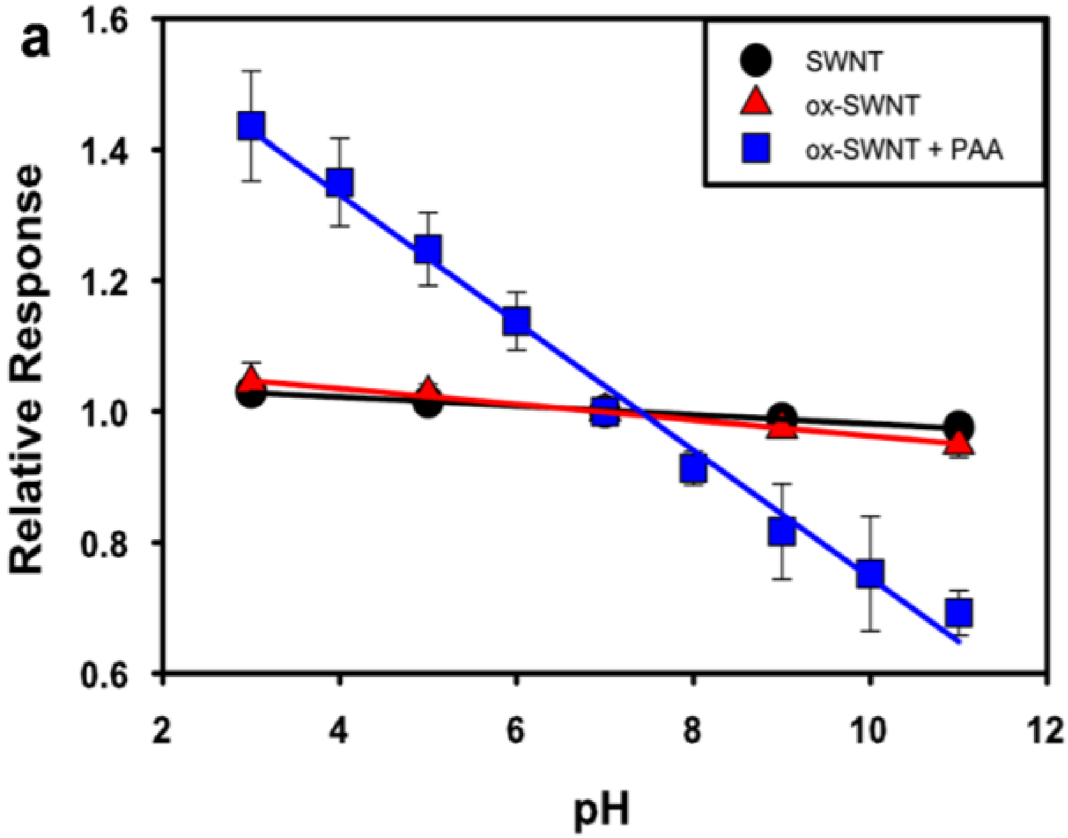


Fig. 30: RFID pH Sensor response (conductivity) to pH variations. [24]

5.2 Embedded Sensing Technologies for Water Pipe Infrastructure

Temperature is an important parameter to monitor in water pipe linings especially while the installed pipe hardens following installation (curing). Periodic monitoring of temperature conditions between the host pipe and linings can be a proxy parameter to indicate the state of the curing process. In the long-term, the temperature conditions can indicate the intrusion of water between the host pipe and the liner.

5.2.1 Fibre optic technology

Fibre optics [25] is a potential technology that can be exploited to monitor temperature conditions along CIPP liners. Before the CIPP liner is applied, the fibre-optic cables are installed. The sensor then measures temperature over the entire length of the optic-fiber cable using laser light signals. Temperature and strain changes can influence the internal structure of the fibre optic sensor, changing the way light travels through the fibre. Over a long distance, this sensing technology will determine the temperature in every metre along the optic-fiber cables.

The location of optical fibre between the host pipe and the linings is shown in Fig. 31. The sensors are based on the Fiber Bragg Grating (FBG) principle. The sensors are positioned at various points along the tubing. The optical cable can be connected to a device on-site for recording temperature data both during curing and over time.

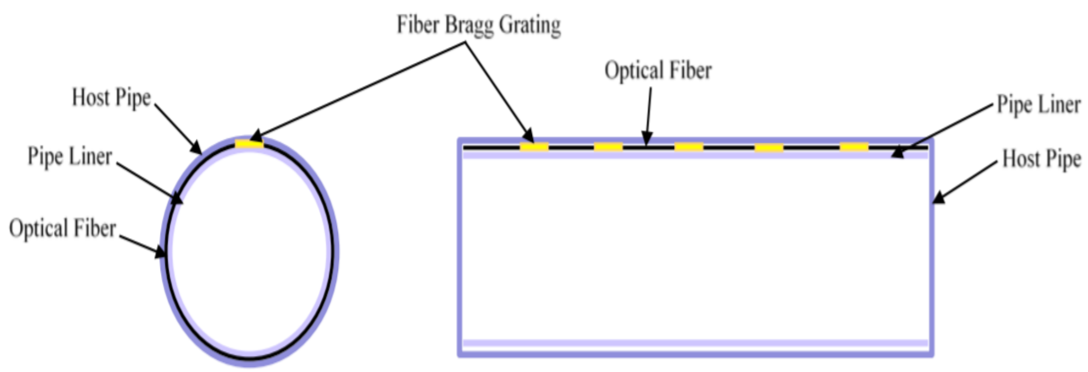


Fig. 31: Placement of optical fibers in water pipes [25].

Pipeline Renewal Technologies, a commercial company, uses fibre optic sensing to track the curing of CIPP linings after they have been installed. With a ±2° Fahrenheit precision, they monitor the temperature in every 1.5-foot range. Fig. 31 depicts the desktop monitoring of the CIPP liner curing process, and the location of an irregular lining temperature is shown in Fig. 32.

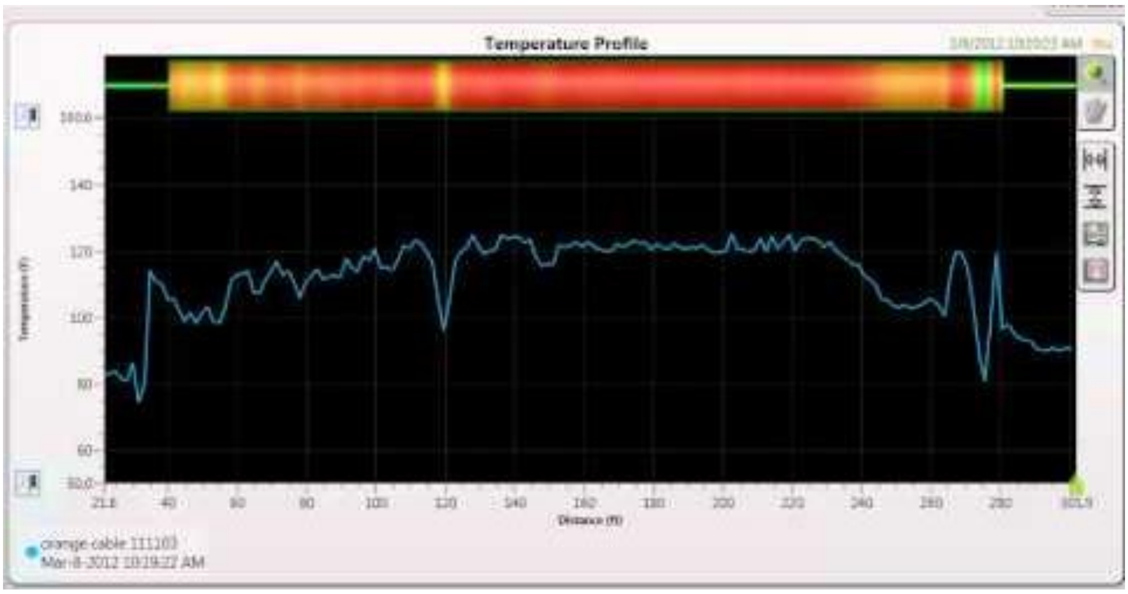


Fig. 32: Temperature monitoring using fiber optics during curing process.

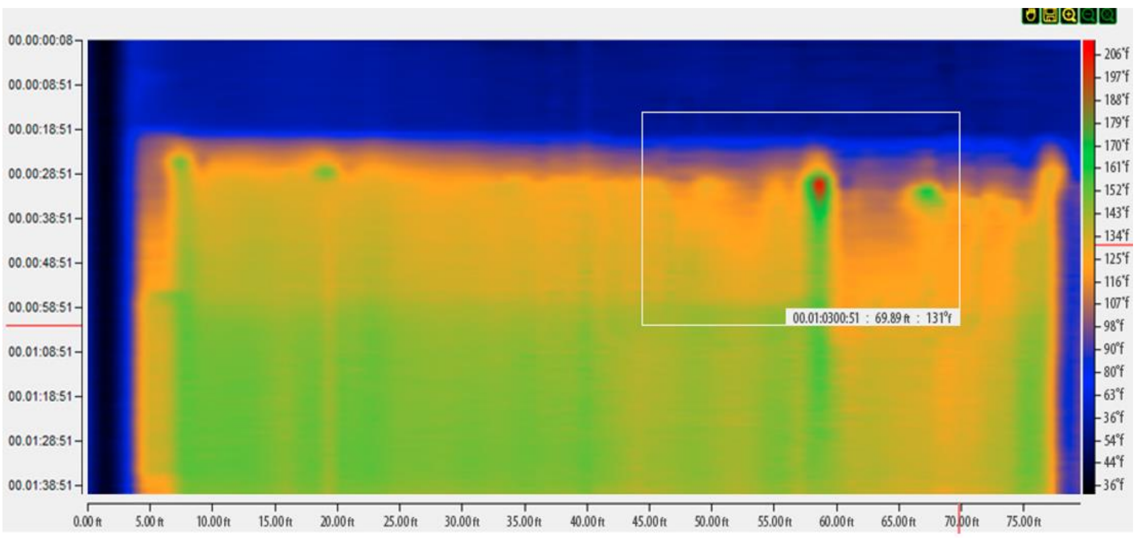


Fig. 33: Detection of a temperature abnormality during the curing process.

For polymeric spray lined pipes, there are no reported embedded sensing technologies for monitoring temperature conditions to the best of our knowledge. Further investigation to evaluate the sensor performance, as well as the inherent challenges that can occur during the installation of the sensor along the pipeline, is recommended.

5.2.2 RFID technology

The radio frequency identification (RFID) tags can be used as a sensor by integrating them to smart materials that exhibit electrical changes when exposed to variations in temperature and humidity. Some of the temperature sensitive materials that can be used with the RFID based sensors are:

- Phenanthrene
- N-Methyl-NButylpyrrolidiniumhexafluorophosphate
- Nano-structured metal oxide

Phenanthrene is a polycyclic hydrocarbon group chemical compound. It's also a sublimation substance, meaning it goes from solid to gas without going through the liquid phase. This material has a dielectric transition temperature of 72°C and exhibits dielectric behaviour. The dielectric constant is permanent for phenanthrene only when the vapour is not de-sublimated. The dielectric constant varies when the material is exposed to temperature variations, particularly after the transition temperature. As a result, this material can be used in chipless RFID tags to measure temperature thresholds.

P14PF6 (N-Methyl-NButylpyrrolidiniumhexafluorophosphate) is an ionic plastic crystal that is temperature sensitive. When the temperature is changed from -15°C to 70°C, this substance transforms from a crystal to a liquid. This property can be used to perform temperature sensing by coating this substance on the top surface of RFID tags.

Semiconducting metal oxides are nano-structured metal oxides. For example, indium oxide and zinc oxide. External temperature fluctuations cause differences in both materials. It should be remembered that indium oxide is extremely scarce. The distance between the valence band of electrons and conduction band is known as band gap. The band difference narrows as the temperature rises. Fig. 34 depicts the band gap activity of zinc oxide material. As a result, nanostructured metal oxides, such as zinc oxides, can be used in RFID tags as a temperature sensing material.

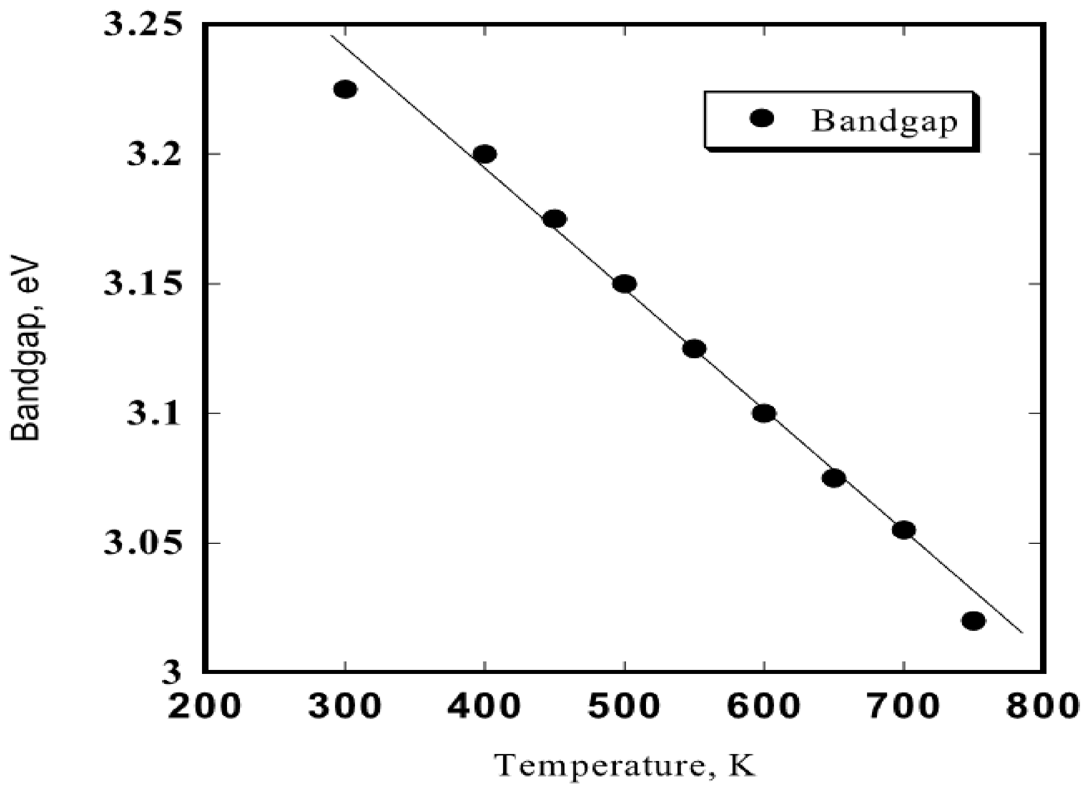


Fig. 34: Band gap behaviour of zinc oxide to temperature changes.

Some of the humidity sensitive materials that can be used with the RFID based sensors are:

- Kapton
- Polyvinyl alcohol
- Graphene oxide
- Carbon nano tubes

Kapton is a polymide with linear dielectric changes in response to changes in ambient humidity. For sensing purposes, this substance can be rendered as a film and adhered to RFID tags. The kapton film has a relative permittivity of 3.25 at 23°C and 25 percent relative humidity. As a result, the material can be used with RFID tags to monitor humidity levels.

Polyvinyl alcohol is a water-absorbent polymer that can be used as an electrolyte-based resistive sensor for humidity monitoring. As the concentration of polyvinyl alcohol in water increases, the relative permittivity decreases at frequencies ranging from 0.2 to 20

GHz, which can be used to calibrate the sensor. For humidity sensing applications, this form of material can be rendered as a film and adhered to RFID tags.

Graphene oxide is a graphene with an oxygen functional group that has been chemically modified. This material can be used in conjunction with RFID tags to monitor humidity changes [26]. The relative dielectric permittivity increases with rising humidity due to water uptake, according to researchers. As this material-based RFID sensor is exposed to various humidity conditions, the transmission coefficient and resonant frequency can change. Fig. 35 demonstrates how the frequency and transmission coefficient of a graphene oxide coated sensor change with humidity.

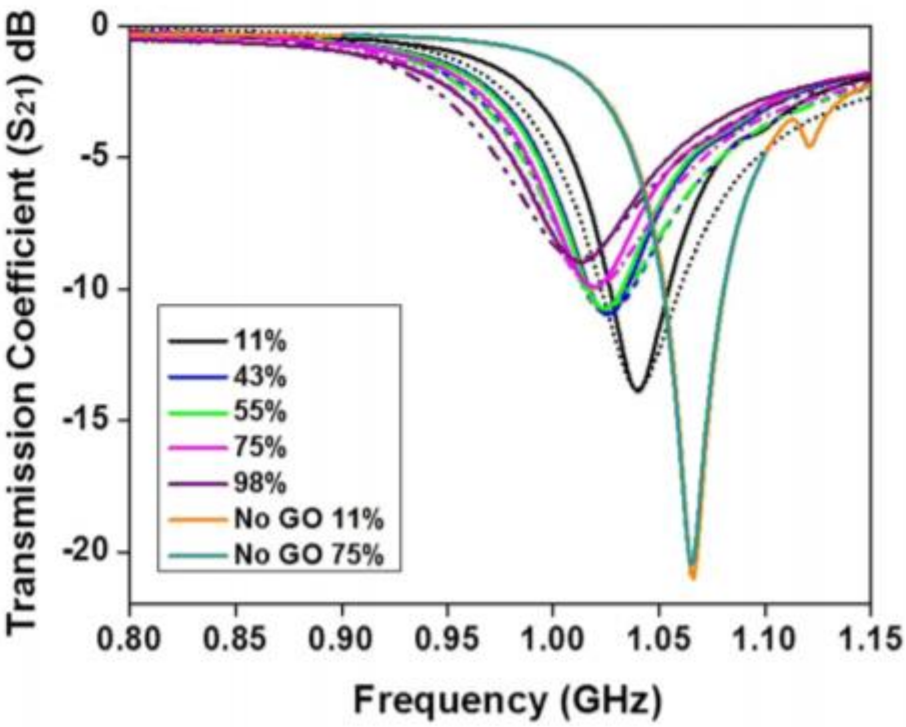


Fig. 35: Frequency and transmission coefficient changes to different humidity conditions. [26]

Carbon nanotubes (CNTs) are cylinder-shaped structures made of carbon nanotubes. They are divided into two categories: single wall CNT and multi-wall CNT. When exposed to humidity or moisture differences, they adjust their electrical conductivity. A polyacrylic acid-coated carbon nanotube-paper composite-based sensor for humidity and moisture sensing was recently created. The electrostatic contact with water molecules and the swelling effect of cellulose fibres change the electrical resistance of the CNT composite when it is exposed to humidity [26].

5.3 Embedded Sensors: Way Forward

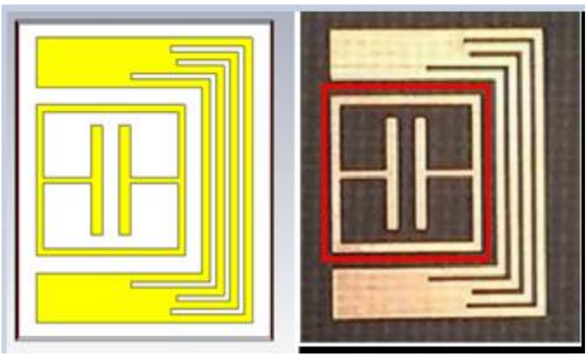
Fibre-optic sensors and radio frequency identification (RFID) sensors are compelling sensor technologies, which warrant further study. Sensing moisture or the presence of water between the liner and host pipe could help detect ineffective CIPP and polymeric spray liners. Whereas, sensing pH to determine acid permeation is an important parameter for sewer coatings.

The fibre-optics sensor technology has been used for monitoring the temperature conditions of CIPP linings. However, this sensing technology needs to be studied in detail for application in polymeric spray lined water pipes. The presence of fragile fibres (in particular their thickness) may have an effect on polymeric spray lined pipes, as application thickness is typically low (3mm). Fibre optic sensors are limited in that the measurements are only taken along the fibre-optic cable and not all around the pipe. Though it will offer a prediction of the conditions around the pipe. Placement of embedded sensors at random, discrete locations is an option to improve spatial monitoring and to minimizing the adverse effects such as debonding (this needs further study). In this context, passive RFID based sensors combined with smart materials are a potential option for monitoring temperature conditions in CIPP and polymeric spray lined pipes.

A significant increase in temperature is common during the drying phase of polymeric spray linings. A robust sensor is required to survive the drying phase of CIPP and polymeric spray liners in order to provide reliable monitoring. This needs further study and experimentation to evaluate RFID sensors made of different materials. Active collaborations with CIPP and polymeric spray lining manufacturers and applicators for testing the potential sensing technology is a way forward for realising this innovative technology.

For monitoring pH conditions in concrete sewer pipe coatings, smart material based RFID sensors embedded in coatings combined with robotic observers seems very promising. Therefore, we did sensor preliminary simulations to understand their characteristics specifically focusing on localization, acid permeation (pH) and moisture ingress. This is blue sky research, which is currently supported through the UTS blue sky research grant. The UTS research team currently has access to a robotic system for monitoring liner imperfections and uneven thicknesses in polymeric spray lined pipes. The RFID sensor readers can be integrated into the robotic platform for data collection and evaluation.

Through the UTS blue sky research grant, we are simulating an implantable RFID sensor for monitoring sub-surface concrete conditions. This is a passive type of sensor. When the radio frequency signals strike the sensor, it gets activated and reflects a portion of the signal back. The reflected signals can be interpreted for monitoring. Fig. 36 shows the sensor design in simulation and a fabricated sensor prototype, Fig. 37 shows the laboratory experimental setup and Fig. 38 shows the enclosure for the sensor.



(a) (b)

Fig. 36: RFID sensor. (a) Simulation design. (b) Fabricated sensor.

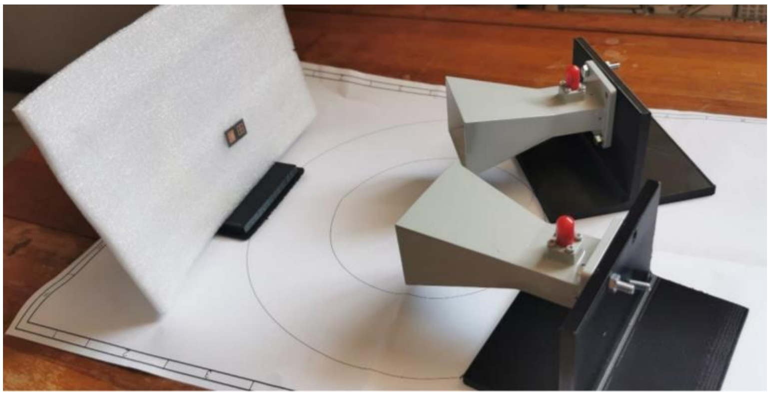
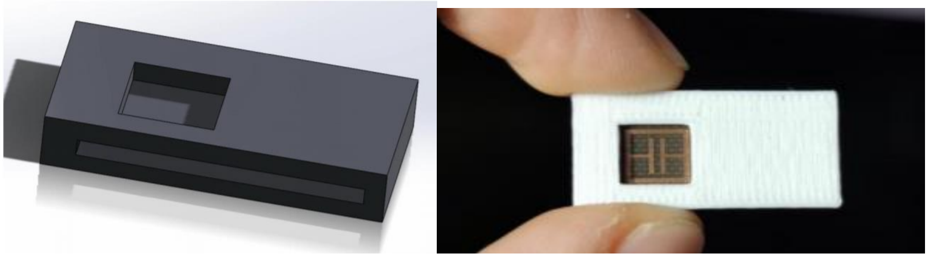


Fig. 37: RFID sensor experimental setup with horn antenna.



(a) (b)

Fig. 38: RFID sensor enclosure. (a) 3D CAD design. (b) Prototype.

Further work is needed to closely simulate effects of pH differences and moisture differences as proxy parameters for acid permeation and moisture ingress. There is an opportunity for any water utility or a consortium to collaborate with UTS to further develop the sensors and evaluate the feasibility of using them in coatings. Sensors may be developed either as a smart aggregate or a sensor which can be placed on the host pipe surface before a coating is applied.Contributors

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Mr Parikshit Archarya, Masters student

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