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Embedded Sensors for Life-Time Monitoring of Concrete

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Concrete strength is depends on a number of factors. The initial strength and the service life of concrete used in structures (especially highway-related structures) are significantly affected by the temperature development and moisture content from the time that it is placed onwards.

A sensor that could detect moisture and temperature of the concrete, pH, and the concentration of chloride, sodium and potassium ions in concrete pore solution would provide critical data for evaluating concrete performance starting with the initial quality control period of freshly mixed or freshly cast concrete, through its useful service life, to the period of deterioration and repair. Such a multi-functional sensor can be so pervasively useful because moisture and temperature are the primary drivers for the hydration of Portland cement, and are essential factors in the most prevalent deteriorative processes such as damage due to freezing and thawing, alkali-aggregate reaction, sulfate attack or delayed Ettringite formation. Furthermore, one of the most devastating yet most common forms of concrete degradation is corrosion of embedded reinforcing steel, which is driven by moisture, temperature, and chloride concentration.

Finally, alkali-silica reaction induces serious cracking and expansion distress in concert when high pH pore solutions are developed in contact with reactive silica or siliceous aggregate components in moist environment.

In this paper preliminary measurement data obtained from prototype sensor and research that is planned will be presented. This work is a joint effort between Advanced Design Consulting a small engineering company, Kenneth C. Hover, P.E., and Federal Highway Administration Department.

Keywords: Sensor, Concrete, Moisture, Temperature, Monitor, Pavement.

Embedded Sensors for Life-Time Monitoring of Concrete

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ABSTRACT: Concrete strength is depends on a number of factors. The initial strength and the service life of concrete used in structures (especially highway-related structures) are significantly affected by the temperature development and moisture content from the time that it is placed onwards.

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1 PROJECT BACKGROUND

An important focus of Federal Highway Administration's vision of the future is long-life pavements and structures. Improved performance of pavements and structures will occur in part through improved quality control of materials and construction. Technology innovations in production, transport, placement, real-time quality control, and automation have been introduced over the years. Significant research has been implemented to address real-time quality control. The real-time quality control provides project field personnel the necessary information to make timely corrections/adjustments and reduce materials and construction variability.

The Advance Design Consultant USA Inc. (ADC) under contract with FHWA completed research study to determine the feasibility of using passive sensors embedded in concrete to measure moisture, temperature, pH and concentration of chloride. Motoring properties of concrete structures will provide critical data for evaluating concrete performance starting with the initial quality control period of freshly mixed or freshly cast concrete, through its useful service life, to the period of deterioration and repair. Data obtained from these sensors will result in longer service life, lower infrastructure costs and the development of more effective means of remediation.

2 SUMMARY OF PROJECT OBJECTIVE

- Development the electronics of remote sensor device.
    - Intelligent micro-controller and electronics circuit board.
    - Develop and test a RFID communications system.
    - Select and integrate sensors modules into the system.
- Packaging. The selection the outer housing that will incase the electronics
- Test the performance of the system in measuring properties of concrete.

3 DEVELOPMENT THE ELECTRONICS OF REMOTE SENSOR DEVICE

3.1 Intelligent micro-controller and electronics circuit board

A printed circuit board (PCB) designed by ADC was attach to various sensors for monitoring environmental conditions. The brain of the PCB is the Microchip PIC18LF2420 microprocessor, which is an 8-bit controller that has a very low power drain idling mode with currents down to 5.8 μA typically. Initial testing of the PCB was conducted with an external battery for both the ease of testing to fully determine what sensors are going to be used.

3.2 Develop and test a RFID communications system

The system RFID interface is consists of a programmable RFID chip, a transmitter, and the sensors. When activated by a signal from the transmitter, the RFID chip will read the information from the sensors and relay this information back to the transmitter.

The Microchip RFID was used in the beginning, but was shifted to the integration of the MCRF450 chip to another commercial off shelf device created by Phidgets, Inc., called the PhidgetRFID 1023. The sensor components consist of temperature and humidity sensors were the first sensors integrated to the RFID system.

3.3 Select and integrate sensors modules into the system

3.3.1 Hydrogel/MEMS research and development

ADC has a patent pending technology for a capacitive pH sensor, which is based on a pH sensitive hydrogel. The critical requirement has been to identify a photo-imagable material that could serve as the flexible electrode, survive many of operating cycles, resist damage from the environment and be compatible with MEMs processing. SU-8 photoresist, first patented by IBM in 1989, was chosen for this purpose. SU-8 is chemically amplified, epoxy-based, and, negative resist. Structures having exceptionally high aspect ratios and straight sidewalls are readily formed in thick films by contact-proximity or projection printing. Cured SU-8 is highly resistant to solvents, acids and bases and has excellent thermal stability, making it well suited for applications in which cured structures are a permanent part of the device. It is also highly elastic, with yield strength of > 80 MPa, making it ideal for this application.

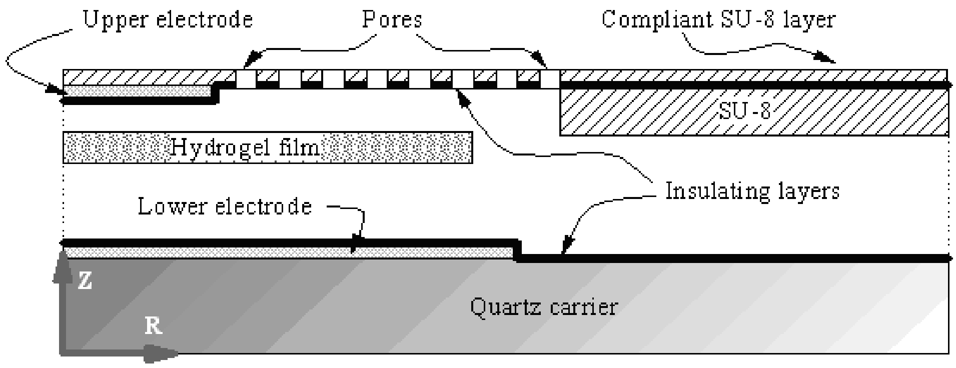

Figure 1: Schematic of a MEMs capacitor with pH sensitive hydrogel film modifying the capacitance

A schematic of the MEMs sensor is shown in Figure above. The device was designed to be built in three parts: a base consisting of an electrode permanently mounted on a quartz chip; a 2µm-thick hydrogel disk; and a perforated membrane of SU-8, with an electrode at its center and a ring of SU-8 beyond, forming the cavity into which the hydrogel would be placed. Experiments in the past have been conducted with parallel plate capacitors in order to study the swelling response of various hydrogels to temperature, pH and salinity. As the hydrogel swells, a change in capacitance occurs due to change in its dielectric constant and deflection of electrode. Tests were conducted with four hydrogels. After an initial rinse in DI water, a sensor can be immersed alternately in buffered solutions of pH 7 and 10 over several 24 hour periods. Capacitance can than be measured periodically. When a sensor is immersed in one of the buffered solutions, there is an immediate changes in capacitance due to the permittivity of the surrounding fluid, about 80 times that of air. A gradual change follows as the hydrogel absorbs or desorbs water over a period of about 24 hours. Two phenomena are at work simultaneously: (1) the permittivity of the hydrogel increases as water is absorbed, increasing the capacitance and (2) absorption of water causes a swelling that moves the electrodes further apart, decreasing the capacitance. If water is being desorbed the effects are the opposite of those described. When first placed in the buffered solution at pH 7 each sensor rapidly absorbed water, increasing its capacitance. All required more than 24 hours to stabilize, most likely due to the large dimensions, with Chitosan/PEG/PNIPAAm and PNIPAAm/PEGDA samples responding more rapidly. These two also provided the most sensitive and repeatable responses. The capacitance of the Chitosan sensor changed by about 15% while the PNIPAAm/PEGDA sample changed nearly 50%. For use with passive RF devices, where the change in capacitance is used to change the resonance frequency of the antenna network, either material would require additional capacitance in parallel to reduce the magnitude of the change.

Monitoring pH of concrete in the laboratory and field is important. Concrete is a porous material (typically about 40 percent of the volume of concrete is occupied (by pores) and, in saturated concrete, the pores contain a solution that includes dissolved alkali hydroxides (NaOH and KOH). The origin of the sodium (Na) and potassium (K) is, principally, the Portland cement

3.3.2 Temperature sensor selection

The Microchip TC1047 temperature sensor initially was examined for its accuracy. The TC1047 is a linear output voltage whose output is directly proportional to the temperature and fits into a small integrated circuit (IC) package. The drawback of this temperature IC is that unable to get it to a low enough accuracy point, ±1.0ºC over a span of 40ºC. The temperature sensor that was selected it has an accuracy of ±0.1ºC over a span of 40ºC with a focused measurement range of –10 to +60 ºC, based on manufacture recommendations. A thermocouple because of the low power and size will be the long term choice.

Concrete temperature monitoring has many advantages including early opening of pavements after construction is becoming a necessary strategy to minimize user costs during rehabilitation and reconstruction operations of congested streets and highways. As opening to traffic criteria rely primarily on the concrete strength gain. Maturity methods have been used extensively in recent years to predict the in-place strength of concrete. For example, HIPERPAV (HIgh PERformance concrete PAVing) is a concrete paving software product sponsored by the FHWA intended to serve as a tool in the proper selection and control of the factors affecting concrete pavement behavior at early ages. One of the many of HIPERPAV features include using the HIPERPAV temperature model to predict the time for a specified strength threshold for opening to traffic. By inputting the real time temperature of the pavement into HIPERPAV, the strength prediction measurements can be made very accurately. (See http://www.hiperpav.com/index.php?q=node/2).

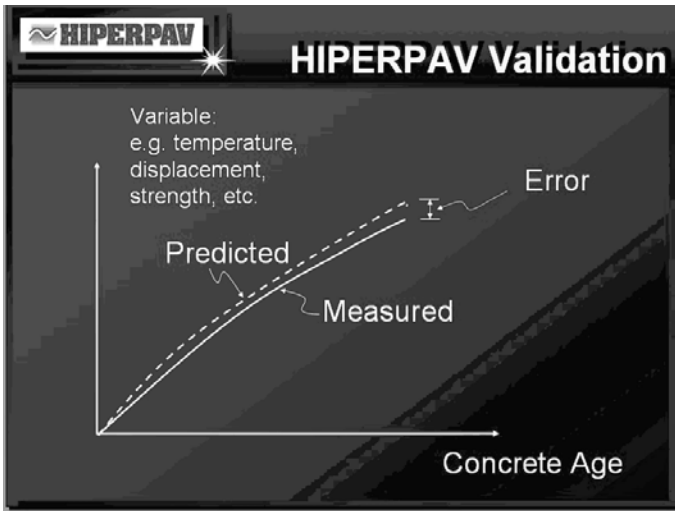

Figure 2: HIPERPAV concrete strength prediction.

3.3.3 Humidity sensor selection

Two commercially available humidity sensors being were tested. The humidity sensor was selected is a humidity sensor (MK33) by the Innovative Sensor Technology Inc. which features a basic capacity of 300 pF providing a large humidity-temperature-range and therefore suitable for this research study. An advantage of the MK33 is that it is a capacitive sensor very much like the hydrogel sensors. The MK33's high solvent resistance and hot water resistance and could directly embed the sensor in the concrete. Available moisture is also important when considering the potential for corrosion and well as ASR-induced damage in concrete field structures. Study has shown that concrete mixtures comprised of highly reactive aggregates and high-alkali cements have shown little or no expansion in certain very dry environments. Likewise, local differences in moisture availability within the same structure have resulted in vastly different performance within that structure. Specifically, portions of the structure exposed to a constant or steady source of moisture (e.g., as a result of poor drainage or poor detailing) have exhibited significant ASR-induced damage, while other portions of the structure that remain essentially dry have shown little or no damage. Therefore, the exposure conditions, in general, and the availability of moisture, specifically, play key roles in the durability of field structures. Limiting the availability of external moisture in field structures is an effective way of reducing ASR-induced damage; however, it is often not feasible to reduce the moisture content below the critical threshold value (i.e., 80 percent relative humidity). However, any attempt at reducing available moisture, whether through proper detailing and design of drainage or through the use of low-permeability concrete, will improve the long-term durability of concrete.

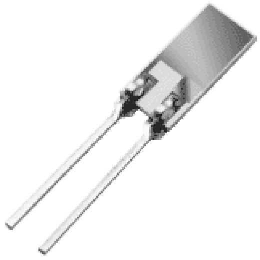

Figure 3: MK33 Humidity Sensor from Sensor Technology Inc.

3.4 Packaging (outer housing)

The choice for packaging is a highly resilient two component clear urethane potting & encapsulating compound. This is semi-flexible and will not place excess stress on electronic components. It also has a low viscosity, which facilitates easy flow and penetration into difficult areas. This product has a convenient one to one mix ratio and is considered DOT non-hazardous.

4 TESTING DEVICE

4.1 Wireless temperature and humidity testing

Using the commercially available parts and sensors, assembled an active battery-powered wireless temperature and humidity sensor suitable for placement into concrete. Reader was used to receive the transmitting data from the sensors which displays information in real time (data updated every 10-30 minutes from the sensor) on an LCD screen. Data was taken at 30-minutes interval. Initially, the urethane packaging that protected the entire device was preventing the humidity sensor from interacting with the concrete. The problem was resolved by carefully preventing urethane from covering the humidity sensor. This sensor performed very well and properly follows expected humidity trends in the first stages of concrete’s life. As can be seen in the graph, at ~38 hours the sensor was placed into wet concrete, causing humidity to jump from 22% to 95%. After that, the humidity value steadily drops as the concrete matures.

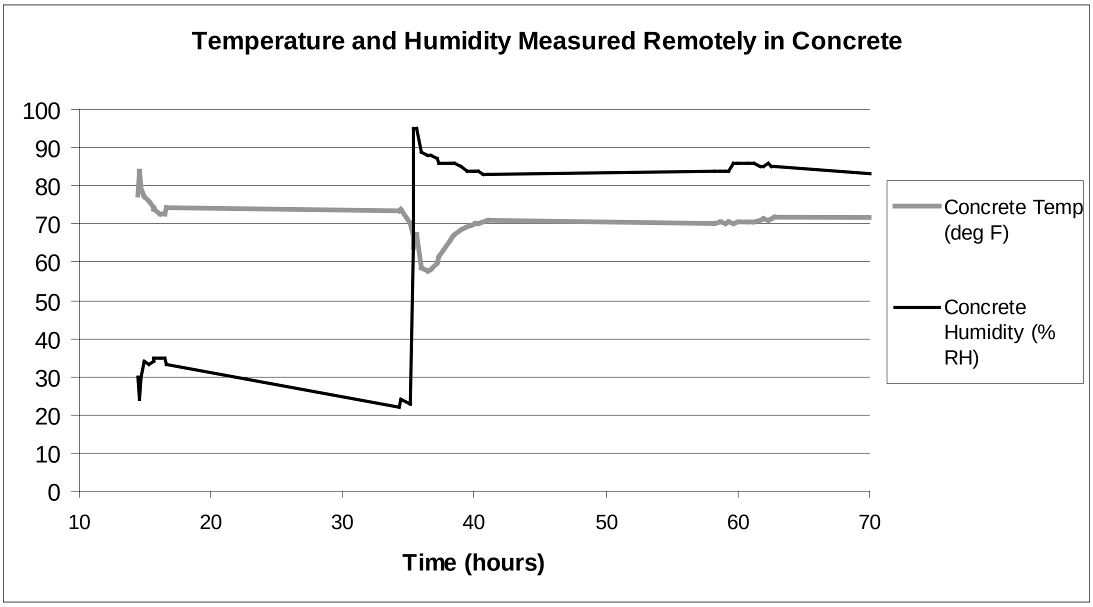

Figure 4: Temperature and Humidity Measured Remotely in Concrete

4.2 PH and chloride ion measurement

In addition to temperature and humidity measurements, measured the pH of the concrete as it cured. The concrete itself changes in pH as it matures and then as it ages. In addition, the water solution seeping through the tiny pores in the concrete touches the metal rebar and can have very negative affects on the health of the rebar. The pH sensor is limited, because it will not provide readings while the concrete is dry. Also, its readings will only be accurate for pore solution and not for the actual pH of the concrete itself. Corrosive conditions could be discovered well in advance of structural failure. Chloride ion measurement uses the same tool, but with a different selective membrane to select only chloride ions (inside of hydrogen ions in the case of pH) for measurement. It is infeasible to include all of these sensors in one small circuit board mounted sensor. We decided on pH, whose effects are the most understood, to measure in our tests.

4.3 RFID testing

The active (battery assisted) wireless sensors test results have proven a viable tool for transmitting data from inside the concrete to a reader. Making these sensors truly long-lasting, however, will require integration of passive RFID technology, where an RFID reader antenna induces a magnetic field from in the sensor from which energy can be drawn to take measurements and send a replying signal

4.3.1 Testing read range of RFID tags

The read rang of RFID tags were tested by first using a low-frequency reader to determine what range could read tags in an unobstructed environment and then placed obstacles between the passive RFID tags and the reader and measured the read range again and entirely covered it in 2 cm of concrete. The data implies that concrete, plastic, and urethane has very little effect on the read range of these low frequency passive RFID devices.

4.3.2 Testing the induced voltage of passive antennas

The voltage induced by the PhidgetRFID passive reader was tested in the commercially purchased RFID tag antennas and discovered that it received approximately 50 mV from the reader at a range of 2.54 cm. To obtain higher reading it was decided to construct a prototype energy-receiving antenna by using 42 gauges thinly insulated copper wire to create a 2 cm diameter coil of wire that was .6 cm long. Placed the new antenna in the field, created by the low-frequency PhidgetRFID reader at very short range, and measured 4 Volts of AC potential energy. Even after being diminished through DC rectification and a smoothing circuit, this voltage produced will be greater than two AA batteries, which we used to power our active wireless system

5 PROTOTYPE INTEGRATED SENSOR DESIGN (MINIATURIZED)

A smaller mold was created to encase the design. We started by combining the microprocessor circuit board with the RFID antenna. This first prototype needed a battery because it provided a continuous stream of data regardless of whether there was an external antenna near. Further prototypes, removed the battery and added the temperature and the humidity sensor and able to communicate with our miniaturized device and will continue perfect the sensor data collected. Photo below is the miniaturized device.

Figure 5: Sensor Developed in Phase I

6 RELATIONS TO FUTURE RESEARCH AND DEVELOPMENT

Consideration has been give to expand the sensor applications to include monitoring the asphalt pavement. This presents many interesting technical challenges as asphalt reaches temperatures up to 176 °C while being installed. This is a challenge for both the electronics and the packaging used in the first phase research. The two-part polyurethane used to package the original sensors has a recommended max operating temperature of 150 °C. Above these temperatures, the urethane will become soft and may expose the electronics to damage. Additionally, standard electronics are not designed to operate at very high temperatures. Alternate packaging and electronics will need to be integrated into the existing platform to deal with these challenges. One of the options to the packaging challenge is using a high temperature and thermal shock epoxy, which is manufactured by the same company we have used for our original polyurethane housing. This high temperature epoxy is specially made for extreme conditions and is specified to have an operating range between -70 to +260°C.

In addition, pressure cell could be integrated to the sensor system to monitor stress in the concrete and asphalt pavement. The requirements for a useful gauge may be different for dynamic or static strain sensors. For dynamic strain measurements, during which the rate of change in strain is much larger compared with the rate of change in temperature even if the time period is long, the allowed apparent strain sensitivity of a gauge can be very high. For static strain measurement over long periods of time both the temperature and strain may vary during the measurement. The allowed apparent strain and drift strain of a useful gauge are much lower than that for a dynamic strain gauge. There is little data concerning what would be the most effective distribution of a large-scale pavement monitoring system. In laboratory-scale tests, sensors can be densely placed, but for cost reasons, sensors in the field will necessarily need to be spaced further apart. Optimal sensor placement is a key factor to maximize the likelihood of identifying future problem.

The condition and testing for asphalt will most likely be different than concrete, since the sensor will reside in a completely different environment. A major part of the development of the sensor for asphalt is the packaging because of extreme heat. When developing the asphalt version of the sensor, high temperature testing will be done with all electronics and sensors before they are integrated onto the sensor platform. This will involve heating the sensors in an insulated container and measuring the changes in performance. Since sensors will need to experience the range of temperatures, tests will include heating them slowly from below freezing to max environmental temperatures and heating them from room temperature to the max temperature encountered in asphalt. Extensive laboratory and field testing will be conducted to determine sensor reliability. Test will be conducted at the ADC. The sensor will be subjected to stressful conditions simulating long-term deployment condition such as FHWA Accelerated Load facility (ALF) at the Turner Fairbank Highway Research. (i.e., Test sections 14m, speed of 17 km/hr, single (425/65 R 22.5) or dual tires (11 R 22.5), load 44 – 90 KN, temperature control of 10 to 76°C).

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