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# Monitoring early hydration of reinforced concrete structures using structural parameters identified by piezo sensors via electromechanical impedance technique

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ABSTRACT

Concrete is the most widely used material in civil engineering construction. Its life begins when the hydration process is activated after mixing the cement granulates with water. In this paper, a non-dimensional hydration parameter, obtained from piezoelectric ceramic (PZT) patches bonded to rebars embedded inside concrete, is employed to monitor the early age hydration of concrete. The non-dimensional hydration parameter is derived from the equivalent stiffness determined from the piezo-impedance transducers using the electro-mechanical impedance (EMI) technique. The focus of the study is to monitor the hydration process of cementitious materials commencing from the early hours and continue till 28 days using single non-dimensional parameter. The experimental results show that the proposed piezo-based non-dimensional hydration parameter is very effective in monitoring the early age hydration, as it has been derived from the refined structural impedance parameters, obtained by eliminating the PZT contribution, and using both the real and imaginary components of the admittance signature.



## 1. Introduction

It is the hydration of cementitious materials which is responsible for the transformation of concrete from a viscous suspension to a rigid load-bearing and durable solid element [1]. Therefore, monitoring the hydration process during the early age can aid for predicting strength development and hydration related cracking patterns. The fact that concrete hydration proceeds by dissolution cum precipitation mechanism was first elaborated by the famous chemist Le Chatilier [2]. Various techniques have been reported in the literature to monitor the hydration process in concrete, such as the ultrasonic techniques, thermal analysis, X-ray diffraction and scanning electron microscopy [3–5]. A comparison of various techniques of monitoring the hydration is found in the publication by Leslie et al. [6].

In recent years, researchers in the field of structural health monitoring (SHM) have been rigorously striving to replace the conventional SHM techniques with the smart material–based SHM techniques, employing smart materials such as piezoelectric materials and fiber optic sensors to monitor damage, debonding and corrosion [7–11]. Recently, the SHM using electromechanical impedance (EMI) technique has been extended to monitor the concrete hydration, curing and strength gain [12–19]. Qin and Li [13] monitored the hydration of cement using embedded PZT patch, by determining the dynamic modulus of the cement paste through the measurement of the ultrasonic pulse velocity. Shin et al. [14] used surface bonded

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PZT transducers for long term hydration monitoring. However, they could not monitor the early hydration as they bonded the PZT patch to the concrete surface only after hardening. Yang et al. [15] developed a reusable PZT based set up to monitor the initial hydration of concrete. Due to repeatable use of the PZT patch, the sensitivity of the signal was observed to reduce. Tawie and Lee [16] monitored the hydration of reinforced concrete (RC) using PZT sensors and used it as an indicator of the bond development at the steel-concrete interface. Quinn et al. [17] developed an embedded wireless sensing system for monitoring initial curing and health of concrete structures. Providakis et al. [18] designed a miniaturized wireless EMI based measuring system to monitor the early age strength of concrete. Based on their experimental studies, they found that the EMI signatures gradually shifted to the right as the concrete curing time increased. Kong et al. [19] monitored the very early age concrete hydration using piezoceramic based smart aggregates.

All the above studies to monitor the early age hydration were based on the raw admittance signature changes and depended on the computation of the root mean square deviation (RMSD) or similar statistical quantifiers. Although the statistical methods using the raw signatures are easy to implement and share the advantage of being non-parametric, their main drawback is that they do not provide any clear picture of the associated changes in mechanical parameters of the structure under question. Also they do not correlate well with the changes in stiffness (of the host concrete) on a uniform scale [8]. In addition, they do not provide significant information on damage severity on a parametric basis [8–11]. Lim et al.[20] also concluded that the PZT patch's resonance is not a direct indicator of the concrete stiffness and strength, because it is strongly influenced by the boundary conditions surrounding the PZT patch, specifically the bonding layer, and suggested the use of PZT patch based wave propagation method for strength evaluation.

This paper presents a new hydration diagnostic approach based on the equivalent system identified by means of the EMI technique. It makes use of real as well as imaginary components of admittance signature for determining damage sensitive equivalent structural parameters. The equivalent system is identified from the experimental data alone no analytical/numerical model is required as a prerequisite. The approach is not only simple to apply but at the same time provides an essence of the associated damage mechanism in terms of increase in stiffness on account of hydration. Besides strength monitoring, the proposed model can be employed in numerous other applications, such as predicting system's response, energy conversion efficiency and system power consumption. This technique can be easily applied in the construction industry to decide the appropriate time of removal of the formwork and the time of commencement of prestressing in the concrete members.

The results based on the experimental data show that the hydration of concrete can be effectively monitored by the piezo-identified equivalent parameters.

## 2. EMI technique

The EMI based SHM technique utilizes small sized PZT patches bonded to or embedded inside the structure as self-sensing actuators/sensors. They simultaneously excite the structure with high-frequency excitations, and monitor changes in the sensor's electrical admittance signature. The self-sensing properties of the transducer allow it to measure the output current produced by the application of specified voltage signal at a particular frequency. Because the PZT patch is bonded directly to the surface or embedded inside the structure of interest, it has been shown that the mechanical impedance of the structure is directly correlated with the electrical admittance of the PZT patch. The various applications of the piezo sensors in SHM, energy harvesting and bio-mechanics can be found in the author's recent publication [9]. The 1D impedance model [21] is detailed in the Fig. 1 and the coupled complex admittance signature of the PZT patch in this configuration was derived as

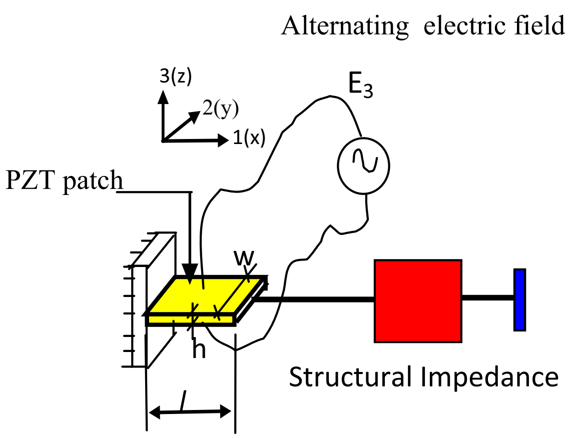


**Fig. 1.** 1D impedance model proposed by Liang et al. [21].