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Building Stone Condition Monitoring Using Specially Designed Compensated Optical Fiber Humidity Sensors

Tong Sun, Kenneth T. V. Grattan, Sudarshan Srinivasan, P. A. M. Basheer, Bernard J. Smith, and Heather A. Viles

***Abstract*—This paper presents the design and implementation of a novel optical fiber temperature compensated relative humidity (RH) sensor device, based on fiber Bragg gratings (FBGs) and developed specifically for monitoring water ingress leading to the deterioration of building stone. The performance of the sensor thus created, together with that of conventional sensors, was first assessed in the laboratory where they were characterized under experimental conditions of controlled wetting and drying cycles of limestone blocks, before being employed "in-the-field" to monitor actual building stone in a specially built wall. Although a new construction, this was built specifically using conservation methods similar to those employed in past centuries, to allow an accurate simulation of processes occurring with wetting and drying in the historic walls in the University of Oxford.**

***Index Terms*—Building stone monitoring, humidity sensor, optical fiber sensor, temperature compensation.**

I. Introduction

MASONRY is widely recognized as an adaptable and sustainable construction material, with a low carbon signature, and is a key element of the world's tangible cultural heritage. Weathering of stone appears to be one of the major reasons for the damage of stone masonry structures, through the occurrence of complex and interlinked chemical, physical and biological process. The deterioration of building stone depends mainly on the temperature and moisture ingress near the surface region. Temperature fluctuations at the surface of the stone cause a temperature gradient inside the material inducing a number of weathering mechanisms and fatigue in the materials. As a result, frequent cycles of temperature changes can cause mechanical disintegration at the surface area of stone, starting usually from the interfaces between different minerals in stone [1]. The deterioration, however, is not contributed solely by temperature variations, but by a combined effect, for example, with the presence of moisture. The influence of moisture is critical for understanding the deterioration processes of building stone. Almost all the weathering processes, comprising physical, chemical and biological processes, take place due to the presence or ingress/egress of moisture.

It is clear that, as a consequence, the monitoring of temperature and moisture in building stone plays an important role in the diagnosis of the material deterioration. The most commonly used techniques for measuring moisture in building materials are gravimetric, electrical and mechanical and chilled-mirror hygrometric methods [2]. Some of these are labour intensive, suitable only for laboratory measurements and often constrained by the cost rather than by the performance. The electrical technique, based upon monitoring the electrical resistance (ER) change as a function of the moisture variation, is widely used for monitoring the presence of moisture in building stone, due to the advantages such as ease of deployment, real-time monitoring and direct measurement. This technique, however, is influenced by the presence of dissolved salts and other chemical changes in the porous structure of building stone, thus the sensor signal change is not uniquely correlated to the level of moisture being present.

This work reported in this paper has aimed to address the above and other limitations of current techniques by providing novel solutions to achieve a *direct* measurement of the moisture content in stonework through the development and evaluation of a minimally-invasive optical fiber humidity sensor. The approach taken has been designed to allow comparison with the performance of existing sensing technologies and indeed to better their performance, when applied to moisture ingress/egress monitoring. The prime objective of the sensor design has been to achieve a better understanding of the decay mechanisms and associated processes occurring in masonry structures through achieving a clearer understanding of the changing moisture and temperature conditions that underpin decay and degradation.

II. Optical Fiber Humidity Sensor and Sensor System Design

A. Sensing Principle

An optical fiber Bragg grating is used in this work as the basis of a moisture ingress monitoring system—the application and

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uses of grating based sensors are discussed in [3]. The structure with the fiber core being periodically modulated, reflects the light at a wavelength termed the Bragg wavelength (λ_B) that satisfies the Bragg condition, given in (1)

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where n_{eff} is the effective refractive index of the fiber core and Λ is the grating period, where *both* are affected by strain and temperature variations, a feature that is reflected in the sensor design.

The shift in Bragg wavelength due to the change in strain or thermal effect is thus given by

$$\frac{\Delta\lambda_\mathrm{B}}{\lambda_\mathrm{B}} = (1 - \mathrm{P_e})\varepsilon + [(1 - \mathrm{P_e})\alpha + \zeta]\Delta\mathrm{T} \tag{2}$$

where $\mathrm{P_e}$ is the photoelastic constant of the fiber, ε is the strain induced on the fiber, α is the fiber thermal expansion coefficient and ζ is the fiber thermal-optic coefficient. The first term of (2) represents the longitudinal strain effect on the FBG and the second term represents the thermal effect, which comprises a convolution of thermal expansion of the material and the thermal-optic effect.

The fiber grating acts as the basis of the sensor principle and the humidity sensing concept used in this sensor exploits the strain effect induced in a FBG through the swelling of a thin layer of applied polymer coating. The swelling of the polymer coating, arising from the absorption of moisture, changes the Bragg wavelength of the FBG, where this can be calibrated to give a direct indication of the humidity level. Thus the shift in the Bragg wavelength in (2) for the polymer-coated FBG can be modified as follows:

$$\frac{\Delta\lambda_\mathrm{B}}{\lambda_\mathrm{B}} = (1 - \mathrm{P_e})\alpha_\mathrm{RH}.\Delta\mathrm{RH} + [(1 - \mathrm{P_e})\alpha_\mathrm{T} + \zeta]\Delta\mathrm{T} \tag{3}$$

where α_RH and α_T are the moisture expansion coefficient and the thermal expansion coefficient of the coated FBG.

The detailed discussions of the fabrication of the fiber Bragg gratings used, the coating material chosen, the coating thickness and the resulting humidity sensor response time have been reported by some of the authors elsewhere [3]–[5].

Due to the sensitivity of the FBG which forms the key sensor element to both strain *and* temperature, it is important to compensate the temperature effect when the coated-FBG is used for humidity measurement as this depends only on the strain induced in the coating.

B. *Sensor Design, Fabrication and Packaging*

The FBGs used in this work were inscribed in boron-germanium (B/Ge) co-doped photosensitive optical fibers using a phase mask fabrication technique. In order to produce a stable sensor which could be used over a wide temperature range, the grating was first annealed for more than 7 h at 200 °C prior to the polymer coating being applied. Subsequently a thin layer of moisture sensitive Polyimide (PI) with a coating thickness of 24 μm was coated onto the FBG using an automated dip coating machine at City University London. Achieving temperature compensation is important as such grating-based devices are temperature sensitive and thus a second grating element is used to create the complete sensor system. To do so, a bare FBG is also included in the sensor design. Fig. 1(a) and (b) shows respectively the schematic diagram and a picture of the humidity sensor probe design, in which both grating elements can be seen—a bare FBG without coating is used for temperature measurement and for temperature compensation of the coated humidity sensor.

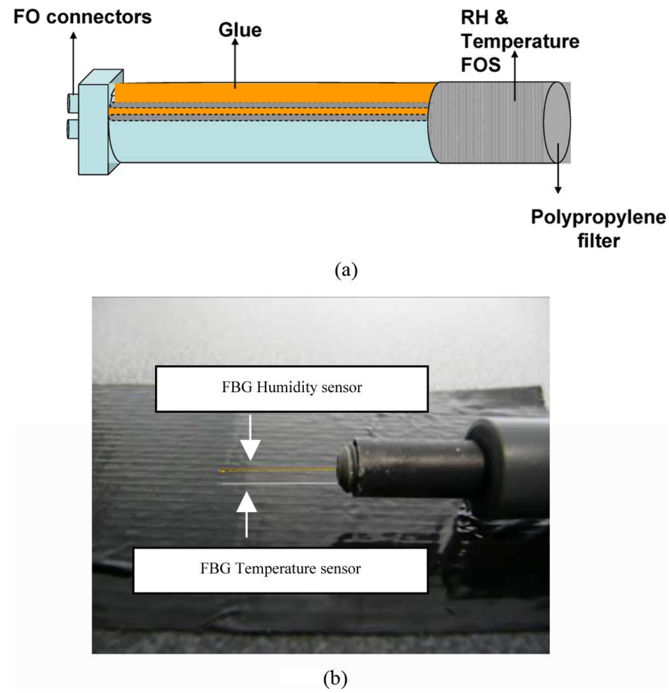
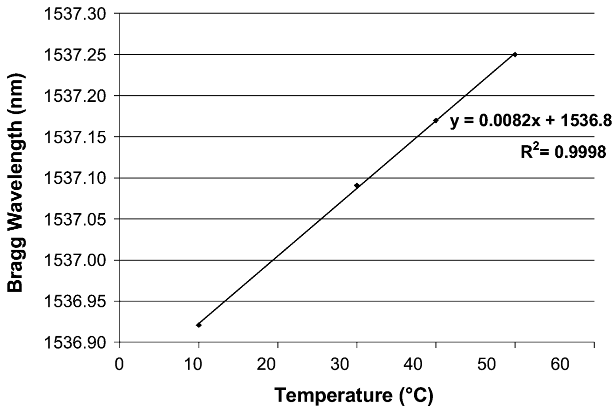


Fig. 1. (a) Schematic diagram of the sensor design (b) Picture of the packaged sensor probe showing a coated grating as a relative humidity sensor and a bare grating as a temperature sensor.

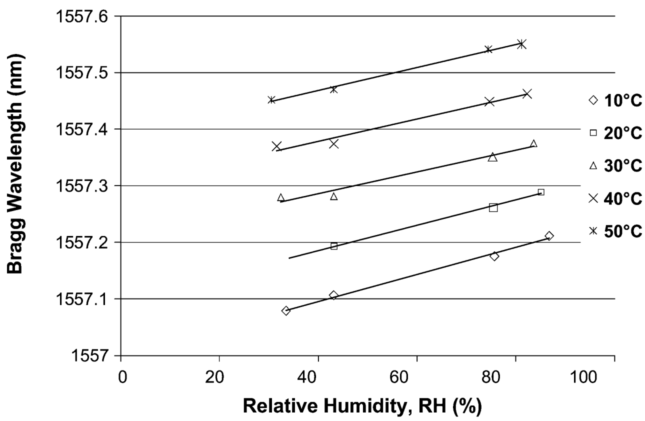
While the authors have reported fiber optic humidity sensor systems in previous research [4]–[7], a critical aspect of the work in this research has been to tailor the design of the sensor system to the requirements of the measurement "in-the-field" and for the stonework itself: this involving developing a specific design of its protection and packaging for use in the harsh environments experienced. As a result, the dual-parameter sensor elements have been protected in this special design created to allow monitoring of the key parameters involved in the deterioration of stone masonry structures, as prescribed by the users of the devices.

C. *The FOS-RH Sensor System*

After the construction of the dual-grating sensor probe illustrated above, an effective humidity sensing system can thus be created, requiring the wavelength-encoded output from the sensor probe to be determined, using a commercial FBG interrogation system. Such an interrogation device can either include a broadband light source, using a F-P filter and a photo-detector to capture the Bragg wavelength or include a swept laser source, using a photo-detector to capture the peak wavelength.



(a)



(b)

Fig. 2. (a) Temperature calibration curve of the optical fiber RH sensor at a constant RH level. (b) The RH calibration curves of the RH humidity sensor at a series of known temperatures.

D. Calibration of the Sensor

In order to show that the sensor was ready for use with exterior masonry, it was tested and calibrated in the laboratory. This involved determining the Bragg wavelength change, separately with both temperature and humidity changes. Fig. 2(a) and (b) shows the calibration data obtained from the specially designed and packaged humidity sensor probe as a function of both (a) temperature and (b) relative humidity (RH) whilst the other parameter is kept constant.

Such an accurate calibration is essential and, for the humidity calibration, this was undertaken using a saturated salt solution technique (which can provide a known and constant RH value), with the probe being placed in an enclosed container with sequentially a series of different saturated salt solutions which then provide a series of standard relative humidity levels—all this was done at a series of known temperatures [8] representative of the range to be used in actual monitoring work.

To achieve a well referenced calibration, the humidity inside the container was also monitored by using a reference hygrometer, to allow comparative measurements with a commercial probe to be made. The temperature inside the container was varied from 10 °C to 50 °C at each specific humidity level so that the influence of temperature on the humidity measurement could be seen from the sensor output. Thus from the humidity calibration graph, the temperature coefficient may be calculated as this is required to provide a correction to the humidity data in situations where the temperature is not constant, thus allowing a correction factor to the apparent relative humidity measurements to be applied. For convenience of operation, the temperature and relative humidity coefficients obtained from the calibration curves were entered into the LabView based software, allowing the user to have a direct readout of the temperature-corrected RH value from the output of the instrument.

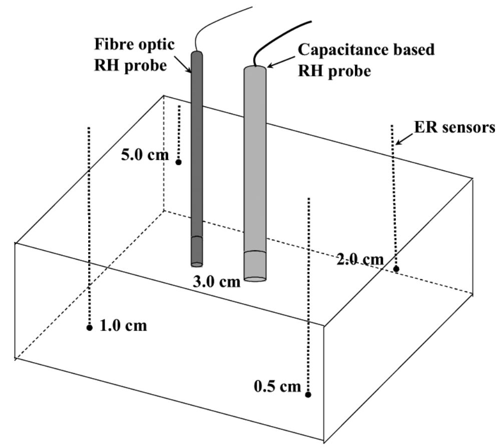


Fig. 3. The layout of the sensors in a limestone block.

III. Evaluation of Sensor Performance

A. Stone Sample Preparation

Following on from the calibration activity reported previously, it was necessary in the laboratory tests to simulate the environment that would be found when the sensor was used in-the-field. Thus to facilitate the evaluation of the sensor performance for *in-situ* testing, a limestone block of the type used in building conservation of dimensions $150\ \mathrm{mm} \times 150\ \mathrm{mm} \times 80\ \mathrm{mm}$ had been specifically fabricated for the planned laboratory tests. Before placing the sensors in the carefully drilled holes in the sample, the block was dried at 50 °C—this being determined when the weight of the sample reached a constant value. The specially designed optical fiber temperature/humidity probe was placed at a depth of 30 mm below the surface, as shown in Fig. 3. In order to validate and provide a cross-comparison of the measurements from the FOS-RH probe, both commercially available capacitance-based RH probe [9] and electrical resistance (ER) based moisture sensors (manufactured at Queens University of Belfast) are placed together in the same stone block and all their outputs were closely monitored during the tests carried out.

As shown in Fig. 3, the capacitance based RH sensor was placed in a position parallel to the fiber optic RH probe and with the active element at the same depth (30 mm below the surface). The ER sensors were placed in drilled holes at four different depths of 0.5, 1, 2 and 5 cm respectively from the exposed surface. These depths were typical of what was required for field use and in this experimental block, the spatial distribution of moisture could be changed to simulate different conditions in-the-field and thus be monitored using the three different

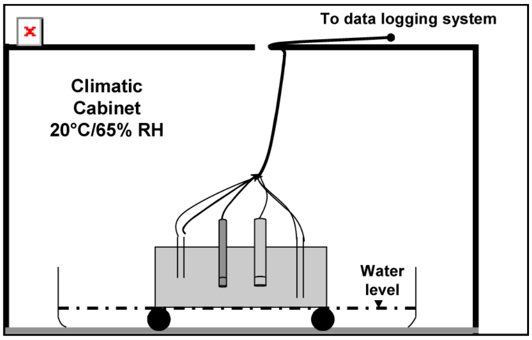


Fig. 4. Capillary rise test setup with sensors.

types of moisture sensors, i.e., the fiber optic RH sensor, the capacitance based sensor and the ER based sensor.

B. *Capillary Rise and Drying Test*

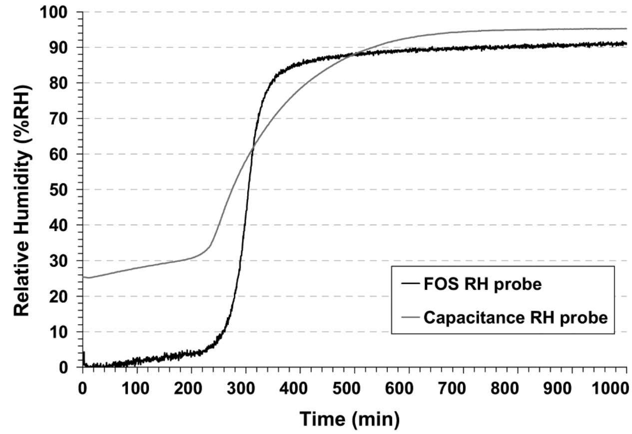
A test, typical of what would be experienced for an actual limestone block in a wall was carried out where the limestone block embedded with sensors was subjected to a "capillary rise" test. As shown in Fig. 4, the sample was placed on a tray supported with two stainless steel rods where the tray was filled with water maintained at 20 °C and to a level such that the base of the block is immersed in the water to a depth of 3 mm.

To provide stability of the conditions during the test, the tray with the sample block and embedded sensors was placed in a climatic cabinet maintained at 20 °C and 65% relative humidity. The water level in the tray was monitored carefully and kept constant by adding any necessary additional water throughout the test. The moisture and temperature changes inside the block were also monitored continuously at an interval of one minute and the data obtained were collected and recorded using a PC.

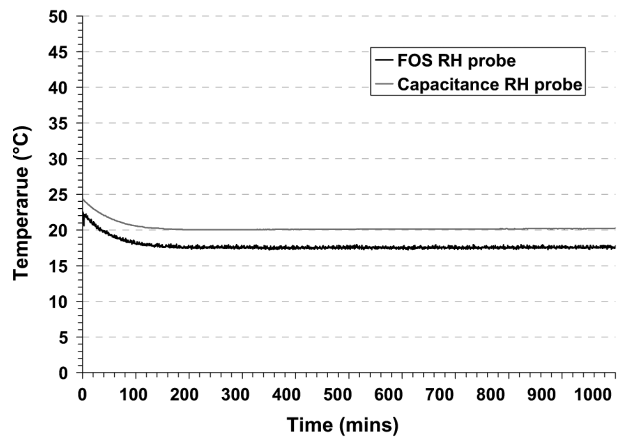
The changes in RH due to capillary rise of water, as measured by the FOS (fiber optic sensor) and capacitance based sensor are shown in Fig. 5(a). As the water front rises to the sensors located at 30 mm from the surface, the FOS-RH sensor responded more rapidly and gave values of RH which were seen to stabilize as would be expected, after 400 minutes. The measurements made by capacitance sensor, however, showed a gradual change in RH and stabilization was reached after 600 minutes. The delay demonstrated by the capacitance sensor is likely due to the larger volume of the sensor probe and the location of the opening allowing moisture into the sensing part of the probe, being placed on the side rather than at the tip of the probe. The temperature measurements made by both RH probes are closely related (agreeing within experimental error) and follow the same trend, as shown in Fig. 5(b).

Table I summarizes the time of arrival of moisture front at different depths from the surface of limestone block measured using the electrical resistance sensors shown in Fig. 3. It takes 600 minutes for the capacitance sensor to respond to the arrival at depth of 3 cm, but in reality the moisture has already reached 5 cm.

After the limestone block was fully saturated with moisture as a result of the capillary rise test, the block was subsequently subjected to a slow heating process, allowing the drying of the block and with that the change of the moisture content to be monitored.



(a)



(b)

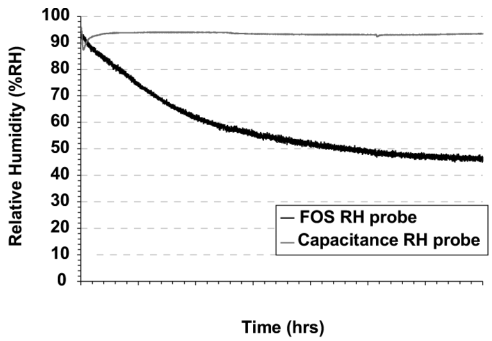
Fig. 5. (a) Changes in RH at 30 mm depth of stone with capillary rise of water. (b) Changes in temperature at 30 mm depth of stone with capillary rise of water.

TABLE I
ARRIVAL OF MOISTURE FRONT AT DIFFERENT DEPTHS IN STONE

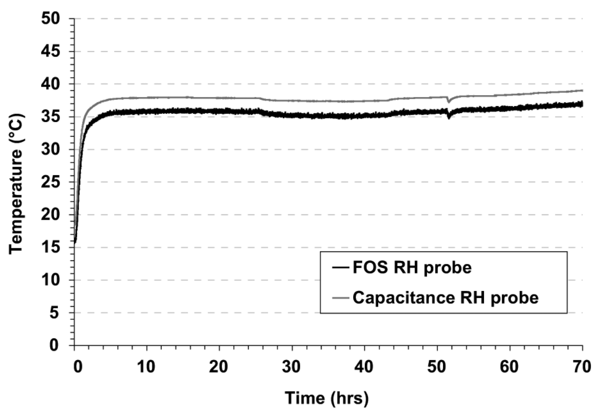
Depth (cm)	0.5	1.0	2.0	5.0
Time of arrival of moisture front (mins)	10	40.5	143.5	597

The heating of the sample was performed in an oven maintained at 40 °C. The changes in RH and temperature were measured using both the FOS RH sensor and the capacitance-based sensor when the limestone block was drying. The results obtained from the sensors are shown in Figs. 6(a) and 6(b). In this experiment, the RH and temperature changes inside the stone were monitored continuously for 3 days. It can be observed from Fig. 6(a) that the RH values, as measured by FOS probe, decreased gradually with time, showing a clear correlation between the response of this humidity sensor and the limestone block drying process with the expected decrease in RH due to the expulsion of moisture from the block.

However, the contrast was seen in the RH measurement made by the capacitance-based sensor which shows only the on-going saturation of the sensor during the experiment—the reading obtained indicated a minimal decrease with the initial few hours of drying but the saturated level is maintained throughout the drying period. This effect was likely due to the condensation of moisture on the sensing part of capacitance based RH probe and



(a)



(b)

Fig. 6. (a) Changes in RH at 30 mm depth of stone with drying of the stone block. (b) Changes in temperature at 30 mm depth of stone with drying of the stone block.

reflects that this sensor is not actually measuring the condition of the stonework, as required. Fig. 6(b) confirms again the good agreement seen in the temperature measurements made with the optical probe.

IV. Field Tests in Oxford

The FOS-RH sensor probe had been designed for in-the-field use and thus the validation was essential as it had been designed originally in consultation with and to meet the needs of scientists who were going to use it for actual measurements on degraded stonework outside the laboratory. Thus an extensive series of tests was planned and subsequently carried out on a test wall in Oxford. To allow for controlled measurements, the wall itself was built specifically using methods similar to those now employed in conservation and which were similar to those used over many centuries. This was necessary prior to any use on a series of historic walls in the University of Oxford. Fig. 7(a) and (b) shows the pictures of the test wall constructed at Wytham Woods in Oxford and the configuration of both types of sensors used in the tests. Again, for comparison, both the specially designed, temperature-compensated humidity sensor probe and a commercial RH probe were used in this study for monitoring of the moisture changes inside the wall. It should be stressed that the fiber optic sensor is much more compact and was specifically designed to be minimally invasive: thus requiring much less damage to the wall for its insertion, with only the drilling of one small pilot hole required for the mounting of the sensor.

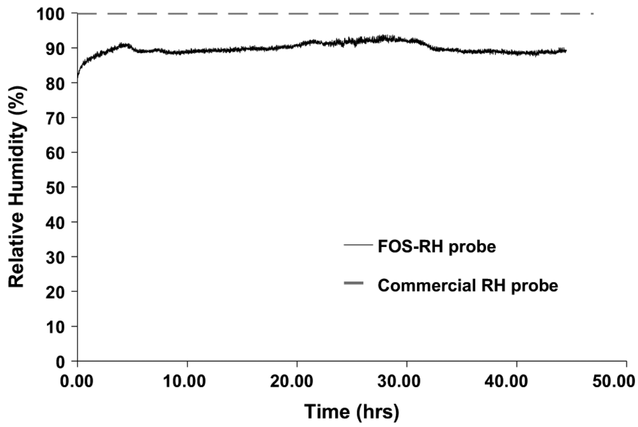
(a)

(b)

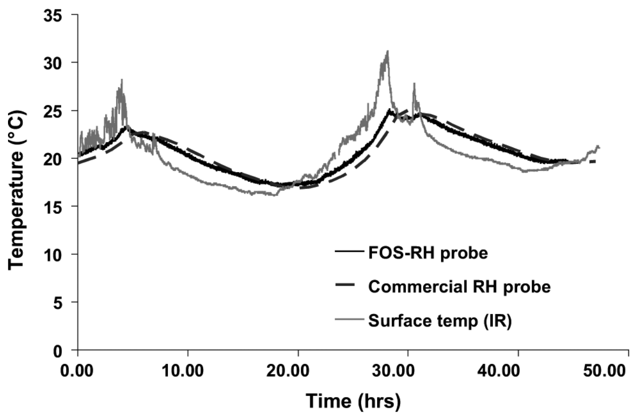
Fig. 7. (a) Front face of test wall showing the monitoring surface of the non-recessed stone block using IR thermometer. (b) Rear side face of the test wall showing the fiber optic monitoring set-up.

In addition to the RH sensors, a commercial infra-red thermometer supported using a truss arrangement and shown in Fig. 8(a) was used to measure the surface temperature of the block. The temperature and moisture changes in the wall were monitored continuously using the FOS-RH probe at a measurement interval of one minute, tests being carried out over a period of two days. The commercial RH probes had already been put in place inside the stone blocks several months before this study and due to the more limited data logging capacity, had been used for monitoring RH and temperature continuously at one hour intervals. The relative humidity and temperature measurements made using the FOS-RH probe and the commercial RH probe were cross-compared and the results are shown in Fig. 8(a) and (b).

It can be observed from Fig. 8(a) that the indication from the commercial RH probe was always 100% RH, whereas the measurements made using the FOS-RH probe showed a variation in RH of less than 100% and between 90%–93% RH, this varying with time. As with the laboratory tests, these results also show that the commercial RH sensor element had simply been saturated throughout the tests and hence the RH measurements was continuously reading an apparent RH of 100%—indicating the failure of the sensor to monitor accurately the true conditions of the wall itself. This indicates a clear drawback in



(a)



(b)

Fig. 8. (a) Changes in RH at 50 mm depth of the recessed stone block. (b) Changes in temperature at 50 mm depth of the recessed stone block.

this conventional monitoring approach and indeed many commercial RH sensors which have a high mass and fail to dry out properly when wet initially during use. By contrast, the optical fiber RH sensor, due to its small size and low mass, has been able to follow the actual change of RH of the wall. The temperature measurements, as shown in Fig. 8(b), indicate that the surface temperature changes rapidly, this depending on the environmental conditions and solar radiation. On the other hand, the temperature changes at 50 mm depth as measured by the FOS-RH probe are, as would be expected, rather slower than the surface changes but consistent with the surface temperature measurement undertaken with the infra-red probe. Also the response of the temperature measurements made by the FOS-RH probe was more rapid, in comparison to the temperature determined using the instrumentation within the commercial RH probe. It can be observed from Fig. 8(b) that the surface temperature of the stone block changes rapidly, recording a more substantial temperature difference (as would be expected due to the mass of the material) than was observed at a depth of 50 mm from the surface.

V. Discussions and Conclusions

A novel, low mass and lightweight optical fiber relative humidity sensor with built-in temperature compensation and tailor-designed for the application in stonework monitoring discussed has successfully been realized. It was tested and evaluated for the real-time monitoring of some key parameters, such as temperature and humidity, inside masonry structures—both within the laboratory and in-the-field. Through a careful design of the sensor packaging to meet the requirements of the scientists involved in the monitoring work, the optical RH sensors have demonstrated their robustness and been shown to be more accurate, with additionally a faster response, when their outputs are compared to those from commercial capacitance sensors: the more so when they are subjected to cycles of wet/dry conditions over several days. This is due to the fact that, unlike most conventional RH sensors, the optical fiber RH probes discussed here are not influenced by condensation of moisture within or on the sensor itself.

The positive outcomes from both the lab-based capillary rise and drying tests and the field tests on the test wall in Oxford have confirmed that the optical fiber temperature/humidity sensors can ideally complement the currently available temperature and RH sensors for enhanced long-term monitoring of moisture changes in building stone and indeed show superior performance when issues such as rapid changes in RH and temperature are concerned—the failure of conventional probes to dry out in the time required is evident from the results obtained.

Further field tests will be carried out to evaluate the robustness and effectiveness of the novel humidity sensor design by casting the sensors into different types of construction materials.

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Sudarshan Srinivasan, photograph and biography not available at the time of publication.

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Heather A. Viles is a Professor of biogeomorphology and heritage conservation at the University of Oxford, Oxford, U.K., and researches on the deterioration and conservation of natural stone artefacts and buildings. Her research focuses on integrated field and laboratory testing methods, including 2D resistivity surveys of moisture regimes.