NDT and E International 99 (2018) 50–63

Contents lists available at ScienceDirect

NDT and E International

journal homepage: www.elsevier.com/locate/ndteint

Wave propagation based monitoring of concrete curing using piezoelectric materials: Review and path forward

ARTICLE INFO

Keywords:
Piezoelectric materials
Concrete curing
Wave propagation (WP) technique
Non-destructive testing (NDT)
Review

ABSTRACT

The in-situ strength of concrete is often evaluated by destructive compressive strength tests conducted on cylinders or cube specimens cast alongside the main structure. Various non-destructive testing (NDT) techniques are also available in the industry. In the past decade, the use of piezoelectric based wave propagation (WP) techniques for monitoring the curing process of concrete has attracted considerable interest from researchers in the civil engineering discipline and hence there is a need to summarize the state of knowledge in order for future research efforts to be focused and relevant. This paper therefore presents a review of recent research and development of the abovementioned research area. Existing NDT techniques and piezoelectric based techniques for the monitoring of concrete curing are initially reviewed. Developments associated with the WP technique employing both embedded and surface bonded piezoelectric transducers are then presented. Finally, successful applications of the WP technique are provided. A wide range of parameters adopted by different researchers as concrete strength indicators are also summarized. Theoretical and numerical models available are reviewed, followed by a summary of practical issues related to the application of this technique. Several studies to date have proven the capability of the WP technique in monitoring the curing process of concrete. More rigorous studies are, however, required before a mature technique is developed that can entice commercial interest. Thus, future areas of investigation are identified in the final section. This article is expected to serve as an introduction for researchers interested in venturing into this area and as a valuable summary to inspire existing researchers for further improving the technique.

1. Introduction

Concrete is the most commonly used civil structural material in modern day construction due to its relatively low material cost, high durability and versatility. It is a non-homogenous material with complex microstructure, consisting of water, cement, aggregates and other suitable materials such as admixtures in required proportions. Concrete is often mixed on site. The quality of the final product, in terms of strength and durability, highly depends on the processes of mixing, handling, placing, compacting and curing. The final properties of concrete also rely on the handling it receives after arriving at the construction site. Therefore, the efficiency and effectiveness of consolidation and curing procedures are critical for attaining the full potential of a concrete mixture [1].

In the construction industry, intensive construction schedules prompted by financial constraints often poses a great challenge to the engineer attempting to minimize the time of construction while ensuring safety throughout the process. One of the key factors affecting the overall time frame is the curing time required for the concrete to attain a desirable strength. Safety considerations often prevent the early removal of formwork because loading on insufficiently cured concrete can be catastrophic. On the other hand, the idle time required for concrete to cure to its desired strength is costly.

The in-situ strength of concrete is often evaluated after 28 days of curing by performing compressive strength testing and material analyses on core samples extracted from the host structure or standard concrete specimens cast alongside the main structure. Such tests yield the materials properties through destroying the integrity of the materials. Despite being straightforward and reliable, destructive tests requiring coring of samples will inadvertently induce damage on the concrete structure, which is undesirable. On the other hand, the strength of concrete in a building or structure could differ from those obtained from cylindrical or cube compressive strength tests. This is especially true in large civil engineering structures, where the curing, mixing and compacting conditions can vary spatially.

Non-destructive strength evaluation techniques, on the other hand, are highly sought-after alternatives as they assess the properties of the materials without destroying their integrity. Evaluation can thus be repeatedly conducted over a long period of time. A wide range of non-destructive techniques have been developed based on various principles through the measurement of thermal, acoustical, electrical, magnetic, optical, radiographic and mechanical properties of the concrete. These techniques, in general, indirectly evaluate the properties of concrete through measuring specific responses induced by external excitation or internal changes during the hydration process.

Some commonly found non-destructive testing (NDT) techniques

https://doi.org/10.1016/j.ndteint.2018.06.002
Received 9 November 2017; Received in revised form 15 May 2018; Accepted 7 June 2018
0963-8695/

include the hydration heat-based monitoring technique, the ultrasonic pulse velocity test and the rebound hammer test. These techniques suffer from a number of inherent drawbacks, ranging from being time-consuming, being labor and cost-intensive, requiring bulky equipment, exposing inspectors to dangerous environments, to being inapplicable to certain inaccessible but critical locations. As a result, an effective, real-time concrete strength monitoring technique that is capable of characterizing the setting and hardening process of concrete is highly sought after in order to ensure safety and cost effectiveness.

The emergence of piezoelectric materials presents an opportunity to overcome most of the abovementioned shortcomings of conventional techniques. Piezoelectric materials, such as the Lead Zirconate Titanate (PZT) based monitoring technique, are proven to be effective in structural health monitoring (SHM) of metallic, concrete and composite structures [2–5]. The advantages of employing piezoelectric transducers in SHM include active sensing, non-intrusive, quick response over wide frequency ranges, high linearity, low power consumption, low acoustic impedance, cost effectiveness and simplicity in implementation. It is also able to provide autonomous, remote, real-time and online monitoring capabilities [6].

In general, there are two techniques available. Firstly, the electromechanical impedance technique (EMI) [7,8] employs a single piezoelectric transducer to harmonically actuate the host structure and simultaneously sense its responses. Any changes in the vibratory behavior of the host structure will be reflected in the electrical admittance signatures. On the other hand, the wave propagation (WP) technique employs two or more piezoelectric transducers with one acting as an actuator, and the others as sensors. Any variations of structural properties along the travel path of the elastic wave generated will be reflected in the changes in electrical signatures [9–11].

Application of the WP technique for monitoring the curing of concrete is a relatively new area of research, by comparison to most conventional techniques such as the UPV and the rebound hammer test. This research area commenced about 10 years ago [12,13]. This paper therefore aims to present a review of recent research and development of the piezoelectric based WP technique for monitoring concrete curing. Critical shortcomings, especially those hindering field applications of this technique, are discussed. Key areas pending further studies are summarized in the final section.

2. NDT based concrete hydration monitoring techniques

During the hydration process, the chemical reaction between cement and water continuously alters the chemical and mechanical properties of concrete. The change in mechanical properties can often be indirectly reflected when measured using different probes. The inhomogeneous, porous, over-cluttering, high-scattering characteristics of concrete with complex microstructure presents great challenges to the development of NDT techniques. Thus, the development of non-destructive techniques for health monitoring of concrete structures has been relatively slow in comparison to metallic structures. Some commonly available NDT techniques capable of monitoring the concrete curing process are briefly introduced in the following paragraphs.

The hydration heat-based monitoring technique measures the heat generated during the chemical reaction of cementitious materials with water as an indicator of the strength. The maturity method, for instance, estimates the strength development of concrete during its curing period by measuring the age and temperature history of the concrete [1]. Thermocouples or optical fibers can be used for heat measurement. In spite of its simplistic nature, it is cost effective and common. However, the accuracy and reliability of the techniques are relatively low.

Ultrasonic wave based strength monitoring techniques make use of the characteristics of mechanical waves travelling through the concrete medium to indirectly evaluate the physical properties of the concrete. For instance, the stress wave propagation technique that uses the spectral analysis of surface waves (SASW) can measure the changes in the elastic properties of concrete during curing. The method involves determining the relationship between the wavelength and velocity of surface vibrations as the vibration frequency is varied [1]. In SASW tests, two receivers are placed on the surface and a hammer is used to generate a Rayleigh wave (R-wave). The receiver outputs are collected and transferred by a signal analyzer to the frequency domain.

The ultrasonic pulse velocity (UPV) is another common stress wave propagation technique that involves measuring the travel time, over a known path length of a pulse of ultrasonic compressional or pressure waves (P-waves) [14]. This method utilizes the relationship between the velocity of P-waves in solid to the elastic modulus and the density of the concrete. These techniques can be restricted by the need to access to the opposite surface area of the concrete structure under investigation in order to attach the transducers. This is often difficult or impossible in cases especially on a construction site.

Ground Penetrating Radar (GPR) makes use of short pulses of electromagnetic waves (microwaves) and their interaction with the concrete medium. Since the dielectric properties of a material like concrete are strongly dependent on the moisture content, microwave measurements can be used to monitor the progress of hydration. This method, however, is not sensitive to the detection of concrete and air interfaces when compared to the stress wave propagation method. Nuclear (radioactive) methods involve the use of high energy electromagnetic radiation to gain information about the internal structure of the test object [1]. Generally, nuclear methods use X-rays and gamma rays. These methods are used to measure the in-place density of both fresh and hardened concrete. Nuclear methods are hazardous, cumbersome and require trained and licensed personnel. They also require highly specialized equipment which can be very costly and hence uneconomical.

Surface hardness methods measure the increase in hardness of concrete with age to reflect the hydration process. They are categorized as indentation based or rebound principle based. The indentation methods make use of a given mass of specific kinetic energy impacting on the surface of concrete and the subsequent measurement of the resulting width and depth of the indentation. The rebound hammer (RH) test utilizes the rebound principle. This device is capable of evaluating the elastic property and the strength of the concrete by measuring the rebound of the impact against the surface of the sample at a defined energy level. Jaggerwal and Bajpai [15] assessed the compressive strength of concrete bridge girders using the RH test. The experimental investigation showed that a good correlation exists between the compressive strength and the rebound number. However, the test only gives an indication of the near-surface properties of the concrete and not its interior [16].

Resonant frequency methods measure the transverse and longitudinal resonant frequency of a concrete specimen of standard size. Both parameters can be used to calculate the dynamic modulus of elasticity and the Poisson's ratio. Empirical relationship can then be established with the static modulus of elasticity and the strength properties of concrete.

3. Piezoelectric based SHM techniques

3.1. Electromechanical impedance technique

The EMI technique, which emerged two decades ago, employs PZT transducers to dynamically actuate the host structure and simultaneously sense its structural responses. In this technique, a mechanically attached (surface-bonded or embedded) PZT patch is dynamically excited by an alternating (sinusoidal) voltage, sourced by an impedance analyzer, uniformly across the patch. The vibratory force generated by the PZT patch, as a result of the converse effect of piezoelectricity, can then be transferred to the host structure. The corresponding structural response at different excitation frequencies will modulate the electric current across the PZT patch, as a result of the direct piezoelectric