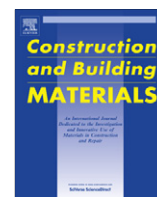




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Wireless sensor networks for temperature and humidity monitoring within concrete structures

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H I G H L I G H T S

- ▶ Different tiny sensors to measure temperature and humidity inside concrete have been tested.
- ▶ A wireless sensor network has been created based on the IEEE 802.15.4 facilitating real-time and long-term monitoring.
- ▶ Shielding avoids the breakdown of the sensors in the high relative humidity/alkaline environment.
- ▶ There is a perfect match between the measured values for the humidity and temperature and the ones obtained by the sensor probe.
- ▶ These research solutions involving WSNs have a tremendous potential in real time structural health monitoring.

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A B S T R A C T

This paper presents the development of an automatic wireless sensor monitoring system for civil engineering structures. The objective is to provide a solution to measure both temperature and humidity inside a concrete structure. The research has been focused in the early age and curing phase period. Four solutions have been addressed. The first one involves the use of a negative temperature coefficient (NTC) thermistor and an IRIS mote allowing for the creation of an IEEE 802.15.4 network. However, the results have shown that the sensor measurements present a 5 °C standard deviation between the actual and the experimental values. The second one considers the use of the SHT15 (humidity/temperature) sensor, together with the PIC18F4680 microcontroller or the Arduino platform. The third solution involves the use of the SHT21S (humidity/temperature) sensor and the eZ430-RF2500 wireless development tool platform for the MSP430 microcontroller. In this case, the temperature readings were successfully performed for the first 16 h, while the humidity values were successfully obtained for the first 24 h of the experiment. Although the set of measured values is very promising for the SHT15 and SHT21S sensors, both sensors have stopped working after some time, showing that direct contact between the sensor and the concrete alkaline environment causes its breakdown. Finally, the fourth solution considers both the SHT15 and SHT21S sensors completely shielded allowing for the creation of a long-term solution. As, the SHT15 and SHT21S sensors have not been affected by the alkaline environment for more than two months of operation, enabling real-time and continuous monitoring with almost non-intrusive tiny devices, the potential of applying the proposed inexpensive wireless sensor network approach is verified.

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1. Introduction

It is now recognised that integrated monitoring systems and procedures have an important and promising role to play in the to-

tal management of concrete structures. Monitoring deterioration would provide an early warning of incipient problems enabling the planning and scheduling of maintenance programmes, hence minimising relevant costs. Furthermore, the use of data from

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monitoring systems together with improved service-life prediction models leads to additional savings in life cycle costs [1,2].

Sensors and associated monitoring systems to assess materials performance form an important element in the inspection, assessment and management of concrete structures. There are more than fifty different types of sensor whose deployment into practical devices facilitates long-term monitoring of structural changes, reinforcement corrosion, concrete chemistry, moisture state and temperature [2].

The development of new sensor concepts allows for a more rational approach to the assessment of repair options, and scheduling of inspection and maintenance programmes in different civil engineering structures. Currently, there is a growing number of recent studies for the development of sensors in concrete structures, to monitoring from earlier-age parameters to environmental conditions that can cause deterioration processes, some of which may be highlighted. Providakis and Liarakos [3] studied an early-age concrete strength development miniaturised sensor system. The idea is to characterise the condition of the fresh concrete at very early stages. It consists of a reusable transducer being strong enough to easily detach from the hardened concrete structure, and to monitor the concrete strength development at early ages and initial hydration stages. Cruz et al. [4] studied the performance of a fibre-optic sensor for monitoring cracks of concrete, masonry and bituminous elements. The proposed sensor does not require prior knowledge of the locations of cracks, which is significantly advanced over existing crack monitoring techniques. Moreover, according to the authors, several cracks can be detected, located and monitored using a single fibre. Duffó and Farina [5] developed an integrated cost-effective sensor system to monitor the state of reinforced concrete structures from the corrosion point of view. The sensor provides measurements of the open circuit potential of rebars, corrosion current density of rebars, electrical resistivity of concrete, availability of oxygen, chloride ions concentration in the concrete, and temperature inside the structure [5].

Insertion of small sensors inside or at the surface of the concrete can be considered as one of the most promising development in order to monitor the long-term behaviour of concrete structures. Corrosion monitoring is possible using different sensors and methods that can work in the alkaline media of concrete for several years. Recorded data for corrosion potential and electrical concrete resistance obtained in real structures exposed to the environment can be used to determine the corrosion rate that corresponds to the concrete structure [6]. Embedded sensors in the concrete near the surface (depth of 50 mm) enable measurements of the spatial and temporal distribution of the electrical characteristics within the cover-zone. Thereby it allows for an integrated assessment of its performance. Regular monitoring can enable cover-zone response to different ambient environments, namely changes in the temperature [7].

Advances in the study of concrete deterioration can be achieved if concrete technologists cooperate with scientists in the relevant sensor sciences, to take advantage of the development of wireless low power smart sensor nodes capable of measuring behaviour, filtering, sharing and combining readings from a large variety of sensors. Key issues are calibration of embedded sensors, robustness of sensors cast into concrete elements and durability of sensors in relation to the long live required for the structures [8].

The monitoring of temperature and moisture level will provide crucial information about the hardening and setting process of concrete as well as the progress of deterioration mechanisms such as corrosion of steel reinforcement, freeze–thaw cycles, carbonation and alkali–aggregate reaction. A new technique to monitor the moisture level and temperature has recently been proposed

in [9]. This innovative technique uses nanotechnology/micromechanical systems (MEMS) to measure temperature and internal relative humidity by using microcantilever beams and a moisture-sensitive thin polymer. Based on the obtained results, it was found that the proposed MEMS survived the concrete corrosive environment, as well as to internal and external stresses. Also it was found that the MEMS output reflects the change in the concrete properties and can be used to effectively measure moisture content and temperature, with high sensitivity. However, serious issues, such as long-term behaviour and repeatability of MEMS embedded into concrete, require further investigation [9]. Resulting from cross-disciplinary research between civil engineering and automatic control engineering, a new measurement technique was recently developed in [9] enabling direct, real-time measurements and continuous monitoring of concrete internal temperature and humidity via wireless signal transmission. The results are very promising with temperature/humidity sensors which monitor the internal temperature and humidity of concrete wirelessly, directly, in real-time and continuously. However, several limitations need to be overcome when embedding electronic components into concrete, such as the continuity and stability of signal transmission, protection of electronic components, as well as the design of encapsulation boxes [10].

2. Motivation and objectives

The primary objective of this interdisciplinary research is to develop a prototype for Wireless Sensor Networks (WSNs) allowing for remotely monitoring certain concrete structures. WSNs are formed by tiny devices, known as *nodes*, that incorporate a microcontroller, sensors, memory, a power unit and a communication module. They are able to sense the environment and communicate the information gathered from the sensors to the sink node through wireless links. Their capabilities include reading the value of physical variables at a given location, detecting the events of interest, whilst performing collaborative signal processing. From the application perspective, WSNs are useful in situations that require quick or infrastructure-less deployment and continuously monitoring [11–13]. Besides, the research work was focused on studying the behaviour of a concrete cube immediately after casting and at earlier ages, whilst monitoring all the temperature and moisture changes in real time. This is accomplished by using an IEEE 802.15.4 network enabling a significant reduction of the installation time and costs. The experiments to be carried out, also aims at expanding the output from this research to the monitoring of other structures regardless the type of material, and to develop a prototype that facilitates to measure several parameters inside a real concrete structure, e.g., humidity and temperature.

In the context of WSNs applied to civil engineering structures it is important to create a monitoring device platform that is able to accommodate a wide range of sensors, depending on the needs, expandability and cost, while sharing the information across the network. For this purpose, remote agents can be collectors of information either by storing the data into a microSD card, to be accessed later on, or by wirelessly transmitting this information, in real time, to a Mote Interface Board (gateway) that is connected to a PC, allowing for a rapid intervention of civil engineers, if needed, as shown in Fig. 1.

Temperature is an important parameter during the curing and hardening of the concrete, since the concrete cannot be too cold or too hot. When the temperature decreases, the hydration reaction slows down. Hence, if the concrete temperature increases the reaction accelerates, creating an exothermic reaction (which produces heat), causing temperature differentials within the

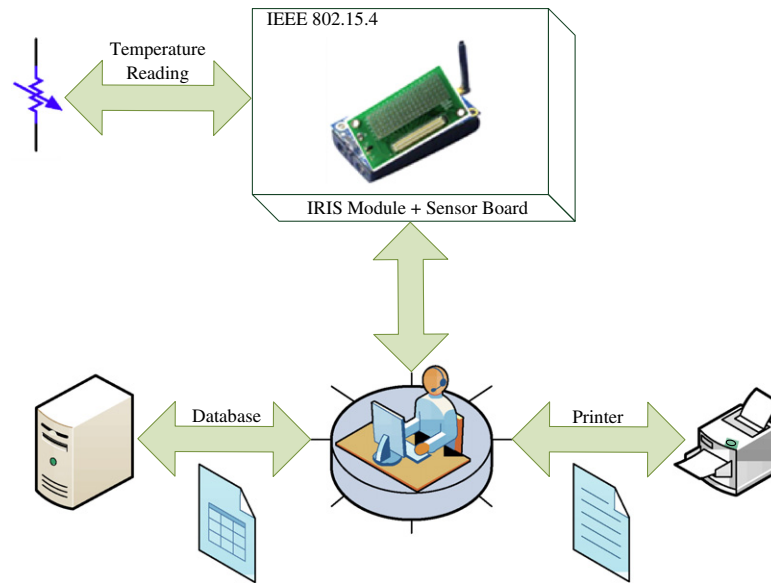


Fig. 1. Wireless sensor network architecture for the monitoring of civil engineering structures.

concrete. This temperature gradient can lead to cracking. Moreover, during the initial phase of the life of the concrete, it is essential to avoid cracking caused by the rapid drying due to increased temperature and the on-going hydration reaction.

The rate of strength development in the early life of the concrete is strongly related to its rate of hydration. As a consequence, it is worthwhile to study the impact of the temperature increase caused by the occurrence of the hydration reaction. Furthermore, structural health monitoring has been identified as a prominent application field for WSNs, since traditional wired-based solutions present some inherent limitations such as installation/maintenance cost, scalability and visual impact. In order to collect the data from the temperature sensors, a WSN was created facilitating the remote monitoring.

The properties of civil structures involve a significant amount of uncertainties in several parameters, caused by the effects from environmental factors, e.g., temperature and humidity. The deterioration process of the underlying structure is caused by these variations. At earlier ages, temperature and moisture plays an important role during the curing and hardening of the concrete, and can have long-term consequences.

Both moisture and temperature at specific operational conditions promote concrete deterioration processes namely, occurrence of undesirable cracks, corrosion of the reinforcing steel, ingress of carbon dioxide and other chemical processes.

3. Experimental work

3.1. Negative temperature thermistor – temperature sensor

The first set of tests consisted of measuring the temperature with a NTC temperature sensor inside a concrete cube (common strength class C25/30, 10 cm length size), as shown in Fig. 2.

The acquisition system consists of a Sensor Board and an IRIS mote, facilitating the creation of an IEEE 802.15.4 network whose primary function is to remotely collect the data from the NTC sensor inside the concrete cube.

3.2. SHT15 humidity and temperature sensor

In the second set of tests, the SHT15 digital sensor was used, facilitating to measure both temperature and humidity with high accuracy in a single chip sensor. Fig. 3 presents a schematic representation of process to measure the temperature and humidity within the concrete cube.

The conversion from the raw value returned by the SHT15 sensor, R_{xval} , to the temperature and humidity values was performed by using the following equations:

$$\text{Temperature } [^{\circ}\text{C}] = (R_{xval} \times 0.01) - 40 \quad (1)$$

$$\text{Humidity } [\%RH] = -4.0 + 0.0405 \times R_{xval} - 0.0000028 \times R_{xval} \times R_{xval} \quad (2)$$

Before inserting the sensor inside the concrete block, the following preparations have been made (as shown in Fig. 4):

- the sensors were placed inside a small size cube (4 cm side length) made of cement mortar for its protection. The mortar was produced using low water content with a cement mortar ratio of 1:3 (the mortar works as shell that can protect sensor wire connections when placed inside concrete during casting; high porosity of this mortar shell easily allows moisture measures of involving concrete);
- coarse sand size was used avoiding fine particles, so that the sensors would not become obstructed.

3.3. SHT21S humidity and temperature sensor

3.3.1. Standalone version

Besides the SHT15 (humidity/temperature) sensor, we tested the new Sensirion SHT21S (humidity/temperature) sensor. Before testing this sensor a cement mortar shell has been used for its protection. This sensor is an updated version of the previous one but with a smaller package. To test this sensor, an acquisition system was designed to facilitate the acquisition of the analogue signal while converting it for its digital representation. As previously mentioned we intend to measure both temperature and humidity inside the concrete block, from the early ages, during setting and hardening period.

The temperature and humidity values are obtained by using Eqs. (3) and (4), respectively:

$$\text{Temperature } [^{\circ}\text{C}] = -46.85 + 175.72 \times \frac{V_{SO}}{V_{DD}} \quad (3)$$

$$\text{Humidity } [\%RH] = -6 + 125 \times \frac{V_{SO}}{V_{DD}} \quad (4)$$

where, V_{DD} is the supply voltage at which the SHT21S sensor works, as presented in the datasheet of the sensor in the interface specifications. In this case, $V_{DD} = 3$ V. Besides, since the SHT21S output is a Sigma Delta Modulated (SDM) signal, normally this signal is converted to an analogue voltage signal by the means of a low-pass filter. The output of low pass filter provides a voltage value (V_{SO}) which is a portion of V_{DD} , depending on the measured humidity or temperature. The developed acquisition system (for the standalone SHT21S) incorporates a microSD module, responsible for storing the values acquired from the SHT21S sensor, as shown in Fig. 5.

The MSP430F449-STK2 module was used to convert the signal output from the RC-filter to the digital format. The algorithm running inside the microcontroller performs five readings (with a 100 ms interval between two consecutive readings for the temperature), storing the fifth reading in a buffer. Then, it switches to the humidity sensor, performing another five readings and conversions with the same duration between consecutive readings, storing the fifth reading in another buffer. Finally, after that it sends the commands to store the temperature and humidity values in separated text files, into the microSD card.

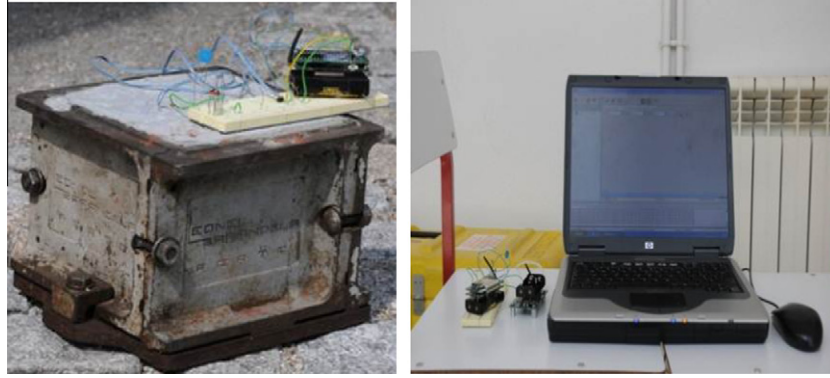


Fig. 2. On-going measurement of temperature with wireless sensors inside a concrete cube.

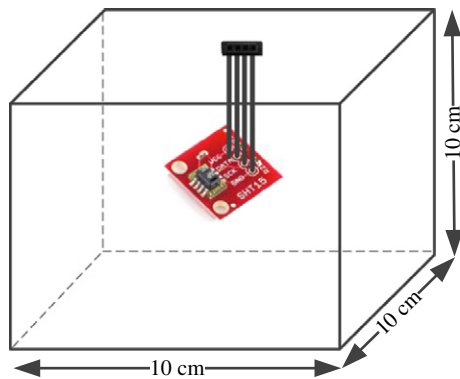


Fig. 3. Schematic representation of temperature and humidity sensor inside a concrete cube (10 cm length size).

3.3.2. Wireless version

The SHT21S wireless prototype aims at creating a Building Wireless Sensor Network (BWSN) capable of measuring temperature and humidity inside a concrete structure. It has two Integrated Circuits (ICs) interfaces via Serial Port Interface (SPI), and an antenna allowing for connectivity with no additional hardware components. Besides, it provides real-time data information and remote interaction with multiple devices (e.g., laptop, PDA, cell phone with ZigBee® capabilities). The MSP430F2274 ultra-low-power microcontroller controls the CC2500 radio transceiver (that operate at the 2.4 GHz band) and establishes a basic wireless network with minimal power requirements, enabling to extend the system lifetime. Fig. 6 presents the acquisition system used to read the signal from the SHT21S sensor.

The computed temperature and humidity values are sent wirelessly to the access point (AP). The end device (ED) reports periodically values each minute to the AP. The user depending on the application scenario can change this reporting periodicity value.

3.4. Joint verification of shielded SHT15 and SHT21S sensors

The main purpose of shielding the SHT15 and SHT21S sensors is to protect the sensor from the concrete high relatively humidity alkaline environment that could affect the sensor inside the concrete. Besides, the unique capacitive sensor element used to measure humidity as well as the band-gap sensor utilised to measure the temperature do not resist to the high relative humidity alkaline environment present in cement. To overcome this limitation, in the second series of tests we have decided to use a filter cap allowing for protecting the SHT15 and SHT21S humidity and temperature sensors against dust, water immersion, condensation, as well as contamination by particles. The cavity inside the filter cap is made such that the volume between the membrane and the sensor is kept minimal, which reduces the impact on the response time for the humidity measurements. The filter cap is made of a single piece of polypropylene (PP) and a filter membrane welded to the single piece, Fig. 7.

Before inserting the filter cap for sensor protection, the following preparations have been made (as shown in Fig. 8):

- the filter cap was mounted on the printed circuit board (PCB) after soldering the SHT15 and SHT21S sensors by sticking the two openings in the PCB;
- the filter cap was fixed by adhesive (melting the pins from the back side by heating them up with a hot iron, was also possible);

- an hermetic seal was applied, which is an adhesive added between the filter cap, sensor housing and PCB, providing higher security against water leakage, condensation inside the housing and corrosion of the soldering paths of the sensors.

After shielding the SHT15 and SHT21S sensors, we have decided to create different humidity and temperature environments and compare the obtained results with a standard climate sensor probe (Rotronic hydroclip probe, for all climatic measurements, operating range $-40 \dots 100$ °C, $0 \dots 100$ % RH) in order to show the accuracy of the measurements, as presented in Fig. 9a–d. We have decided not to include markers in the curves for the temperature and humidity variation, in order to facilitate their interpretation. The response of the sensors was tested in four different conditions. The first test consists of creating a controlled relative humidity of 75% inside a desiccator. Therefore, the bottom of the desiccator was partially filled with sodium chloride saturated water solution (salt mixed with water), Fig. 9a. The test was performed during 23 h, in which the standard climate sensor probe from Rotronic was used to confirm the measured values with SHT15 and SHT21S sensors.

During the first 4 h, the SHT15 was not connected to the Arduino platform, so we did not measure any temperature and humidity value. After 4 h, we powered up the SHT15 sensor and it started to measure both humidity and temperature values. Between the 4th and 23rd hours, by comparing the results obtained from the SHT15 and SHT21S sensors with the ones obtained from the sensor probe, we conclude that the results are similar. Moreover, after 7 h, both humidity and temperature values started to have a constant behaviour, where the humidity is about 75% and the temperature is about 23 °C. After 16 h we decided to open the desiccator to observe if there is any variation in the temperature and humidity values. As presented in Fig. 9a there is a decrease in the humidity values and an increase in the temperature values.

In the second set of tests, Fig. 9b, the bottom of the desiccator, which was filled with a salt solution, was replaced by ice cubes. Therefore, during the first 3 h there is a decrease of the temperature and an increase of the humidity values. After 30 h the air inside the desiccator reaches the equilibrium, where the humidity is about 100%, and the temperature is ambient dependent. The SHT15 sensor was connected only after 42 h. Between the 42nd and 63rd hours, by comparing the results obtained from the SHT15 and SHT21S sensors with the ones from the sensor probe, we conclude that the results are similar. In Fig. 9c, the ice cubes inside the desiccator melted, and the bottom of the desiccator is filled with water. Therefore, as expected the humidity inside the desiccator is around 100% and the temperature is ambient dependent. In addition there was an increase of the temperature during the day and a decrease during the night. Finally, the last test consists of replacing the bottom of desiccator previously filled with water, by silica gel particles. As presented in Fig. 9d, there is a fast variation in terms of relative humidity inside the desiccator, especially during the first hour. The values for the humidity show an average standard deviation of 2% by comparing the SHT15 and SHT21S sensors. This can be explained by the fact that the positions inside the desiccator are not the same, leading to small variation in the measurements of the humidity values. Besides, we have also noticed that there was an average standard deviation of 2–4% between the relative humidity measured by the standard climate sensor probe from Rotronic and the SHT15 and SHT21S sensors, respectively. This is due to the fact that the sensor probe [14] is not as accurate as the digital humidity and temperature sensors when fast variations occur.

4. Results and discussion

4.1. Negative temperature thermistor – temperature sensor

The first experimental approach for reading temperature inside a concrete cube involves the use of a negative temperature

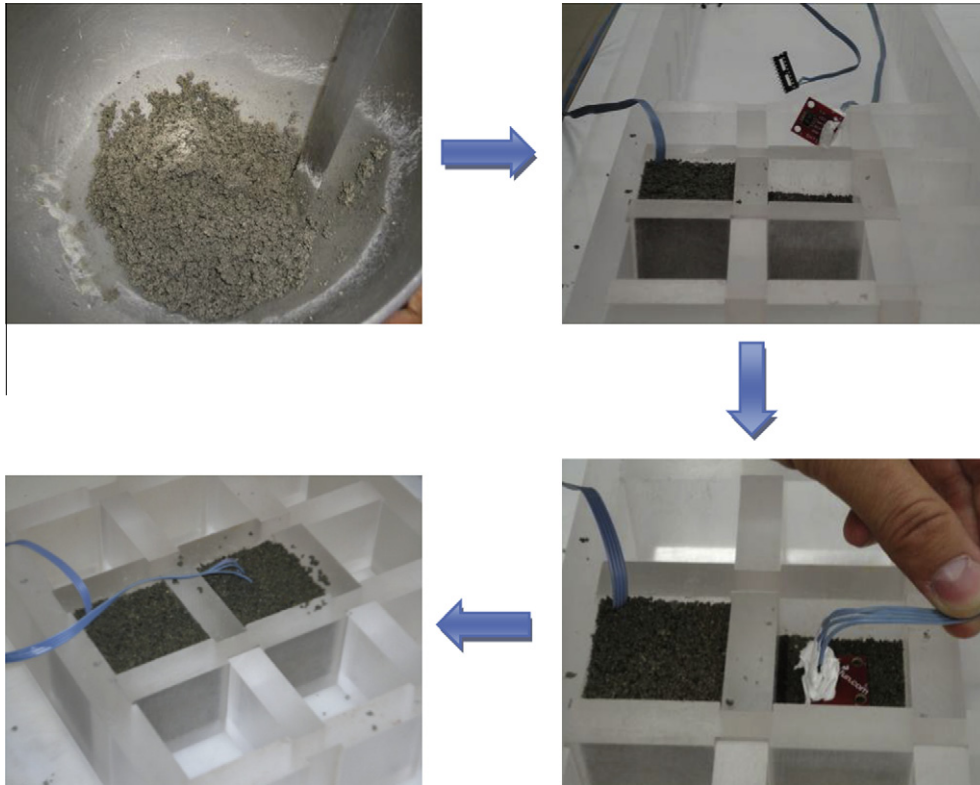


Fig. 4. Preparation and placement of the temperature and humidity sensors inside a mortar cube for its protection.

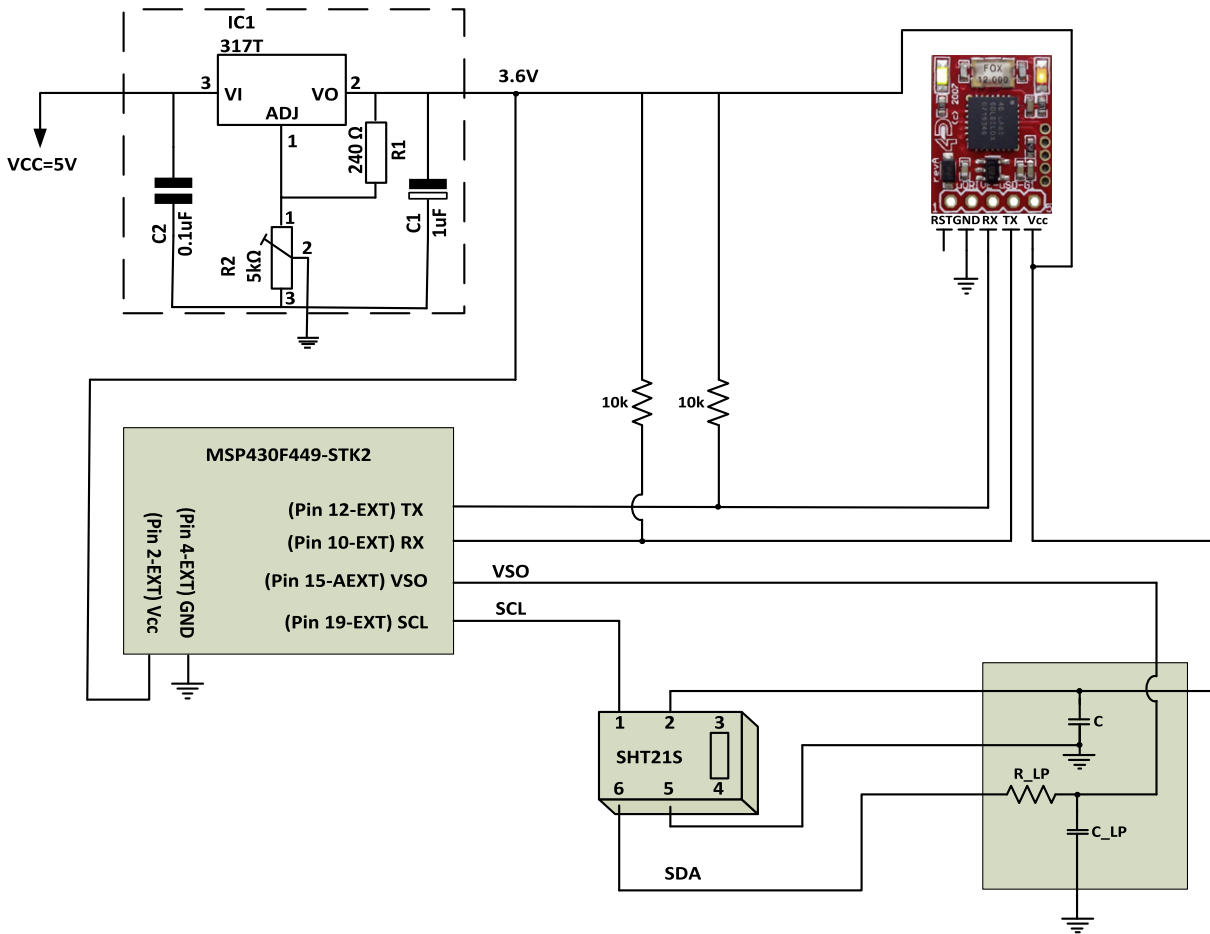


Fig. 5. SHT21S acquisition system for the standalone version.

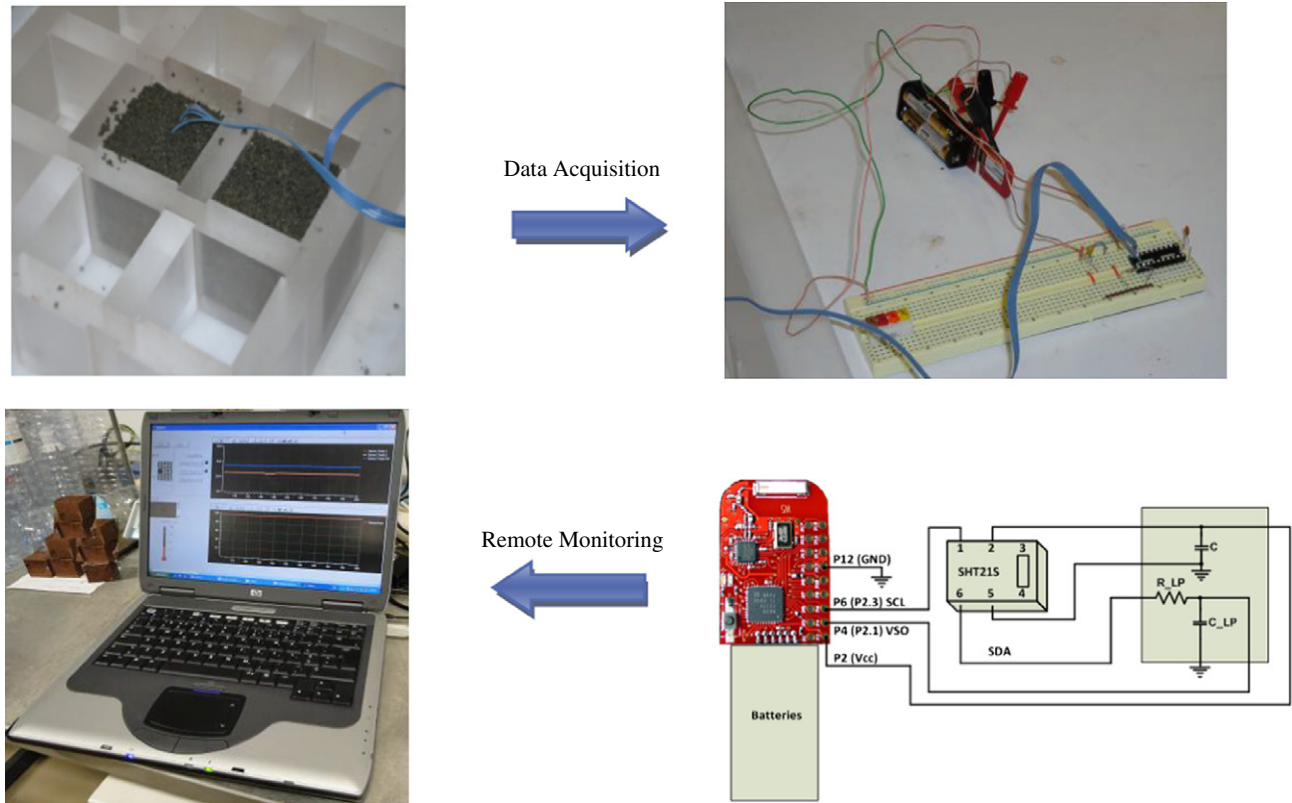


Fig. 6. SHT21S wireless acquisition system.

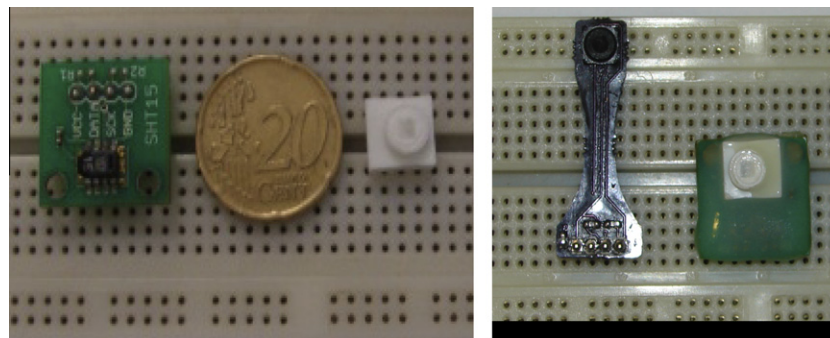


Fig. 7. Filter cap protection for the SHT15 and SHT21S sensors.

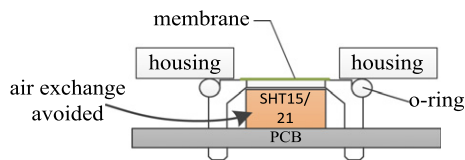


Fig. 8. Mounting schematics of the filter cap protection for the SHT15 and SHT21S sensors.

coefficient (NTC) thermistor and an *IRIS mote*. This setup foresees an automatic wireless monitoring system.

The temperatures inside the concrete cube and environment have been compared. Fig. 10 presents the values obtained for the temperature by the probe and calibrated sensors.

As shown in Fig. 10, there is a difference of 5 °C between the actual and measured temperatures. This is due to some failures

during the calibration of the sensor, resulting in inaccurate values. Based on this fact, we can conclude that using a NTC sensor with an “unknown” behaviour is not the most adequate approach to the problem. Besides, this kind of sensor is not able to simultaneously measure temperature and humidity inside the concrete structures.

4.2. SHT15 humidity and temperature sensor

The second set of tests considers the use of the SHT15 sensor, allowing for measuring both the humidity and temperature. Two solutions were tested, one with the PIC18F4680 microcontroller and another one using the Arduino platform. Before using the SHT15 sensor in a real scenario, some tests have been performed to verify the accuracy of the temperature and humidity readings. By using a temperature of 16.3 °C inside a fridge chamber, and by comparing the results obtained from the sensor with the ones

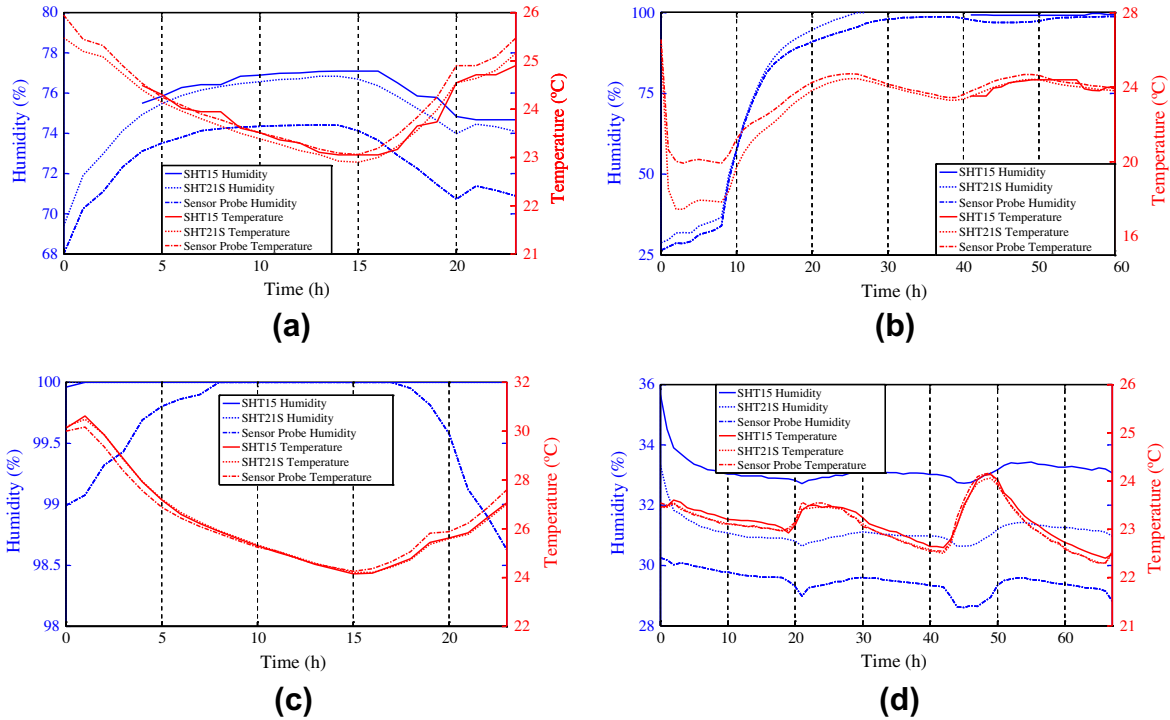


Fig. 9. Results for the humidity and temperature obtained using the SHT15 and SHT21S sensors: (a) humidity of 75%, (b) silica gel particles replaced by ice cubes, (c) desiccator filled with water, and (d) water replaced by silica gel particles.

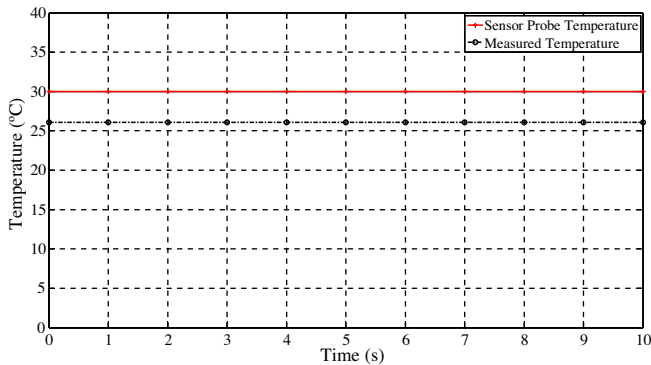


Fig. 10. Verification of the sensor probe and measured temperatures inside the concrete cube by using an NTC temperature sensor.

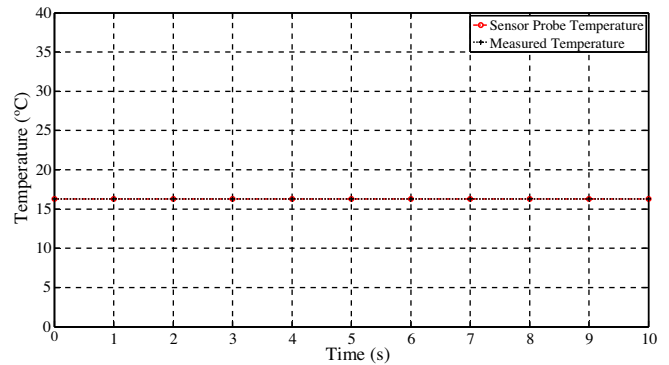


Fig. 11. Sensor probe temperature versus measured temperature inside the fridge chamber by using an SHT15 temperature sensor.

obtained from the sensor probe, we conclude that the results are very similar, as shown in Fig. 11.

To measure humidity we place the SHT15 sensor inside a small mortar cube for sensor protection, as explained in Section 3.2. When, the cubes were placed in a tray (with 2–3 mm water level), we observed the rise of water inside the cube by capillary, as shown in Fig. 12. After around one minute, the humidity reaches a value of 98% RH. The objective of this test was to verify the sensor integrity, as well as the porosity effect of its mortar shell. The results obtained from both PIC18F4680 and Arduino platform were identical. The tests were carried out during several hours, to observe if any variation of humidity and temperature could be detected.

In another experiment a SHT15 sensor with a mortar shell was fully immersed in water. One observes that the temperature was decreasing while the humidity was increasing. After 20 min of accurate measurements, we have decided to prolong the test during one week. However, after one day, the SHT15 temperature

sensor went off. Then, after 4 days the same happened to the humidity sensor. It is believed that the primary reason for this occurrence is that some chemical reactions inside the mortar shell have affected the capacitance of the sensor. Sensor components might not resist to alkaline ions present in cement, namely calcium hydroxide, which can be released in water from its mortar shell during immersion. To solve this problem, instead of making a cement-based mortar shell it may be preferable to shield the sensor using other material, textile or polymer based.

4.3. SHT21S humidity and temperature sensor

4.3.1. Standalone version

The SHT21S sensor protected by a mortar cube was placed inside a concrete cube during casting, as shown in Fig. 13. The values measured by the sensor were recorded into the microSD card. The data collected from the sensor is shown in Fig. 14. The measurements were performed in outdoor environmental conditions

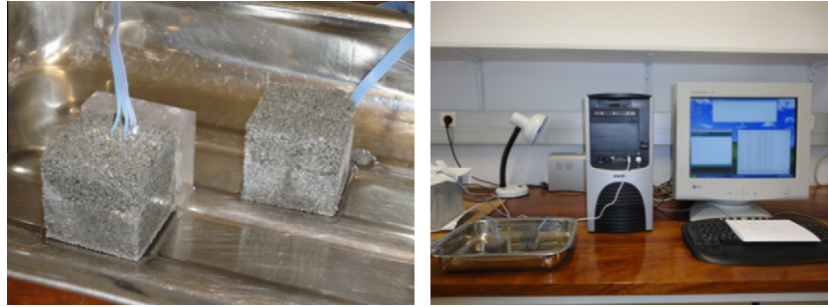


Fig. 12. Setup to measure temperature and humidity using an SHT15 sensor inside a mortar cube for sensor protection.



Fig. 13. Preparations to measure early age concrete temperature and humidity using a SHT21S sensor inside a mortar shell.

during summer. During the first 12 h there has been a constant and progressive variation; while between the 12th and 16th hours a decrease in the temperature and humidity values has been observed. After 16 h, the sensor stopped reading the temperature values. Only the humidity values have been measured beyond this time instant. As occurred with SHT15, the SHT21S sensor components have not resisted long time inside the concrete alkaline environment. To overcome this limitation, shielding of sensor is also advised in this case, e.g., with textile, polymer (Polybutylene Terephthalate) [15] or even metal shielding.

4.3.2. Wireless version

In scenarios of remote monitoring, there is a need of extracting and recording the data gathered by the sensor nodes. To avoid the need of regularly visiting, remote access to the collected data is essential. Moreover, solutions involving WSNs have a tremendous

potential in real time structural health monitoring, since they potentially reduce costs.

The SHT21S wireless version allows for collecting the information from any given structure. Fig. 15 presents the SHT21S eZ430-RF2500 C++ software program responsible for the acquisition of the values from the SHT21S sensor. The acquired values are shown in two different ways either plotted in a chart as a function of time, or by the instantaneous observation of the values in a segment display (while the AP receives the data packets). To analyse the acquired values we can export the data to a Matlab® file.

As shown in Fig. 15 the results obtained for temperature and humidity are quite accurate. Therefore, the use of a porous cement mortar as protective shell does not affect the sensor readings. This method of protection of the sensor is similar to those developed by Chang and Hung [10] and recently published, although unknown to authors during the experimental phase. However, the presented solution does not consider an encapsulation box for the electronic acquisition system components (since it is outside the “brick”), as presented in Fig. 6. This way we are able to obtain more accurately values for the temperature and humidity, since the sensor is placed as close to the environment as possible. By using an encapsulation box the detected temperature and humidity may not be the actual structure temperature and humidity, as stated in [10]. Besides, in the work developed by Chang and Hung [10] the Radio Frequency Integrated Circuit (RFIC) transmitter is inside the brick, being the maximum effective reception range below 20 m. The research conducted by Quinn and Kelly [16], also considers a package to protect the sensor from the aggressive environment. Preliminary results show that the transmission distance is strongly affected by the steel backed formwork, showing that the maximum distance achieved without the formwork is 7.5 m. In our case, by considering the open field scenario (since the acquisition systems is outside the “brick”) the eZ430-RF2500 can achieve a minimum effective reception range of 35 m. In this experiment, the SHT21S sensor temperature readings have been successfully performed

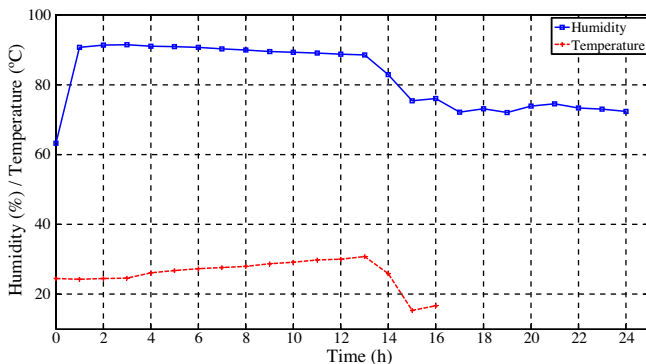


Fig. 14. Results for the humidity and temperature for the SHT21S sensor obtained in a cube placed in the exterior during a summer day.

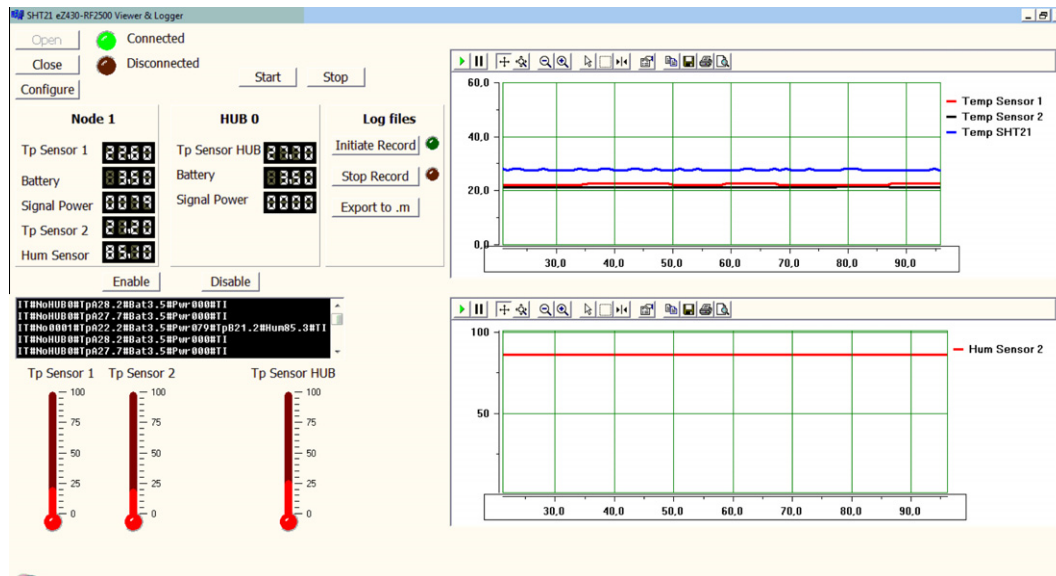


Fig. 15. Software program for the acquisition of the SHT21S eZ430-RF2500 sensor data.

during the first 16 h, while the humidity values were successfully obtained during the first 21 h. After this period, the sensor went off, possibly also caused by the alkaline concrete environment that stopped the sensor operation.

4.4. Joint verification of shielded SHT15 and SHT21S sensors

In this set of experiments, the SHT15 and SHT21S sensors previously shielded were inserted into two small size mortar cubes (4 cm of side length) before being inserted into the concrete block. To test the accuracy of the measurements, the mortar cubes were first placed in a tray with water. After some time, we observed the rise of water inside the cube by capillarity. Then, the cubes were removed for drying, Fig. 16. The cube containing the SHT15 sensor initiated the drying process after 10 h, while the cube containing the SHT21S sensor started the drying process after 60 h. After 97 h, we have repeated the test of placing the cubes in a tray with water, in order to observe the increase of the humidity values. The standard deviation between the humidity measured by the SHT15 sensor and the SHT21 sensor is explained by the fact that the small cubes are not exactly the same, so some variations in terms of humidity may exist during the drying process. Besides, if the SHT21S is exposed to conditions outside the normal operation range (humidity > 80%), an offset could exist. Therefore, in high relative humidity environment it is advised to use the

SHT15 sensor. The measured temperature is similar to the ambient temperature, in which the small variations are also due to the drying process.

Then, the SHT15 and SHT21S sensors previously shielded and protected by a mortar cube were placed inside a concrete cube during the casting, as shown in Fig. 17. The values measured by the sensors were recorded into the microSD card. The data collected from the sensors is shown in Fig. 18. The tests were performed during 6 days. During the first 12 h there is an increase of the humidity for the cube containing the SHT15 sensor, while the humidity inside the cube containing the SHT21S sensor achieves the maximum value (i.e., 100%). Moreover, during the curing process the temperature inside the cubes was about 37 °C after the first 11 h. These results are similar to the ones presented in Fig. 14. Therefore, we may conclude that by using a filter cap (shielding the sensors) as shown in Fig. 7, we protect the humidity and temperature sensors, allowing for the creation of a long-term solution, which is one of the objectives of these experiments. Finally, it was verified that both sensors were performing measurements inside the concrete after 2 months of experiments.

4.5. Limitations and challenges

In this work, we proposed several tiny systems, capable of (but not limited to) measuring both temperature and humidity, within concrete structures. In the context of sensing devices (i.e., the SHT15 and SHT21S sensors) only the sensor is inside the structure (the instrumentation, test control, and data acquisition is outside the structure allowing for using the same sensor and different acquisition systems, if needed).

However, the proposed systems are battery operated. Hence, the service lifetime of the electronic components could be a major concern if there is no possibility to replace batteries and energy harvesting is not exploited in the mote. The need for a system with long-term lifetime is a major concern. To overcome the service lifetime limitation of the electronic components, energy harvesting systems must be addressed facilitating to extend the service lifetime (e.g., by using solar panels or thermal energy scavengers).

In remote monitoring scenarios, the data needs to be transmitted wirelessly. Hence, there is a need to study the influence of the concrete material in the transmission of data (e.g., interference of

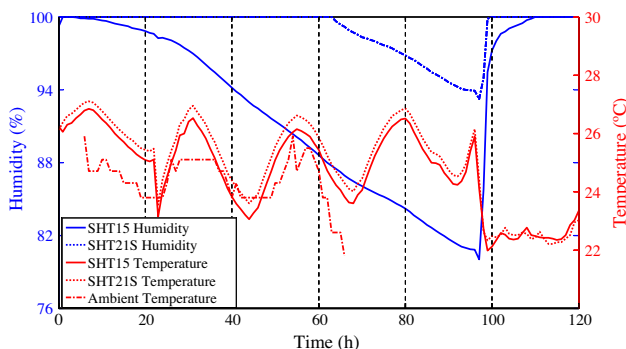


Fig. 16. Results for the humidity and temperature obtained using the SHT15 and SHT21S sensors during 5 days.

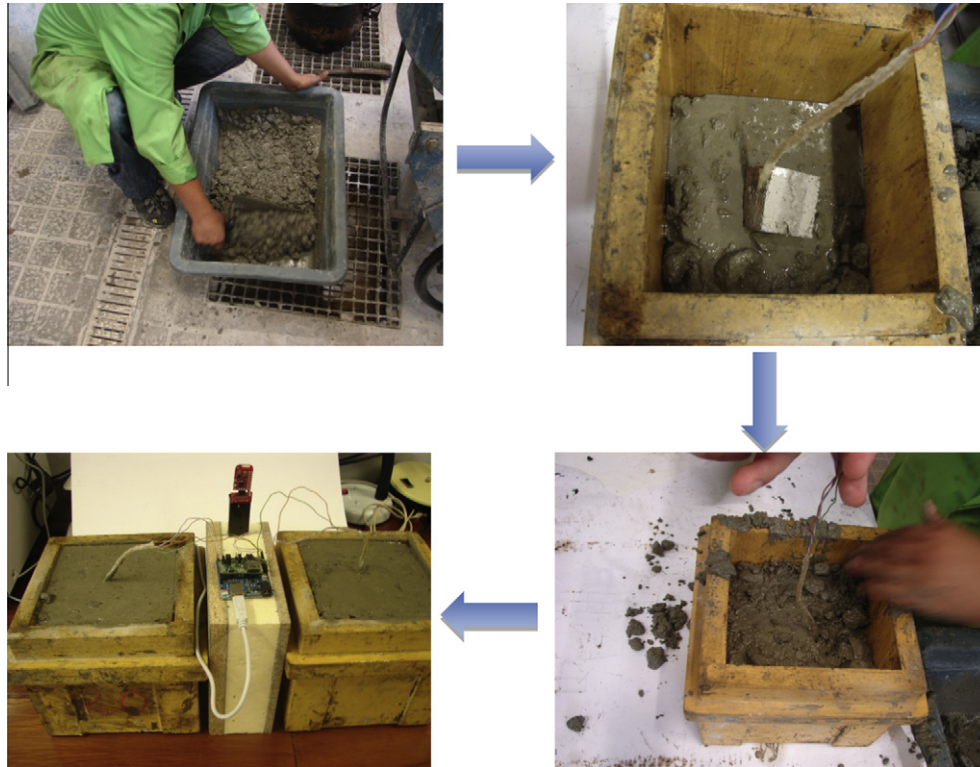


Fig. 17. Preparations to measure early age concrete temperature and humidity using the SHT15 and SHT21S sensors inside a mortar shell.

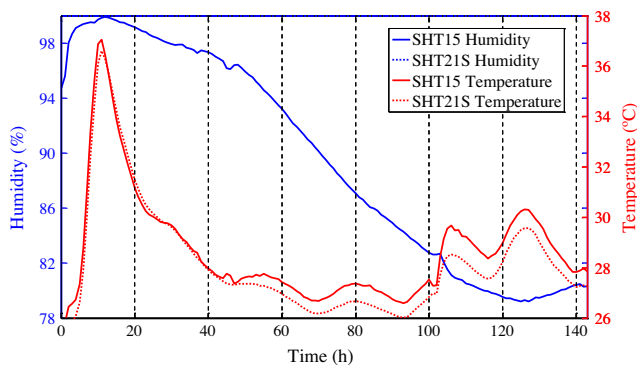


Fig. 18. Results for the humidity and temperature obtained using the SHT15 and SHT21S sensors inside a mortar shell for 143 h.

electromagnetic field of steel bars), in order to provide a general-purpose solution that could be applied not only to new structures but also in the existing ones. From the experimental point of view, we only have measured the humidity and temperature in a single point inside the concrete cube. So, the creation of a system allowing for a distributed multipoint humidity and temperature measurement set up is envisaged as future research.

5. Conclusions

This work addresses the development of an automatic measurement system allowing for monitoring the temperature and humidity within civil engineering structures. This system can be very useful when carrying out large works in concrete, such as dams or bridges where the volume of concrete involved is massive. Since the curing process is the process that defines the concrete quality, if the values of humidity and temperature are known, the

premature drying of the concrete surface can be avoided by hydrating it. This decreases cracking and increases concrete quality. Moreover, this system can be implemented in existing structures where the concrete is going to be applied in an aggressive environment, therefore preventing corrosion of the reinforcement steel.

Several types of hardware implementation have been conceived in order to read the temperature and humidity inside a concrete cube. A wireless sensor network has been created based on the IEEE 802.15.4, allowing for the creation of a continuous monitoring system capable of sending data wirelessly. In this network, the *motes* used two types of sensors, the SHT15 and SHT21S ones, to read both humidity and temperature, in real-time and continuous monitoring basis. The obtained results show two types of sensors and the measurement procedure have highly potential for inexpensive concrete structure monitoring. However, during the first set of experiments the SHT15 temperature sensor stopped working after one day. Besides, after four days, the same happened to the humidity sensor. The temperature readings from the SHT21S sensor have been successfully performed during the first 16 h of the experiment, while the humidity values were successfully obtained for the first 21 h. After this period the sensor went off. The initial sets of results were very promising, although SHT15 and SHT21S sensors went off after some time inside concrete. This is explained by the fact that the components of the sensors do not resist to concrete high relative humidity alkaline environment. The experiments carried on also shown that a porous cement mortar could be used as shell to protect sensor wire connections. High porosity of this mortar shell easily allows moisture and temperature measures of involving concrete. Still this solution does not protect sensors of the alkaline environment. Hence, it is advised to shield the sensors before using them within the structure, especially during the construction phase. It is also advised to use sensors that can resist in concrete alkaline environment. In the second set of

experiments, the SHT15 and SHT21S sensors were shielded by a filter cap, so that they are not affected by the alkaline environment, allowing for real-time and continuous monitoring basis. The SHT15 and SHT21S sensors are working since the beginning of this second phase of the experimental research work, for more than two months.

One verifies that there is a perfect match between the measured values for the humidity and temperature and the ones obtained by the sensor probe, which confirms the potential of the proposed wireless sensor monitoring approach.

Finally, it is worth mentioning that the solutions involving WSNs have a tremendous potential in real time structural health monitoring, since it reduces the cost and prevents from the risks associated to monitoring systems (e.g., inaccuracy in the measured values or negative impact of dangerous environments) in the measurement procedure.

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