A WIRELESS MONITORING SYSTEM TO STUDY THE SETTING AND HARDENING PROCESSES OF CEMENTITIOUS MATERIALS

Sofía APARICIO, CAEND (CSIC-UPM), Arganda del Rey, SPAIN
Miguel MOLERO, CAEND (CSIC-UPM), Arganda del Rey, SPAIN
Ignacio SEGURA, CARTIF, Valladolid, SPAIN
José Javier ANAYA, CAEND (CSIC-UPM), Arganda del Rey, SPAIN
Miguel Ángel G. IZQUIERDO, ETSIT (UPM), Madrid, SPAIN
José Vicente FUENTE, AIDICO, Valencia, SPAIN

1. Abstract

Traditionally, the study of cementitious materials has been performed using wired sensor technologies. Because these technologies are expensive and difficult to install, the use of wireless sensor networks has gained increasing importance.

There is plenty of literature dedicated to the study of the problematic use of wireless networks to monitor the structural integrity of materials. Considerable improvements have been achieved in the sensorization of different structures. But it is still necessary to enhance the reliability of these networks to evaluate and monitor structures during the setting and hardening processes. Power consumption of Wireless Sensor Networks (WSN) must be minimized for an efficient use of this technology in the above mentioned applications, since the continued use of WSN for long periods of time relies on the duration of the batteries. Since data communication/transfer between network nodes consumes more energy than data processing, it is essential that the data acquired by each node is significantly reduced before it is sent to the base station. Data reduction is especially important for dynamical monitoring processes, which require a huge sampling rate. The base station should receive the data from each node and provide diagnostics to detect anomalous states. Furthermore, the base station is the access point to the network through remote control and must allow monitoring, control and configuration of the network for storing and post-processing of the received data.

To accomplish all the above requirements, a monitoring system based on a WSN should incorporate a computation system distributed through the network. Optimization of the sensor sampling rate is also required.

In this paper we report the construction of a WSN using Cricket and Micaz motes to monitor the setting and hardening processes of cementitious materials. Since these processes are time limited, the use of this technology is appropriated. These motes were purchased from Crossbow Technologies [1]. For our research, the most important capability of Cricket motes is that they host transmitter/receiver in the ultrasonic wavelength region.

Cricket motes were intended for indoor location systems and they have an ultrasound transmitter/receiver for time of flight ranging. They have been adapted by reprogramming the application for inspection of concrete structures. A through transmission method was used to compute the velocity of the ultrasonic signal in concrete.

The setting and hardening processes duration is optimum for the energetic capacity of these motes (1 month aprox.), allowing to monitor the setting process using the velocity measurement and adding humidity and temperature sensors. Multi-hop data transmission techniques were used to monitor the velocity data. Power consumption has also been considered, since this parameter affects the life duration of a WSN.

The WSN proposed was tested experimentally using several motes in the laboratory and in a precast concrete company. The first preliminary results are promising.

2. Introduction

In the 90's research and development of WSN technology with embedded sensors to monitor structures were initiated (Structural Health Monitoring, SHM). SHM refers to sensors,

instrumentation and methods for "in situ" monitoring of the integrity of critical structures such as airplanes, bridges and buildings. Long term analysis was required to distinguish between the effects produced by external factors and those induced by intrinsic degradation of the structure [2].
Numerous publications were dedicated to study WSN for evaluation of the structural integrity [3-4]. Promising results on the sensorization of different structures were obtained but more work is required to improve its reliability for use in the structure evaluation. An exhaustive analysis in the literature about WSN for being use in the monitoring of structures can be found in [5]. Nowadays commercial wireless systems are increasing its capacity of storage and processing while decreasing its power consumption. But due to the complexity of the proposed application, they are still limited in some aspects. It is still necessary to continue research on some important aspects such us the reliability of communications, the operative system, the network topology, the processing load distribution, the temporal synchronization, the strategies of use, the possibility of using alternative energy systems, efficient algorithms for extracting the sensorial information, etc. All these aspects are essential to construct efficient, reliable, and easy to maintain monitoring systems.
This paper presents a wireless sensor system which can be used to monitor the setting and hardening processes of cementitious materials. "The setting and hardening processes of concrete is considered to be the most critical time period during the life of a concrete structure"[6]. The advantage of using low cost commercial platforms to monitor these processes is that the most interesting part occurs during the first 72 hours. Therefore the energetic needs are limited. The parameters selected are the temperature and humidity inside and outside the cementitious material, and the ultrasonic velocity through the material. In the literature many works have studied the use of the ultrasonic velocity in the monitoring of theses processes and its relationship with the temperature and the humidity measurements [7-9]. Ultrasonic SHM methods are appealing because they offer the possibility of interrogating a large material volume using a small number of sensors. The objective of this work is to test the viability and robustness of these systems in a real environment as in a precast company.
This paper is organized as follows. Section 3 describes the wireless sensor system employed. The hardware platform used is based on two different commercial wireless sensor devices, Micaz and Cricket motes. These motes have been adapted to study the setting and hardening processes of cementitious materials. Some existing routing protocols have been used for the Micaz motes and a simple algorithm has been implemented for the Cricket motes. The importance of power consumption in this kind of networks is also explained. Section 4 and 5 gather some experiments performed in the laboratory and in a precast concrete company. The results obtained show that the system can be used in a real environment to monitor the setting and hardening processes of cementitiuos materials. Finally, section 6 contains the conclusions and draws some guidelines for future research.

3. The wireless sensor system

In this section the wireless sensor system developed by the authors is described. The system is based on commercial devices which have been adapted to study the setting and hardening processes of cementitious materials.

3.1. Hardware platform

The hardware platform presented here is composed of two WSN using Berkeley Micaz connected to a sensor and data acquisition board, MDA100, and Cricket motes. Programs for motes are written in NesC (an object-oriented extension of C) and run under the TinyOS operating system [10].
These motes were purchased from Crossbow Technologies [1]. This platform was selected mainly because it is an open source wireless sensor platform with open access hardware and software designs.
Two different WSN were used to test which network is more suitable in a real environment where external factors can affect the communications. Cricket motes are provided with ultrasonic sensors but they run under an old and unsupported version of the TinyOS-1.x operative system. Instead,

Micaz motes do not have ultrasonic sensors but they run under the new version of the TinyOS-2.x operative system which supplies routing protocols and efficient algorithms for power save. Therefore, ultrasonic measurements are computed with Cricket motes but temperature and humidity are calculated with Micaz motes.

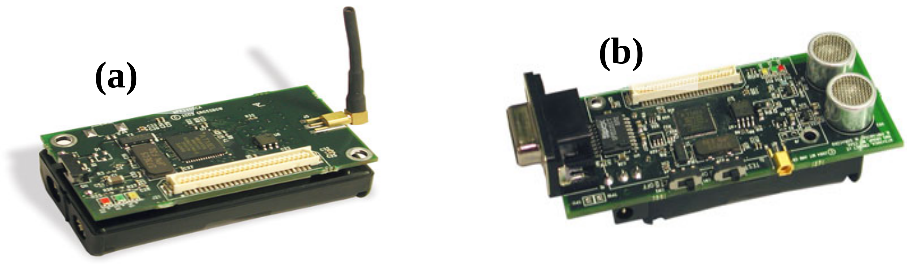

Figure 1. (a) Micaz mote (b) Cricket mote

To measure the temperature and humidity inside the material, 4 SHT75 sensors purchased by Sensirion were adapted using protective vents supplied freely by the GORE™ company.
Cricket mote modules can be configured as both listeners and beacons. Beacons are placed throughout a building or facility and transmit concurrent RF and ultrasound pulses. These devices were adapted for inspection of concrete structures. First they were transformed to be configured as base station or as listeners and beacons at the same time, called base station and mixed mode respectively. The base station mode is used to configure the mote, which is attached to a host using a serial cable. Its task is to listen for new messages and to send them to the host device. The host device (to which the listener is attached) must run software to process the data obtained from the base station. On the mixed mode the ultrasonic pulses propagated through the test piece are received on the reverse side of the same mote. Second, the ultrasound transducers were extracted from the motes to be placed on the material surface. Third, the software was adapted to be able to transmit the ultrasonic pulse through the material.
Cricket motes are composed of a command interface to configure and read various parameters. The command interface is accessible using standard utilities like HyperTerminal or minicom. These utilities have been adapted to send commands or files to Cricket motes to change the mode (listener, beacon, base station, mixed), the number of pulse cycles, frequency and gain of the ultrasonic pulse, the number of motes, the waiting time for the next ultrasonic shot and the number of shots. It is possible to select the number of consecutive ultrasonic shots that we want to carry out before sending the velocity data. The final ultrasonic data sent to every mote is computed determining the median between every velocity data obtained on each ultrasonic shot.

3.2. Routing algorithms

The routing algorithms used in this system are different for each network.

3.2.1 Micaz network

The TinyOS-2.x operative system provided a well tested routing protocol called collection tree protocol (CTP). CTP is a tree-based collection protocol. Some number of nodes in a network advertises themselves as tree roots. Nodes form a set of routing trees to these roots. CTP is address-free in that a node does not send a packet to a particular root; instead, it implicitly chooses a root by choosing a next hop. Nodes generate routes to roots using a routing gradient [11].
The CTP was tested in our laboratory with 4 Micaz motes and almost 100% of the messages were received.

3.2.2 Cricket network

Cricket motes run under the TinyOS-1.x operative system. This system supplies different libraries for routing protocols, Route, MintRoute, etc. These algorithms were tested but they did not work properly and many messages were lost because the processing load to generate and to measure the

ultrasonic signal was too high. Due to this fact and since this version of the operative system was unsupported, a simple algorithm was implemented by the authors for the Cricket network.
The algorithm is based on the fact that the motes are sorted by its identifier number (id). When a mote is programmed, it is provided with an id. Usually the 0 id is used for the base station. The closer a mote is from the base the lower is its id. These ids must be in sequential order. The mote with the highest id, id_1, starts the process and every fixed number of seconds sends and receives an ultrasonic pulse. The velocity data of this pulse through the material is sent to the motes with id lower than id_1. When these motes receive the velocity data, they send this data to all motes with id lower than its id. If, in addition, the mote with id id_1-1 receives this message it starts the ultrasonic process and sends the velocity information to all motes with id lower than its id.
It should be noted that our main interest was to test if these systems can be used in a real environment. Therefore, a lineal routing algorithm was implemented for this particular case.
This algorithm was tested in our laboratory with 4 Cricket motes and more than 90% of the messages were received.

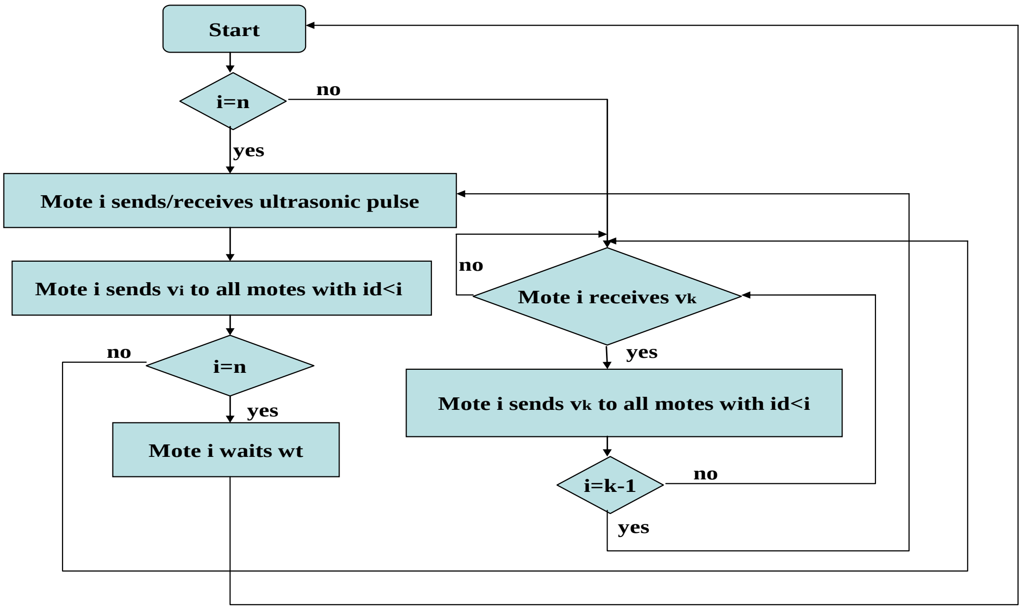

Figure 2. Algorithm scheme implemented in the Cricket motes. The variable n is the total number of motes, v_i is the ultrasonic velocity computed by mote i and wt is the waiting time to start the process again.

3.3 Power supply

Power efficiency is a vital factor in software for systems built around battery powered wireless sensor platforms. Not only must sensor system software operate correctly, it must also be structured to conserve battery power to be able to operate on relatively small batteries (e.g., AA) from six months to a year or beyond.
Asynchronous low power listening (LPL) is a strategy provided by TinyOS-2.x used to duty cycle the radio while ensuring reliable message delivery [12]. The LPL library is used for Micaz motes and they consume only a few µA when they are sleeping.
The TinyOS-1.x operative system provides a method to decrease power consumption. This method was tested by us on Cricket motes but it did not lower the consumption. Because the TinyOS-1.x is not longer supported by the company, we could only reduce power consumption to 2-3 mA by switching off the radio after they have sent the ultrasonic velocity.
In the experiments reported here power supply was not taken into account. The main purpose of this work was to test if these systems can be used in a real environment to study the setting and hardening processes of cementititous materials, and we were only interested in the first 72 hours.

4 Experimental

Several tests were performed in our laboratory and the results were very promising. The authors decided to test these networks in a real environment. In this section the setup used in the laboratory experiments and in the precast company are presented.

4.1 Laboratory setup

The system described above was first tested in our laboratory. For that purpose, several test specimens of 0.15x0.15x0.15 m size were constructed using the same type and quantities of cement and aggregates as the one used in the precast company "Hermanos Gadea".

The experiment was based on two different sensor networks, one for temperature and humidity measurements and a second one for ultrasonic measurements. These networks were composed of several Micaz and Cricket motes respectively. For each network one mote was configured as a base station and the remaining motes were sensorized.

4.2 Real environment setup

Our main interest was to test if these systems can be used in a real environment where the material is exposed to external factors, such as noise, vibrations, weather conditions, etc. The "Hermanos Gadea" precast concrete company from Paterna (Valencia) gave us the possibility to test this system in two 2x2x3 m concrete catch basins, one of them with CII cement and the other with CI sulphur-resistant cement [13].

To construct these catch basins the operators proceed as follows: they make the catch basins using cement and they expose the basins to vibrations for compacting. After that, they cover them with a transparent film during 24 hours to preserve temperature and humidity. Finally they move the catch basins to a different place to cure for 28 days.

The experiment was also based on two different sensor networks, one for temperature and humidity measurements (WTH) and a second one for ultrasonic measurements (WUS). These networks were composed of 5 Micaz and 5 Cricket motes respectively. For each network one mote was configured as a base station connected to a laptop, one was used as repeater and the remaining motes were sensorized. The WTH sensorized motes were equipped with three different temperature and humidity sensors, two of them monitoring the interior data of the material and a third one monitoring the ambient temperature and humidity. The WUS sensorized motes were configured with 2 transducers of 50 kHz each, as transmitter and receiver, and the measurement of the ultrasonic velocity was computed. For that purpose, 5 consecutive ultrasonic burst pulses with a frequency of 40 kHz and gain of 70 dB were transmitted and received. The median of these values was computed every 2 minutes. They also provided the information of the ambient temperature.

A system was designed to place the WTH and the WUS motes on the material's surface. Each WTH and each WUS were placed together to obtain the temperature, humidity and ultrasonic information for the same area. The transducers were coupled to the concrete material using a clamp and a coupling liquid.

Two of these systems, WTH2/WUS2 and WTH3/WUS3, were placed in the CII catch basin and another system in the CI sulphur-resistant catch basin, WTH4/WUS4. The WTH2/WUS2 and WTH3/WUS3 systems were placed in two opposite faces of the same catch basin. The transparent film was removed from the face where the WTH2/WUS2 was located and this system was exposed to sunlight.

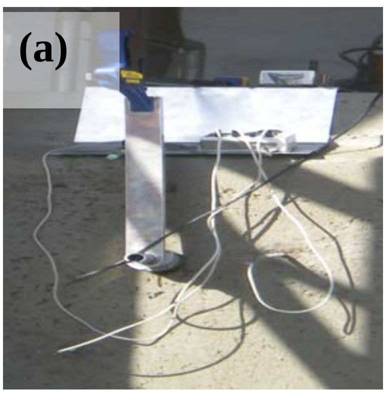

Figure 3. (a) System with WTH2/WUS2 motes displayed on the catch basin. (b) WTH3/WUS3 and WTH4/WUS4 motes displayed on the CII and CI sulphur-resistant catch basins respectively.

5 Experimental results

In this section the results obtained in the laboratory and those obtained in a real environment, a precast concrete company, are presented.

5.1 Experimental results obtained in the laboratory

Some experiments were performed in the laboratory. The temperature and humidity results corresponding to the concrete interior and the ambient measurements are shown in Fig. 4 for WTH mote 1 and 2. Probably the temperature values did not increase very much for WTH mote 1 because the transparent film was removed from the specimen after the first 5 hours. Therefore, the concrete interior was not thermally isolated.

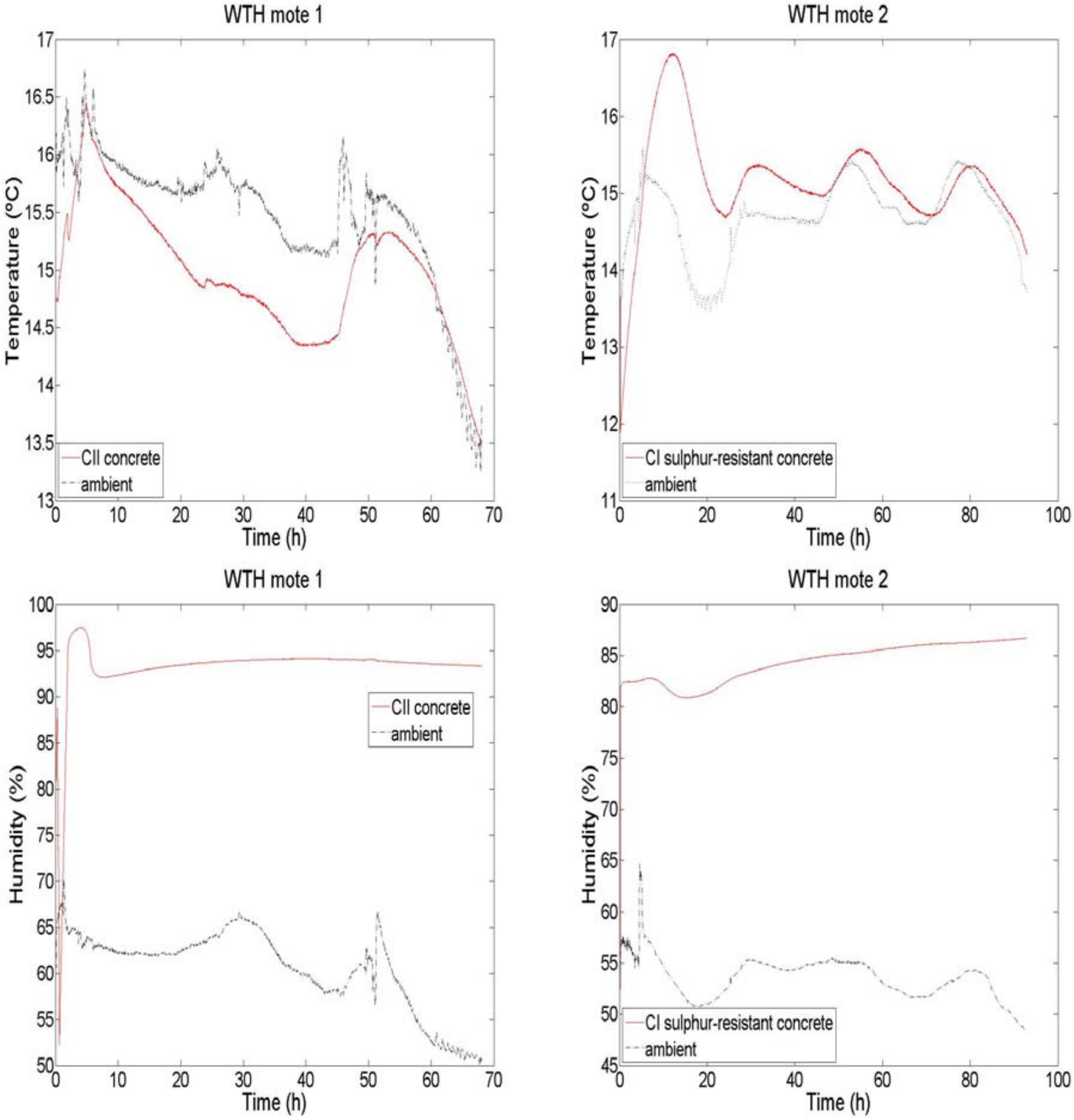

Figure 4. Temperature and humidity measurements obtained by WTH motes 1 and 2 corresponding to the concrete interior and the ambient temperature and humidity. WTH mote 1 was measuring the CII concrete specimen with the transparent film covering the specimen during the first 5 hours. After that time, the transparent film was removed. WTH mote 2 was measuring the CI sulphur-resistant concrete specimen with the transparent film covering the specimen.

The ultrasonic velocity values measured by the WUS motes are presented in Fig. 5. The velocity profile is characteristic of the setting and hardening processes, in agreement with previously published data [14].

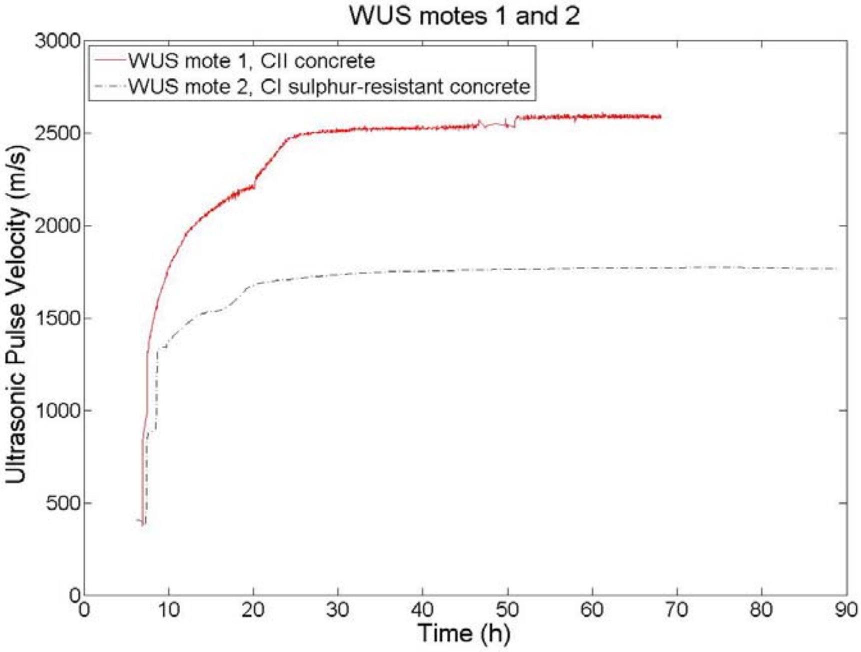

Figure 5. Ultrasonic pulse velocity obtained by the WUS mote 1 and 2 in the CII and CI sulphur-resistant concrete specimens respectively.

5.2 Experimental results obtained in a precast concrete company

The experiment performed in the precast concrete company lasted 3 days. After 24 hours the basins were moved to a different place to be cured. The base stations attached to the laptop were moved accordingly to be in the covered range of the motes.

The WTH network worked well for 24 hours, until the basins were moved. After that, the WTH base station stopped working for two hours. Once this problem was fixed, the network operated properly. All sensors functioned as expected except sensors 1 and 3 from mote 4. Probably they got wet.

Despite the high external noise and vibrations typical of a concrete company, the WUS network sent and received signals normally. There was, however, a problem with the coupling system of the transducers and with the coupling liquid used. Because of that problem, after 4 hours only mote 3 started to receive the ultrasonic pulse. But after moving the basins the signal got lost because the transducers were displaced. The signal was recovered but it was just for a few hours.

In general, it was observed that the WUS network was more stable than the WTH network. At the beginning of the experiment we got some problems with the radio communication channel of the WTH motes. The covered range was lower with the WTH than with the WUS network. We therefore decided to add a repeater. It was realized that the working conditions at the company affect the radio channel of the WTH network much more than the one of the WUS network.

Fig. 6 shows the temperature and humidity results obtained with each sensor by WTH mote 2 and 3. The processes of setting and hardening are clearly identified [15]. Probably the temperature values measured by mote 2 did not increase very much because the basin was without the transparent film and the temperature was not so well preserved as WTH mote 3. Fig. 6 also shows the humidity results obtained by each mote compared to ambient humidity. As expected, the humidity in the fresh catch basin is close to 100%.

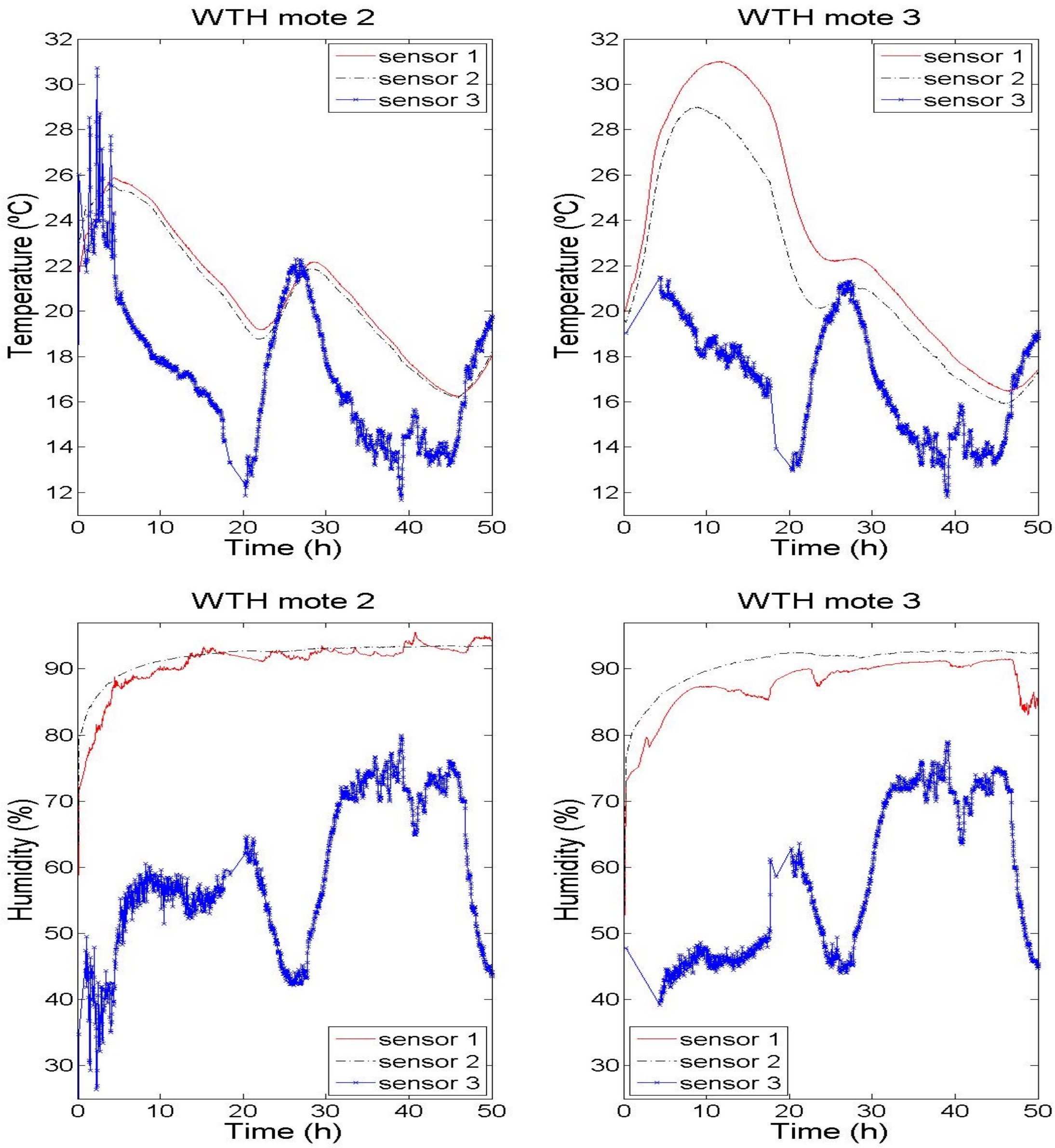

Figure 6. Temperature and humidity measurements obtained by WTH motes 2 and 3 during the setting and hardening processes. Sensor 1 and 2 were inside the basin while sensor 3 was measuring the ambient temperature and humidity outside the basin. During the first 6 hours WTH mote 2 was exposed to sunlight. WTH mote 3 was measuring a basin covered with a transparent film during the first 24 hours.

The loss of messages due to obstacles presented in the covered range and multiple reflections in this kind of systems should be taken into account. The percentage of received messages by the WTH base station using the CTP protocol implemented in TinyOS-2.x is: 30.73% from WTH mote 1, 99.82% from WTH mote 2, 99.64% from WTH mote 3, and 100% from WTH mote 4. WTH mote 1, the repeater, was not in the covered range of any other mote after the basin was moved. That explains the low rate of 30.73% for mote 1.

The ultrasonic velocity values measured by WUS mote 3 are presented in Fig. 7. The data obtained corresponds to the first 16 hours. After this time, the operators moved the catch basin to a different place for curing. As a consequence of this movement, this mote stopped working. The velocity profile is characteristic of the setting and hardening processes, in agreement with previously published data [14].

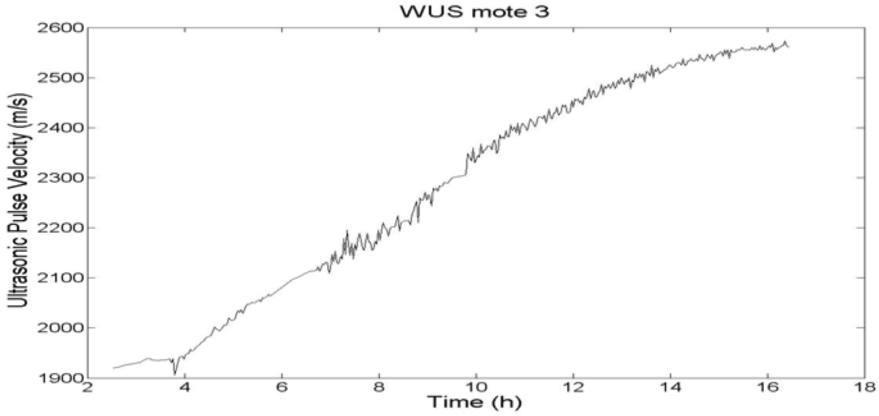

Figure 7. Ultrasonic pulse velocity obtained by mote 3 during the first 16 hours.

The percentage of received messages by the WUS base station using the algorithm explained before is: 96.99% from WUS mote 1, 98.37% from WUS mote 2, 99.30% from WUS mote 3, and 99.79% from WUS mote 4. As expected, it was found that the number of lost messages per mote decreases following the sequence WUS mote 1 → WUS mote 2 → WUS mote 3 → WUS mote 4. This is a consequence of the way the algorithm is constructed. The message created by mote 1 is sent directly to the base station, but the message created by WUS motes 2, 3 and 4 is sent directly to the base station, and, in addition, it is sent to the base station through other motes with a lower identifier. For instance, the message created by WUS mote 4 is sent to the base station directly and also through WUS motes 3, 2 and 1. Therefore, the possibility that a message created by WUS mote 4 is lost is lower than for any other mote.

6 Conclusions

The objective of this work was to design and to test a wireless sensor system to monitor the setting and hardening processes of cementitious materials. The system was based on two WSN composed of commercial devices called Micaz (WTH) and Cricket motes (WUS) for each network respectively. The WTH network was in charge of the temperature and humidity measurements inside and outside the material. The WUS network was responsible for the ultrasonic velocity measurements. Two different WSN were used to test which network is more suitable in a real environment where external factors can affect the communications. Cricket motes are designed for indoor location systems. Because they have an ultrasound transmitter/receiver for time of flight ranging, we adapted them by reprogramming the application for inspection of concrete structures. A through transmission method was used to compute the velocity of the ultrasonic signal in concrete.

The system presented above was tested in a precast concrete company and in the laboratory. In both scenarios, we faced some problems with the WUS network. But these problems are not intrinsic to the WUS network, they were related to external aspects as the coupling system and they can be solved easily. We showed that both networks operated well in the laboratory. In a real environment, the precast concrete company, it was also observed that the WUS network was more stable than the WTH network. At the beginning of the experiment we got some problems with the radio communication channel of the WTH motes. The covered range was lower with the WTH than with the WUS network. It was realized that the working conditions at the company affect the radio channel of the WTH network much more than the one of the WUS network.

The results obtained showed clearly the different phases presented at early stages of the concrete. Therefore this system was suitable for being used to monitor the setting and hardening processes of cementitious materials.

In the future, it will be interesting to update the WUS motes using the new version of the TinyOS-2.x operative system. Then, only one WSN composed of WUS motes would be necessary. For that purpose, the routing protocol CTP could be used.

This system would be improved considering power save algorithms for use of long term applications of several months duration.

7 Acknowledgments

Support from the Spanish Science and Innovation Ministry, through research projects BIA2009-14395-C04-01 and BIA2006-15188-C03-01, and from the Spanish Ministry of Public Works, through research project C01/2007, is greatly acknowledged.
The authors wish to thank the “Hermanos Gadea” precast concrete company from Paterna (Valencia) for their help on testing the wireless sensor system. We are grateful to the "GORE™” company for kindly providing free adhesive protective vents. Dra. S. Aparicio was financed by the postdoctoral JAE-Doc program of the Spanish National Research Council (CSIC). Dr. M. Molero was supported by the department of education of the Community of Madrid and the European Social Fund. Dr. I. Segura was financed by the postdoctoral Torres Quevedo program of the European Social Fund.

References

[1] Crossbow Technology. http://www.xbow.com/
[2] Phares, B.M., Wipf, T.J., Greimann, L.F. and Lee, Y.S., Health Monitoring of Bridge Structures and Components Using Smart Structure Technology, Wisconsin Highway Research Program Project #0092-01-14, 257 pp, 2005.
[3] Santana-Sosa, H., Zao-Bello, S., Pérez-Álvarez, I., Raos, I., Mendieta-Otero, E., López-Pérez, J., Validation of a HF Spread Spectrum MultiCarrier Technology through real Link Measurements. European Transactions on Telecommunications (ETT). Vol 17, No.6, pp. 651-657, 2006.
[4] Grosse, C.U. and Krüger, M., Inspection and Monitoring of Structures in Civil Engineering. NDT.net, Vol. 11, No. 1, 2006.
[5] Lynch, J.P. and Loh, K.J., A Summary Review of Wireless Sensors and Sensors Networks for Structural Health Monitoring. The Shock and Vibration Digest, Vol. 38, No. 2, pp. 91-126, 2006.
[6] Voight, T., Shan S. P., Nondestructive Monitoring of Setting and Hardening of Portland Cement Mortar with Sonic Methods, Proceedings of the Sixth International Symposioum on Non-Destructive Testing in Civil Engineering 2003, Berlin, Germany, 2003.
[7] Robeyst, N., Gruyaert, E., Grosse, C.U., De Belie, N., Monitoring the setting of concrete containing balst-furnace slag by measuring the ultrasonic p-wave velocity,Cement and Concrete Research, 38(10), pp. 1169.1176, 2008.
[8] Öztürk, T., Kroggel, O., Grübl, P., Popovics, J.S., Improved ultrasonic wave reflection technique to monitor the setting of cement-based materials, NDT & E International, Volume 39, Issue 4, Pages 258-263, 2006.
[9] Del Río, L.M., Jiménez, A., López, F. Rosa, F.J., Rufo, M.M., Paniagua, J.M., Characterization and hardening of concrete with ultrasonic testing, Ultrasonics, Volume 42, Issues 1-9, Pages 527-530, 2004.
[10] TinyOS Community. http://www.tinyos.net/
[11] Fonseca, R., Gnawali, O., Jamieson, K. and Levis, P. Collection tree protocol. http://www.tinyos.net/tinyos-2.x/doc/html/tep119.html.
[12] Moss, D., Hui, J. and Klues, K., Low Power Listening. http://www.tinyos.net/tinyos-2.x/doc/html/tep105.html
[13] Hermanos Gadea company. http://www.gadeahermanos.es/
[14] Zhang, Y., Zhang, W., She, W., Ma, L. and Zhu, W., Ultrasound monitoring of setting and hardening process of ultra-high performance cementitious materials, NDT&E Int, doi:10.1016/j.ndteint.2009.10.006, 2009.
[15] Carino, N-J., The maturity method: theory and application. Cement, Concrete and Aggregates Vol. 6, No. 2, pp. 61-73, 1984.