Cement & Concrete Composites 55 (2015) 337–347

Contents lists available at ScienceDirect

Cement & Concrete Composites

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

Monitoring freshly poured concrete using ultrasonic waves guided through reinforcing bars

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ARTICLE INFO

Article history:
Received 27 September 2013
Received in revised form 2 August 2014
Accepted 15 September 2014
Available online 12 October 2014

Keywords:
Guided waves
Ultrasonic
Longitudinal waves
Freshly poured concrete
Compressive strength
Pullout strength

ABSTRACT

Durability and strength of mature concrete can be judged a great deal from its properties when it is freshly poured. This paper demonstrates an ultrasonic in-situ monitoring technique for freshly poured concrete. The solidification and curing of freshly poured concrete is monitored through the propagation of ultrasonic waves in waveguides such as steel reinforcing bars. As concrete solidifies and cures, more wave energy escapes into the surrounding concrete resulting in signal attenuation. RC beam specimens are monitored with carefully selected ultrasonic signal patterns during the first 24 h of setting of concrete. Destructive tests such as bar pull out and compressive strength are also performed at different stages of setting of concrete. The ultrasonic signals have been calibrated for determination of early age concrete properties.

1. Introduction

In-situ concrete that is poured at site into a formwork where it sets and becomes solid offers great flexibility of creating structures in various aesthetically pleasing shapes with fewer joints. However, it is challenging to consistently achieve the laid down quality parameters. Modern day concrete that has to satisfy a number of rather demanding performance parameters uses many admixtures that are sometimes not compatible. Thus, it is more susceptible to deficiencies that may show up at a later stage. Monitoring the early age characteristics of freshly poured concrete when it transforms from fluid to solid can be an effective tool for predicting its future performance.

At the time of pouring, concrete mix must easily flow into the formwork. Once placed, calcium silicate hydrate formation leads to hardening of concrete and the reaction may continue up to a few years. Monitoring the rate of hardening at an early stage, one can determine the time of removal of formwork and finally the time when the structure can take the design load and serve its intended purpose. More importantly, such monitoring can detect anomalies at an early age and can facilitate easy removal of defective concrete e.g. by washing and avoid the hardship of removing solidified concrete later. Hence, it is extremely important to set performance parameters for freshly poured concrete and monitor them in-situ. Conventional methods for monitoring freshly poured concrete include slump cone test, flow table test, penetration needle test, hydration temperature measurement and pull-out test. They are more suitable for laboratory applications. Rheological testing methods that use different types of viscometers apply shear force on fresh concrete that destroys the microstructure in the early ages of hydration process. A non-destructive and in-situ technique for monitoring solidification of freshly poured concrete can be of great help.

Ultrasonic wave propagation offers an exciting way of monitoring the solidification of concrete [1]. Velocity of ultrasonic pulses through a material increases as it solidifies. Thus, time taken by it to traverse through the depth of concrete is proportional to the degree of solidification [2]. Based on this approach, ultrasound and acoustic pulse velocity experiments have been reported for characterizing the setting and early hydration of cement based materials [3–10]. More recently, the ultrasonic wave reflection method has been reported in monitoring the setting behavior of concrete [11,12]. The reflection technique can use a single transducer that acts both as transmitter and receiver. Thus, the technique needs to access concrete at only one surface. The method has been applied to study the strength, elastic and stiffening properties of early age cement-based materials [13–15]. During the setting of concrete longitudinal and shear waves can monitored for variation in their velocities [16], resonant frequencies [17,18],

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http://dx.doi.org/10.1016/j.cemconcomp.2014.09.011

signal amplitudes [19] and a combination of velocities, frequencies and energy content [20,21] to discern the microstructural changes leading to solidification.

With the development and easy availability of piezoelectric patches, researchers have embedded them in concrete to investigate its quality. An embedded piezoelectric bender element was proposed for correlation of longitudinal and shears wave velocities with concrete setting [22]. Dhonde et al. [23] studied piezoelectric based monitoring using *smart* aggregates that had embedded transducers. Tawie and Lee [24] used PZT sensors embedded in concrete by attaching them on steel reinforcing bars to study bond development process of concrete.

Concrete is almost always reinforced with steel bars. Ultrasonic waves propagate more easily through steel than concrete. The bars can be used as guides to carry the wave into the concrete. Thus, the attenuation of bulk waves through concrete can be alleviated and large structures can be monitored. As concrete sets, its bond with steel gets stronger. Studying the bond development between the rebar and concrete, its setting process can be assessed. The existing methods of bond assessment between rebar and concrete include destructive tests such as pull out [25,26] or break off [27] which are not in-situ tests. In recent past there has been significant progress towards development of non-destructive evaluation of concrete using a wave guide. Pu et al. [28] reported increase in shear wave velocity in concrete during setting and correlated it to the shear modulus. The concept was extended by using shear transducers with a view to generate a torsional mode in mortar samples [29]. A pulse echo technique has been attempted to monitor setting of mortars at different water–cement ratios and in presence of accelerating and retarding admixtures [30,31]. Correlation between the wave amplitude and hydration time of mortars has been attempted [30].

This investigation introduces a few unique features to study setting time using ultrasonic guided waves. Instead of small mortar samples, realistically sized concrete samples have been used. The reinforcing bar inside the concrete has been used as the wave guide. Thus, no additional wave guide is necessary. Moreover, unlike the torsional modes [29–31] the longitudinal wave modes have been used in this investigation. Longitudinal modes are generated simply by attaching the transducers at the end of the bar and they are less attenuative. Thus more energy can be pumped into the wave guide allowing investigation of larger domains. The initial setting point of concrete has been captured by simultaneously carrying out the needle penetration test and correlating them with the trends in ultrasonic transmission signals. Transmissions after the initial setting have been correlated with the non-destructive ultrasonic pulse velocity test as well as the destructive techniques such as compressive and pull out strength tests. Thus, on one hand, correlation between the existing non-destructive techniques with the guided wave method is presented. On the other hand, the strength parameters and guided wave transmission have been compared. Moreover, the most suitable ultrasonic guided wave modes have been chosen based on the authors' prior research. The authors have reported that specific ultrasonic guided wave modes are effective in monitoring core and surface areas of waveguides [32]. By studying the modal displacement and energy distribution functions, specific modes can be identified that are sensitive to surface changes [33,34]. The authors used signals from specific modes to identify different types of corrosion of steel bars and correlate them with parameters such as mass loss, residual strength and pull out strength [33]. In this investigation, the modal excitation technique is applied to monitor the development of bond between steel and concrete. The present methodology has the ability to be developed into an in-situ and non-invasive technique for monitoring freshly poured concrete.

2. Guided waves in reinforcing bars in concrete

In an infinite bulk of a perfectly elastic material, ultrasonic waves travel creating longitudinal and shear strains. They propagate at constant velocities. They are non-dispersive and decay in amplitude because of the spread of the wave front. But in a finite perfectly elastic media like a reinforcing bar, the ultrasonic wave is reflected from its boundaries and the energy is contained within the bar as a guided wave. The complex effect of the bar boundaries results in dispersion of the wave and generates different modes that have predictable properties such as mode shapes and frequencies. They can be calculated by solution of the wave propagation equations [35]. The velocity–frequency relationships of guided waves are displayed as dispersion curves [36].

For a cylindrical system like a reinforcing bar, waves propagate in three modes due to dispersive effect of boundaries i.e. longitudinal (L), flexural (F) and torsional (T) modes. The frequencies belonging to a mode are numbered in increasing order [37]. Flexural waves are produced by placing the transducers perpendicular to the bar. A wedge is necessary to connect the round bar surface and the transducers. These waves exhibit high attenuation. To create torsional waves, a couple is formed by placing two synchronized transducers at equal distance from the bar axis by means of a connector. The coupling system absorbs substantial energy limiting the size of the domain that can be investigated. Longitudinal waves can be generated by simply attaching a transducer at the end of the bar [38–40]. This configuration is simplest and it generates strong longitudinal waves. Hence, in the present investigation longitudinal modes are chosen. They were generated by attaching ultrasonic probes of different resonant frequencies at the end of the reinforcing bar by means of a holder assembly that maintains a steady contact pressure. The bar acts as a waveguide that assists its propagation. Concrete around the bar allows the energy to leak from the bar to its surrounding. The leakage depends on the relative elastic and damping properties of the surrounding concrete layer [41]. Thus, the steel–concrete interface can be characterized by ultrasonic investigations [41–46].

(a) Front View

(b) Side View

Fig. 1. Set-up used for UPV measurements.