Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 10 (2011) 484–489
Engineering Procedia

ICM11

T-WiEYE: An early-age concrete strength development monitoring and miniaturized wireless impedance sensing system

a*C. Providakis, E. Liarakos

Applied Mechanics Lab, Department of Applied Sciences
Technical University of Crete, GR-73100 Chania, Greece

Abstract

This paper develops an innovative active wireless sensing system that consists of a miniaturized electromechanical impedance measuring chip and a reusable piezoelectric transducer appropriately installed in a Teflon-based enclosure to monitor the concrete strength development at early ages and initial hydration states. To identify the degree of concrete strength evolution, electromechanical impedance (EMI) changes associated with decision boundaries based on extreme value statistics (EVS) are utilized during the hydration process. Experimental results have presented that prove the effectiveness of the proposed miniaturized sensing system to monitor concrete structures from their earliest stages.

keywords: Reusable PZT sensor; Wireless USB data transmission; Early age concrete monitoring; Extreme value statistics

1. Introduction

One of the most prominent reasons for failures of large concrete structures during construction stages was overestimating the degree of strength development of concrete at early stage, so that forms were removed unsafely and the partially mature concrete was not strong enough to support upper levels of the structure. It is well known, that the strength and durability of concrete structures are enhanced

---

* Corresponding author. Tel.:+30-28210-37637; fax: +30-28210-37866.
E-mail address: cpprov@mred.tuc.gr.

doi:10.1016/j.proeng.2011.04.082

significantly by proper moist and curing of early-age concrete and if rapid loss of moisture happens then this problem could lead to insufficient strength development.

Currently, various techniques for investigating the changes of early-age concrete in situ have been explored including Windsor and pullout probe tests, ultrasonic pulse velocity, impact-echo method, microwave method, maturity method and so on [1]. But, those techniques perform localized measurements and the monitoring of large concrete structures requires an extensive amount of time and effort leading to costly usage. In the same time, the advent of smart materials, such as piezoelectric materials, shape-memory alloys, and optical fibers has attracted interests among researchers and engineers to develop new nondestructive monitoring techniques. However, findings from those studies show that they could not monitor the early hydration of fresh concrete occurring in the first three days since concrete needed to be hardened, followed by surface drying and one more day for hardening of the epoxy.

The feasibility of reused piezoelectric (PZT) transducer setups was first investigated by Yang et al [2] using a piece of PZT bonded to an aluminum or plastic enclosure with two bolts tightened inside some holes drilled in the enclosure. They acquired the PZT impedance signatures obtained from concrete specimens at different stages of the first 48 hours after casting. However, using aluminum as enclosure they met the problem that some cement hydration residues remained on the aluminum surfaces and thus, the repeatability of their measures has been slightly affected after a few reuses.

In the present paper, the objective was to extend the study of Yang et al [2] to develop an innovative reusable PZT transducer being strong enough to easily detached from the hardened concrete structure without any damage to the PZT or the enclosure. A specially designed Teflon-based enclosure was fabricated to be used as the enclosure of the new reusable PZT transducer.

To overcome the problem of using bulky and expensive impedance analyzers, in this paper we made use of a recently produced impedance converter network analyzer, termed as AD5933 [3], which fully helped the miniaturization and wireless integration of the proposed electrical impedance sensing system. Further, the adoption of wireless technology in our innovative system eliminates the need to install cable for data communication. In order to use EMI sensing technique for quality control in practice, a quantitative index must be sought. The idea is to characterize only the condition of the fresh concrete at very early ages (3 hours) after casting and that baseline data are used as a reference. When data are measured during continuous monitoring, the new data are compared with the reference and could be considered as a concrete strength development feature. These features are then analyzed using a statistical method known as extreme value statistics (EVS).

Preliminary experimental data based on the proposed PZT transducer for proof of concept is presented here. This innovative PZT transducer is termed Wireless Teflon-based integratEd monitoring sYstEm or rather T-WiEYE.

2. Experimental Implementation

2.1. T-WiEYE sensor design

We decided to use for our piezoelectric material a PZT patch of type PIC151 with a size of 10X10X1 mm produced by PI Ceramic Co [4]. The PZT patch was then soldered to a shielded cable that was connected on the other end to one of the pin connectors located on the evaluation board EVAL-AD5933 of AD5933 impedance miniaturized chip. To meet the strict installation requirements for the protection of AD5933 chip, we chose to use Teflon as enclosure material. Two 1/8” diameter holes were drilled through the outer perimetrical wall of the Teflon-based enclosure and a custom-made circular plate was also fabricated from the same Teflon material and finally, placed as the cap of the enclosure. Figure 1 depicts the design of the sensor implementation.

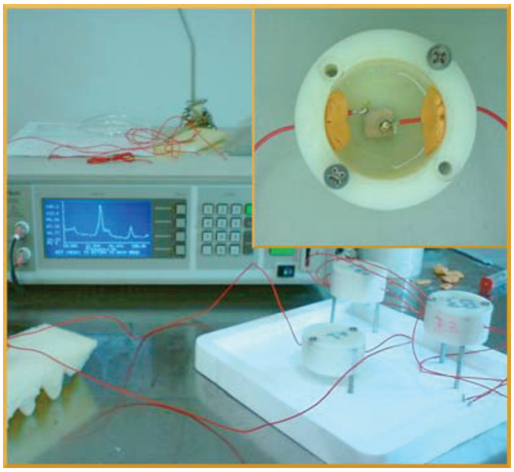


Fig. 1. Geometry design of the T-WiEYE sensing system

2.2. The proposed integrated monitoring system

T-WiEYE monitoring system utilizes a piezoelectric (PZT) transducer enclosed in the Teflon-based case as described previously, an evaluation board of AD5933 impedance measurement chip, a 802.11g wireless USB 2.0 sender and receiver system and a computer, as shown in Figure 2.

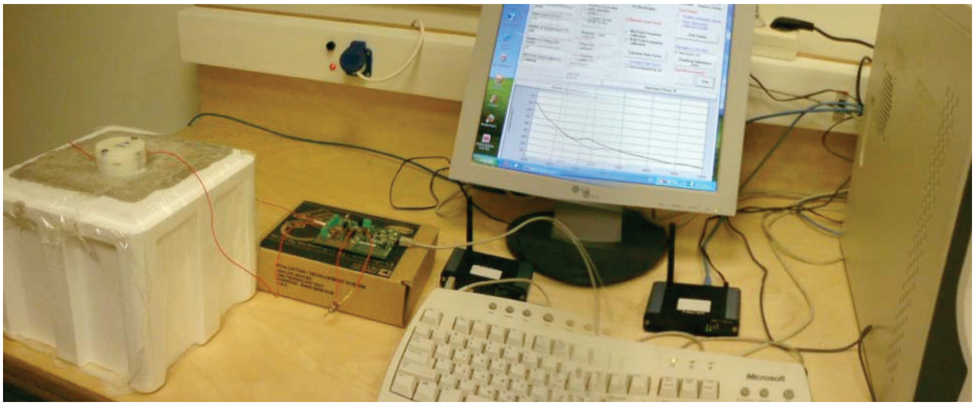


Fig. 2. Wireless USB 2.0 sender and receiver integrated monitoring system as connected to the PC.

The user interfaces to the USB microcontroller through a Visual Basic® graphic user interface located on and run from the user PC. Using the USB interface, the microcontroller then transmits the measured data providing data storage. After the measurement in the respective time slot is done, the microcontroler reads and transmits the data from AD5933 circuit for data storing and further processing. The software application implemented in the present paper is based on the core of the software provided with the evaluation board EVAL-AD5933 from Analog Devices Inc. Besides the measurement control, setup, and calibration, the adapted software integrates the wireless capability of the T-WiEYE monitoring system and enables remote saving of measured data at specific time intervals, which can be saved to a table format, e.g. MySQL, for further post-processing, analysis or evaluation.

3. Extreme value statistics and concrete hardening

In order to determine the hardening time of concrete we bonded a T-WiEYE monitoring system on the surface of a concrete specimen and began to monitor the impedance generated at the PZT surfaces 3 hours after the pouring of concrete and that baseline impedance data are used as a reference. The idea is to characterize the electromechanical impedance condition of the fresh concrete at early ages (from 3 hours after casting and so on) and compare the baseline data with any subsequent impedance measurement.

To identify the system we first began by experimentally measuring impedance of the PZT actuator/sensor of a T-WiEYE system bonded at a point of the surface of a concrete specimen. Parametric models are based on ordinary or partial differential equations that describe the dynamic system. For the frequency domain identification (using the Frequency Domain Identification Toolbox, FDIDENT[5] developed in MATLAB environment [6]) the parametric model structure is simply obtained by using appropriate Fourier transformations. Then, by considering the detrended measured data of impedance as output response and detrended data of voltage as input for every frequency ω_k, the fundamental folding leads to a multiplication of the form in the s-space:

$$Z_j(i\omega_k)=G(i\omega_k,P)V_j(i\omega_k)+N_Y(i\omega_k),\ k=1,2\ldots F \qquad (1)$$

with $Z_j(j\omega)$, $V_j(j\omega)$ and N_Y $(j\omega)$, representing the Fourier coefficients of the measured input values V_j, output values Y_j and output noise, respectively, while F being the total number of the frequencies used in the frequency response analysis and $i=\sqrt{-1}$. The parameter vector P contains the unknown parameters of the frequency response function (FRF) (or transfer function) G(s), ($s=i\omega$). Once the coefficients of the transfer function G(s) are evaluated with the baseline data (at 3-hours from the casting of concrete), the frequency-domain parametric model in (1) is then employed to predict the impedance output response signal using a new input voltage signal. If this impedance output response signal is measured for every investigated frequency under a concrete strength condition different from the condition where baseline impedance output response signal was obtained, the predicted model would not reproduce the new impedance output response signal well and there would be a *residual error*. To analyze the outliers, generalized extreme value (GEV) statistics approach [7] of Statistical Toolbox of MATLAB is employed in the present work.

Once the parametric model is established, effective threshold limits for the outliers' analysis can be accurately computed by using GEV analysis of Statistical Toolbox of MATLAB and measured impedance data.

4. Results and discussions

4.1. Experimental setup

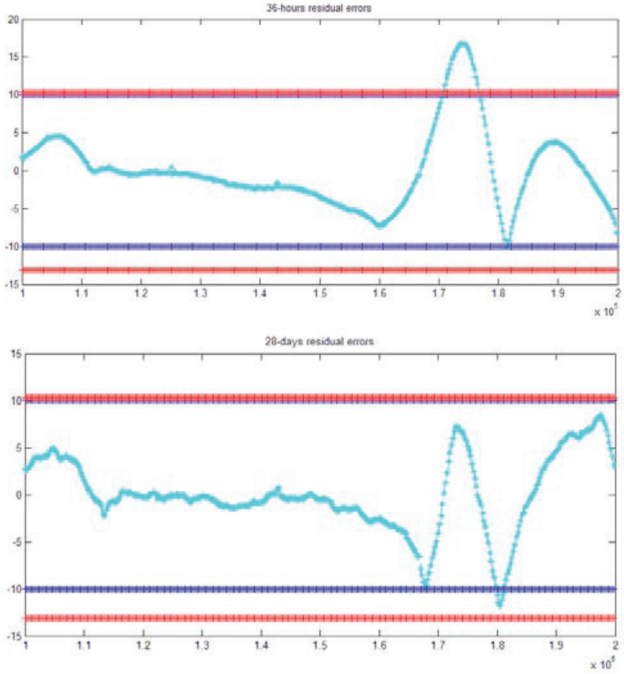
Three concrete cubic specimens with dimensions of 150X150X150 mm, which are normally used for compressive strength evaluation, were prepared for this experiment comprising of Type I Portland cement

(C), water (W), well-graded washed sand (FA), and gravel coarse aggregate (CA). The mixing proportion of the concrete is 1:0.62:2.25:3.83 (C:W:FA:CA, ratio by mass of cement). The attachment of T-WiEYE system on the surface of the fresh concrete was done just after casting of the cubic specimen. The first impedance measurement was carried out at the age of 3 hours. Then impedance signatures were acquired continuously every one hour from the 3rd hour to the 120th hour from casting. After that period the impedance signatures were acquired at the ages of 7, 9, 11, 14, 17, 21, 24, and 28 days. The impedance signatures are measured at a frequency range of 100-200 kHz from the self-sensing T-WiEYE system so that, finally, they contain 400 data points.

4.2. EVS-Based concrete strength development metric

In order to proceed with the statistical process analysis the impedance measurement at the 3rd hour from concrete casting and the Frequency Domain system Identification (FDIDENT) Toolbox of MATLAB were used to obtain the transfer function the transfer function G(s) = Z(s)/V(s) of the measured input (Z(s)) and output (V(s)) response values of the monitoring system. Once the coefficients of the transfer function are estimated, the residual errors for the predicted current output response values are extracted as a concrete strength development-sensitive feature.

Figure 3 shows the detrended residual errors for the 36-hours' and 28-days' concrete strength development condition, and the 99.5% GEV and Gaussian distribution confidence limits as estimated from the 28-days residual errors. In this figure, no outlier beyond the 99.5% GEV distribution confidence intervals is shown for the case of 28-days' concrete development state.



a)

b)

Fig. 3. a) Residual errors 36-hours from casting, B) Residual error 28-days from casting (Red lines: 99.5% GEV confidence limits, Blue lines: 99.5% Gaussian confidence limits).

However, if the number of outliers is drawn based on the continuous progress of hydration we can obtain Figure 4. In Figure 4, one can observe that the impedance signature in terms of the number of outliers from 11-hour to 44-hours varies by 0 to 22 outliers. On the other hand, the signature from 44th hour and so on does not change significantly. The greater number of outliers from the baseline signature is observed between hour 3 and 44, while the number of outliers is zeroing at 44-hour measurement.

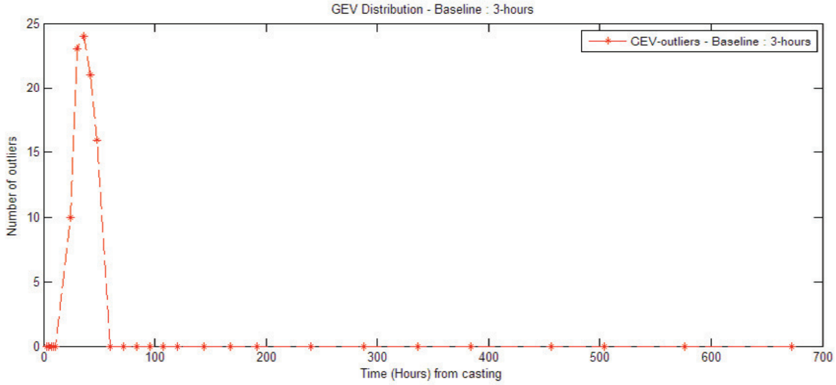


Fig. 4. Generalized Extreme Value outliers as a function of time from casting

This concludes that 99.5% GEV confidence interval leads to a constant number of outliers almost equal to zero at 44-hours from concrete casting which in turn leads to a reliable concrete hardening time criterion scheme. However, this criterion needs further study, because it may be changed as the baseline is changed.

Acknowledgements

The authors gratefully acknowledge the support of the research by the European Union (European Social Fund) and national resources under the Act "HERACLITUS II" Operational Programme for Education and Lifelong Learning.

References

[1] ACI Committee 228 2003 In-place methods to estimate concrete strength *Report 228.1R-03* (Farmington Hills, MI: American Concrete Institute).

[2] Yaowen Yang, Bahador Sabet Divsholi and Chee Kiong Soh, A Reusable PZT Transducer for Monitoring Initial Hydration and Structural Health of Concrete, *Open Access Journal "Sensors",* ISSN 1424-8220, www.mdpi.com/journal/sensors

[3] Analog Devices, USA, www.analog.com

[4] PI Ceramic, www.piceramic.com

[5] Kollár, István, "Frequency Domain System Identificaton Toolbox (FDIDENT) for Matlab", *Gamax Ltd*, Budapest, 2004-2009

[6] MATLAB, www.mathworks.com

[7] Castillo E. Extreme Value Theory in Engineering. Series in Statistical Modeling and Decision Science, *Academic Press: San Diego*, CA, 1988.