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PASSIVE WIRELESS SENSOR SYSTEM FOR CONCRETE MATURITY MONITORING

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Abstract

Determination of strength in curing concrete is a crucial requirement for quality assurance in industrial construction projects. ASR&D is currently developing a wireless concrete maturity and post-cure thermal history monitoring system utilizing passive surface acoustic wave temperature sensors. These novel sensors use energy contained in an interrogating RF signal to activate the sensor, measure the temperature, and radiate a device identification and temperature measurement response back to the receiver. This response can be used to implement a well-known non-destructive method for determining the strength of curing concrete called the "Maturity Method".

The embedded portion of the system consists solely of the SAW sensors with antennae, providing a small, rugged, low cost alternative to existing maturity monitoring systems. These devices require no batteries, can operate at extreme temperatures, and have almost unlimited lifetimes. Thus, these sensors can provide post-cure thermal history monitoring of the structure, data critical for thermal stress analysis.

The system under development will provide structural engineers with a non-destructive method to automatically and cost-effectively monitor (in-situ) the thermal history and strength of curing concrete throughout a structure. This will allow construction to proceed as rapidly as possible while assuring safety through adequate quality assurance of the construction.

BACKGROUND

Determination of the strength of curing concrete is a crucial requirement for the quality assurance of many industrial construction projects. A non-destructive way to determine the in-situ concrete strength can provide significant advantages to construction schedules, while assuring safety through adequate quality assurance of the construction. Completion of projects on or ahead of schedule can result in significant fiscal benefits to contractors for major infrastructure projects.

Strength development in concrete is primarily controlled by two factors, time and temperature of hydration. In-situ strength measurements are the most relevant, as they provide information about the actual structure under construction, rather than relying on separate concrete test structures. Using typical technology, test specimens (cylinders or beams) are cast from the same batch of concrete that is used in the construction project. These test specimens then undergo a range of strength tests to determine their in-place strength as they cure. However, due to the potential difference in conditions between the placement of the test specimens and the structure, the thermal history of the test specimen can vary substantially from that of the structure under construction. This can lead to errors in strength estimations for the structure.

An alternative non-destructive method for determining the strength of curing concrete is called the Maturity Method. This method calculates the degree of cementious hydration that has occurred within the concrete mass (the “Maturity Index”), based on the actual thermal history of the concrete, and uses this value to predict strength based on comparisons to established strength-maturity relationships for the specific mix used. This is a well known method, and is based on the work of McIntosh [1], Nurse [2], and Saul [3]. The two principal methods for calculating the Maturity Index are the Nurse-Saul method and the Arrhenius method. The Maturity Method has been adopted as a standard approach to determining the strength of curing concrete in ASTM C 1074 [4,5]. Verification of the strength-maturity relationship is required per ASTM C 1074 prior to performing critical operations, such as removal of formwork or post-tensioning.

The Nurse-Saul Material Function provides the maturity index as a function of time [6]:

$$M(t) = \sum (T_a - T_0)\,\Delta t \qquad (1)$$

Where:

$M(t) =$ maturity index (as time-temperature factor) in ^{o}C-days or ^{o}C-hrs

$T_a =$ average temperature of concrete during each time interval

$T_0 =$ temperature below which cementious hydration is assumed to cease (datum temperature)

$\Delta t =$ time intervals (hours or days)

And $\sum$ represents a summation over all time intervals of interest (time since the pour) of the time-temperature product. The datum temperature is mix-specific, and is affected by numerous mix parameters, including water-to-cement ratio and admixtures. This parameter should be determined per ASTM C 1074 in order to obtain accurate strength estimations using the equation above.

An alternative method for calculating the maturity index is the Arrhenius method. This method takes into account the activation energy of the concrete, and calculates the maturity as an equivalent age as shown below [7].

$$M_A(t) = \sum_{t=0}^{t}\left[e^{-\frac{Ea}{R}\cdot\left(\frac{1}{T+273} - \frac{1}{T_r+273}\right)} \cdot \Delta t \right] \qquad (2)$$

Where:

$M_A(t) =$ maturity index, (as equivalent age) in days or hrs

$T =$ average temperature of concrete during each time interval (^{o}C)

$T_r =$ reference temperature (^oC)
$\Delta t =$ time intervals (hours or days)
$E_a =$ apparent activation energy (J/mole)
$R =$ universal gas constant (8.3144 J/mole/K)

Using either maturity index and pre-determined strength-maturity relationships established for the specific concrete mix, the mechanical strength of the concrete can be calculated.

Current techniques for measuring the in-situ temperature of concrete and implementing the maturity method for strength calculations involve embedding either wired temperature sensors or entire sensor/data logging systems in the wet concrete. In the simplest case of wired sensors, such as various types of thermocouples, the temperature data is tramsmitted in real time via wired connections from the temperature sensor to a datalogger outside the concrete surface. This data can then be manipulated and maturity and concrete strength calculated. Other current wired-sensor implementations utilize both a sensor and a data-logging system (battery, memory, and associated electronics) to take and store temperature data on the embedded sensor module, downloading the data via wired connection to a computer or external data logger as needed (personnel download stored data). These wired system implementations have the substantial drawback of fragile wires and connections that can be easily damaged in the construction environment. This can result in the need to remove sections of concrete to locate and re-connect to buried sensors if the wires are severed during the pour or thereafter. Currently available wireless maturity monitors consist of a temperature sensor, microprocessor, memory, associated electronics, antenna, and battery manufactured within a ruggedized case. This unit can be attached to rebar or other structures prior to the pour, and can then be used to monitor temperature. These systems log temperature data, and store data regarding the concrete mix so that maturity method calculations can be performed. They utilize RF communications to transmit this data to the surface, either to a specially equipped PC or to a hand-held data collection and evaluation device. These systems are generally capable of providing raw temperature data as well as processed maturity information. They are capable of operating relatively near the surface of the concrete (through up to about 8” of concrete) without external antennae, and their range can be extended by utilizing external antennas connected to the embedded system by cables. This approach, placing the antenna end of the cable near or at the surface of the pour, can extend their operating range to several feet of concrete. The range of the interrogation systems used to download data from these embedded systems varies. The operational system lifetime is generally more than sufficient to cover the normal curing time for concrete structures, but the battery will eventually run down and no further information can be gained from these systems. The cost of such embedded sensor systems (which are considered disposable, as they cannot be recovered after use) is relatively high, due to the expensive components (battery, microprocessor, memory, etc) used. These systems are also fairly large (often bars that are several inches long by an inch or so in each other direction).

DESCRIPTION OF PASSIVE WIRELESS MATURITY MONITOR

ASR&D is currently working with strategic industrial partners to develop a wireless concrete maturity monitor product based on passive surface acoustic wave (SAW) temperature sensor technology. This system utilizes multiple, uniquely identifiable wireless temperature sensors that are completely passive. These sensors use the energy contained in a radio frequency (RF) interrogation signal to activate the sensor, measure the desired parameter (in this case temperature), and radiate a device response back to the receiver. The system operates using spread spectrum communications, allowing for enhanced range through the concrete relative to standard RF communications techniques. The simplicity of these devices allows for the embedded portion of the sensor system to consist solely of SAW temperature sensors with attached antennae. These sensors can be substantially smaller and less expensive than current embedded systems, while providing similar temperature data. Also, since they are not dependent on a battery for operation, these sensors have essentially unlimited lifetimes (such devices used in military and communication systems have been demonstrated to last over 30 years). The low cost and small size of these sensors combined with their inherent ruggedness will allow structural engineers to monitor the thermal history of the curing concrete in numerous locations throughout a structure. It is possible for hundreds of these sensors (or more) to be distributed throughout a volume to be monitored, and for monitoring to occur automatically using the proposed interrogation system. This will provide the data necessary for the engineer to visualize what is happening within the structure as it cures. This interrogation system can then report when desired strength has been achieved in particular portions of the structure, or it can alarm or contact a job engineer/supervisor if the temperature is close to a level of concern.

A number of SAW temperature sensor devices are well-known. SAW reflective delay lines have been used as tag (ID) devices for years, and have also been used as sensors [8]. SAW differential delay line temperature sensors have recently been demonstrated [9], including those using a novel coding known as Orthogonal Frequency Coding (OFC) [10, 11]. OFC, which is a spread spectrum approach, has the advantage of increased processing gain relative to ordinary approaches. This allows for improved accuracy and increased sensor detection range.

ASR&D and a team of researchers led by Dr. Donald C. Malocha at the University of Central Florida, Orlando, FL (UCF) have been actively collaborating on development of OFC SAW sensors for a range of applications under NASA-funded small business technology transfer for research (STTR) contracts (NNK04OA28C, NNK05OB31C, NNK06OM23C and NNK06OM24C). As part of these NASA programs, a demonstration was conducted wherein OFC SAW temperature sensors were used to wirelessly measure the temperature of curing concrete. ASR&D is also working with a strategic industrial partner to complete product development efforts.

The SAW temperature sensors demonstrated utilize an ultra-wideband (UWB) spread spectrum coding technique known as orthogonal frequency coding (OFC) invented at UCF. The theory behind these sensors and details of implementation are provided in references [10] and [11]. Basically, OFC uses a set of "chips" that are sequential rectangular pulses in time, each with a different carrier frequency, to generate the code on a given device. The ordering of these chips determines the code. The frequencies and bandwidths of each chip are selected in such a fashion that they meet orthogonality conditions, a feature necessary to minimize interactions between adjacent chips. OFC waveforms can be implemented in a straightforward manner in SAW devices using a wideband transducer attached to the antenna for RF signal reception and regeneration, and shorted reflector grating sections with different periodicities to effect the generation of the orthogonal chip responses. In practice, a differential delay line configuration such as that shown in Figure 1 below would be used. This device structure utilizes two sets of reflector gratings, mirror imaged about the centre of the device, and offset from the input transducer by different distances. When an RF signal is incident on the antenna, an acoustic wave is generated in the central transducer, and propagates outward in both directions. The wave will reach the reflector bank on the right of the device first, and each chip will reflect back that portion of the broadband wave that corresponds to the chip carrier frequency.

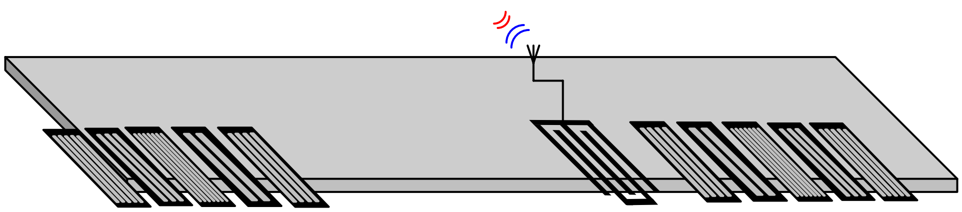

Figure 1. SAW differential delay line implementation of OFC temperature sensor.

Once this entire reflected signal has been received by the central transducer, the left-propagating wave will begin to reflect from the left reflector bank, producing a second response signal incident on the central transducer. Once these two response signals reach the central transducer, they are converted from mechanical back into electrical signals, and are transmitted via the antenna back to the interrogating system.

The response received by the transceiver will consist of two sets of chips in the time domain, separated by a delay. An example of such a response from one of the temperature sensors developed at UCF is shown in Figure 2 below [11]. This figure also shows a comparison between theory and experiment for this device.

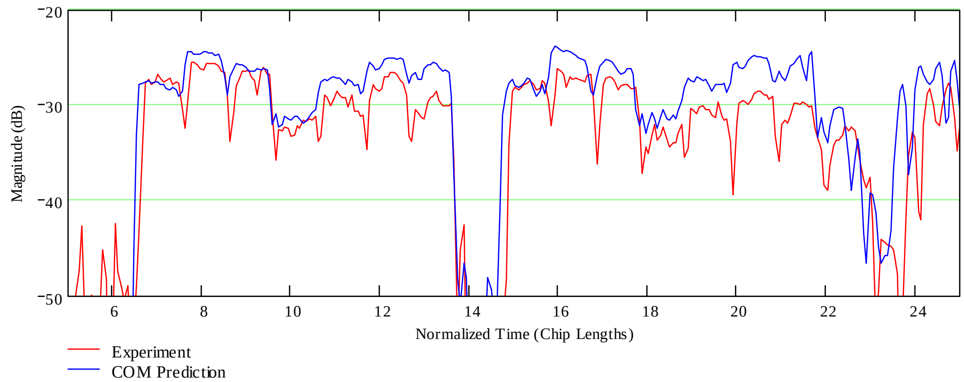

Figure 2. Time domain response of diferential delay line OFC device [11].

This response is correlated with a set of possible (known) codes in the transceiver, producing a signal composed of two compressed pulses (see Figure 3 below). The differential time delay between these compressed pulses provides a measure of the sensed temperature. The differential nature of this measurement eliminates all common-path variations, resulting in a measurement of temperature at the sensor that is only a function of the difference between the offset of the left reflector bank relative to the central transducer and the offset of the right reflector bank relative to the central transducer. Thus, any change in propagation delay due to sensor device location, multipath, and related effects do not impact the accuracy of the temperature measurement.

Preliminary SAW temperature sensor results are shown in Figure 4 [11]. This plot compares the OFC sensor with thermocouple measurements. The measurements were conducted using an RF probe station and a temperature-controlled chuck. The device was tested between 15°C and 50°C in 2.5°C increments. This data shows good correlation with thermocouple measurement. Wireless interrogation of these sensors while submerged in curing concrete was demonstrated in the laboratory using a network analyzer as an interrogating system.

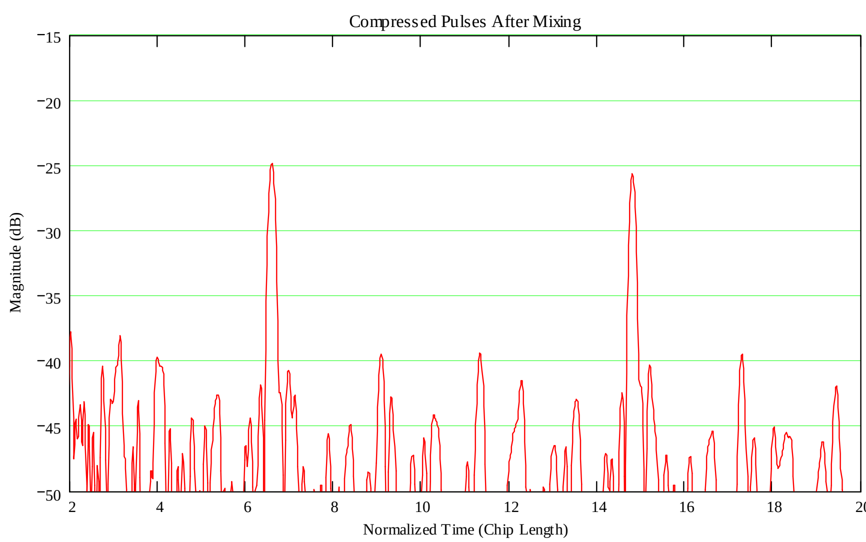

Figure 3. Compressed pulses formed from the response of a diferential delay line OFC device [11].

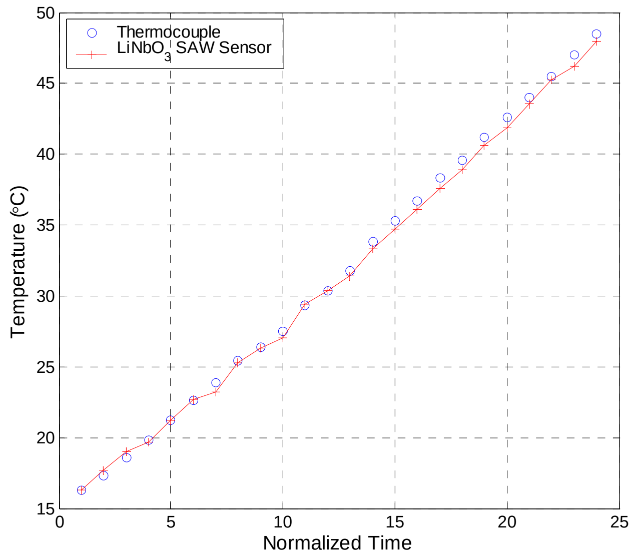

Figure 4. OFC SAW temperature sensor tested between 15°C and 50°C and compared to thermocouple measurements [11].

The change in concrete temperature during cure was successfully recorded. A commercially-available wireless maturity monitoring system from International Road Dynamics (IRD) was used to obtain comparative data, and the sensor measurements were in good agreement with the monitor measurements. However, due to the small volume of concrete under test and the lack of insulation, the rise in temperature during cure was quite small (less than 10°C). Tests will need to be conducted with larger volumes of concrete in order to observe sensor device performance over a temperature range more characteristic of real-world applications.

Recent work has involved development of an IC-based interrogation system for use with these sensors, which will be ready for demonstration in March of 2007. ASR&D is actively seeking partners interested in evaluating this technology in a realistic application environment. Consortia, governmental, academic, infrastructure contractors, and concrete industry participants potentially interested in providing beta-test sites for this new technology are sought.

CONCLUSIONS

This paper summarizes work to date on a novel spread spectrum acoustic wave temperature sensor and its application to concrete maturity monitoring. These devices have been demonstrated to provide accuracy similar to standard thermocouple measurement techniques, and wireless interrogation of the devices while embedded in curing concrete has been confirmed. The unique coding of these devices enables unique sensor operation and identification in multi-sensor environments. The spread spectrum nature of the wireless communication scheme makes this system inherently secure, along with providing added processing gain for enhanced range. ASR&D and industrial partners are currently developing a concrete maturity monitoring product based on these sensors, which will be available for field testing and initial release in early 2009. These sensors will be approximately one order of magnitude less expensive than current wireless concrete monitor “tags”, with interrogation systems that are competitive in cost to current commercially-available systems. Availability of inexpensive monitors such as those being developed by ASR&D will allow structural engineers to monitor more locations within a structure, in-situ and in real time, thereby obtaining a clear picture of the actual strength of concrete throughout the pour. This enhanced understanding will enable engineers to ensure that adequate strength is achieved prior to removing forms, post-tensioning, and other critical steps.

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