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Practical issues related to the application of piezoelectric based wave propagation technique in monitoring of concrete curing

Yee Yan Lim [a,*], Kok Zee Kwong [b], Willey Yun Hsien Liew [c,d], Chee Kiong Soh [e]

[a] Civil Engineering, School of Environment, Science and Engineering, Southern Cross University, PO Box 157, Lismore, NSW 2480, Australia
[b] Civil Engineering Program, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[c] Mechanical Engineering Program, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[d] Material and Mineral Research Unit (MMRU), Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia
[e] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

HIGHLIGHTS

- Practical issues related to the application of WP technique in monitoring of concrete curing are investigated.
- Performance of WP technique is reliable and consistent for 365 days.
- 5 peaks sinusoidal tone burst of 30 kHz or 120 kHz are recommended as actuation frequency.
- Smooth and even surface of the host structure is preferred for bonding.
- WP technique is capable of differentiating concrete of different strength.

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ABSTRACT

Smart piezoelectric material, namely, the Lead Zirconate Titanate (PZT) has recently found its application in concrete curing and strength development monitoring using the wave propagation (WP) technique. Real-life application of this technique is sometimes questioned as various practical issues have not been attended. In this paper, a series of experimental studies are performed to investigate a range of practical issues related to the application of this technique, in an attempt to reduce the gap between laboratory studies and real-life applications. Issues such as the consistency of wave velocities and repeatability of the sensor's electrical signatures, the optimum frequency of actuation, the effect of PZT transducer's spacing and sizes, the waveform of actuation signatures, the effect of input voltage amplification, the effect of different surface roughness, the environmental effect and the effect of different types of coarse aggregates are experimentally studied. Results showed that 5-peaks sinusoidal tone burst actuated at 30 kHz or 120 kHz are preferred input voltage. Spacing of transducers should be approximately 90 mm. Smooth and even surface of the host structure is preferred for bonding. The WP technique is found to be reliable and its performance is consistent across different specimens up to a period of 365 days. It is also capable of differentiating the strength concrete with different types of coarse aggregate. Studies conducted in this paper provide basic understanding into various practical issues, which is expected to serve as guidelines to future development, design, optimization and commercialization of a more effective PZT based WP technique in monitoring of concrete curing.

1. Introduction

Concrete is a cementitious material consists of water, aggregate and cement. The hydration process is a chemical reaction process for concrete formation. This process is a series of simultaneous and consecutive reaction between the constituents of cement and water. The cement is hydrated when water is applied to the mixture and forms a "cement gel" which will crystallize and binds

Abbreviations: WP, Wave propagation; NDT, Non-destructive testing; PZT, Lead Zirconate Titanate; EMI, Electromechanical impedance; TOF, Time of flight.

* Corresponding author.
E-mail addresses: yee.lim@scu.edu.au (Y.Y. Lim), charleskwongkz@gmail.com (K.Z. Kwong), wyhliew@ums.edu.my (W.Y.H. Liew), csohck@ntu.edu.sg (C.K. Soh).

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the aggregates and sands, imparting strength to the concrete. The concrete strength is being developed throughout this hydration process.

Current industry relies heavily on conventional compression test on standard cube or cylindrical samples for strength evaluation. An effective concrete strength monitoring system with autonomous, remote and real-time monitoring capability is highly sought after. A real-time monitoring system can provide useful information in understanding the development of the concrete strength and the time when the falsework (formwork and shoring system) can be safely removed. Furthermore, determining the optimal time of de-molding is important to increase the efficiency of in-situ casting or precast of concrete element, which can lead to significant savings in time and cost.

This leads to the development of various strength development monitoring techniques for cementitious materials. Current monitoring system can be broadly categorized into destructive testing and non-destructive testing (NDT) techniques. The most commonly used destructive evaluation technique is the compression test. This method is relatively simple and reliable in evaluating the concrete strength. However, it is not a satisfactory for large-scale, *in-situ* structure, consisting of a large number of structural elements where the concrete strength may vary spatially. Real-time monitoring is also unachievable.

Some of the commonly used NDT techniques include impedance meters, ultrasonic-based monitoring technique [27], ultrasonic pulse velocity UPV) test [3] and rebound hammer test [2]. These conventional NDT techniques suffer from common drawbacks such as being time-consuming, labor and cost-intensive, requiring bulky equipment, exposing inspectors to dangerous environment, and inapplicable to critical but inaccessible locations.

The advent of smart piezoelectric materials, such as Lead Zirconate Titanate PZT) transducer has the potential of overcoming most of the shortcomings of the conventional structural health monitoring SHM) techniques. When an electric field is applied across a piezoelectric material, mechanical strain will be induced. Conversely, it produces electric displacement when subjected to applied stress. These unique properties, commonly known as direct and converse piezoelectric effects, enable piezoelectric materials to be utilized as collocated actuators and sensors. Some distinct advantages of PZT transducer include non-intrusive, active sensing, quick response, high linearity, wide frequency response, low power consumptions and low acoustic impedance, low cost and ease of installation [26].

There are two types of piezoelectric based monitoring techniques, namely the electromechanical impedance EMI) technique and the wave propagation WP) technique. The EMI technique employs a single PZT transducer to harmonically actuate the host structure and simultaneously sense its responses at high excitation frequency in the kHz range). Any changes in the host structure such as presence of damage [1,13,16] and stress changes [17,18] can be reflected from the electrical admittance signatures. Concrete hydration monitoring [24] and concrete strength prediction [26] had also been investigated.

On the other hand, the WP technique usually employs two or more PZT transducers. Utilizing the piezoelectric effect, one transducer acts as actuator and the others as sensors. They can be embedded into or surface bonded onto the host structure. This technique has first been developed for damage detection in metallic structure [9,6]. It is later extended to damage monitoring [20], hydration monitoring [15,30] and strength monitoring [8,28] of concrete structure.

The WP technique using embedded PZT, often known as "Smart Aggregate", is proven by different researchers to be promising in reflecting the curing process from the changes in sensor's electrical signatures. On the other hand, WP technique using surface bonded PZT transducer on concrete structure has also been attempted by several researcher. Kong et al. [11] has successfully investigated the three states fluid state, transition state, and hardened state) of very early age concrete based on the classification the sensor's electrical signal. Recently, Kwong et al. [12] conducted experimental study to predict mortar strength from surface wave velocity using the WP technique. Lim et al. [14] proposes a semi-analytical concrete strength predictive model based on WP propagation technique. The model is found to be simple and effective in producing strength calibration chart for concrete with different water-to-cement ratio.

Yang et al. [34] conducts a series of experiments to study various issue related to the real-life application of the EMI technique in aluminum structures, including the durability of PZT transducers, and the effects of bonding and temperature under conceivable nominal construction site conditions. The electrical signatures acquired from the PZT transducers surface bonded on aluminum structures are found to be highly repeatable up to a period of one and a half years. Giurgiutiu et al. [7] investigates the durability and survivability of piezoelectric wafer active sensors for SHM using EMI technique on metallic structure. Lin et al. [19] explores the durability and survivability issues associated with various environmental conditions (cryogenic and high temperature, temperature cycling, outdoor environment, operational fluids, large strains, fatigue load cycling) on piezoelectric wafer active sensors for structural health monitoring on metallic structure, over a long period of time. Results indicate that high temperature can lead to failure of piezoelectric wafer active sensor.

Fengqi et al. [4] investigates the practical issues related to the application of embedded EMI technique in concrete SHM, including the influences of mass variations of concrete structure and vibration condition. Kamas et al. [10] investigates the degradation of the piezoelectric material in an increasing temperature up to 230 °C. The trends of variation on piezoelectric material degradation with temperature are deduced from experimental measurements. Mustapha and Ye [21] investigates the effect of adhesive on the waveform and the propagation velocity of the transmitted wave signals.

Qing et al. [23] studies the effect of adhesive thickness and its modulus on the performance of adhesively bonded piezoelectric elements for the purpose of monitoring structural health. Experimental results reveal that an increase in adhesive thickness alters the EMI as well as the amplitude of the sensor signal. Xu et al. [33] investigates the effects of temperature and load on the impedance and conductance spectra from an EMI based embedded piezoelectric sensor. The baseline of conductance spectra shifts with increasing temperature, and the resonance frequency is also highly dependent on the temperature.

In a nutshell, most of the practical issues related to the piezoelectric based SHM studied thus far, focuses on the metallic structure and on the EMI technique. Various practical issues affecting the real-life application of the PZT based WP technique in concrete hydration monitoring has not been addressed. Affirming the consistency, reliability, durability of this technique and understanding its behavior under various environmental conditions is essential before real-life application is possible.

This study aims at bridging the gap between laboratory and real-life application of PZT based WP technique through a series of experimental studies. Some key practical issues related to its effectiveness, including the effect of different actuation waveform, the effect of varying actuation frequency, the consistency and repeatability of the sensor's electrical signatures, the effect of PZT transducers' spacing and their sizes, the effect of voltage amplification, effect of surface roughness of the host structure, the performance of the technique under varying environmental conditions and the effect of different coarse aggregate, are studied.