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Ultrasonic guided waves for monitoring the setting process of concretes with varying workabilities

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HIGHLIGHTS

- In-situ ultrasonic guided waves for monitoring setting of concrete is demonstrated.
- Setting is estimated by monitoring the steel–concrete interface.
- Effect of varying workabilities on concrete setting has been demonstrated.
- The results are correlated with conventional tests.
- Relationships between strength parameters and ultrasonic signals is presented.

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ABSTRACT

Quality of mature concrete can be judged a great deal by monitoring its properties at the time of pouring. However, modern day concrete varies greatly in composition and rheology that result in considerable variation in setting behaviour. This paper demonstrates an ultrasonic, in-situ guided wave monitoring technique for studying the setting characteristics of freshly poured concrete with varying workabilities. The solidification and curing of freshly poured concrete is monitored through the propagation of ultrasonic waves in embedded steel reinforcing bars. As concrete solidifies and cures, more wave energy escapes into the surrounding solidifying concrete resulting in signal attenuation. Two types of concrete specimens are prepared – one with moderate slump (80 mm) named as Conventional Concrete (CC) and other with high slump (675 mm) referred as Self-Compacting Concrete (SCC) and are monitored with carefully selected ultrasonic signal patterns. Destructive tests such as compressive strength and reinforcement pullout strength are also performed at different stages of setting of the two concrete types. Relationships for estimating the strengths from ultrasonic tests are developed. The ultrasonic guided waves are very promising for discerning the early age characteristics of concrete with varying workabilities.

1. Introduction

Reinforced concrete is the most widely used construction material worldwide and an overwhelmingly large proportion of structures is built with in-situ concrete. They are designed with a wide range of ingredients to cater to varying performance parameters. Whether the concrete could successfully meet the design requirements can be ascertained only after the curing period is over. In case of any deficiency it becomes a very difficult decision whether to accept the deficient concrete or to demolish and rebuild. The problem can be alleviated by monitoring the initial setting and hardening of concrete at the time of pouring. Corrective actions are far simpler if the defect is detected at that stage.

During the setting process concrete goes through a phase transformation from fluid to solid. Right rheology is important for the concrete to flow and fill the formwork. Through gradual solidification the concrete becomes suitable for meeting the service requirements. Studying the early phase transformation process one can predict the strength and durability performance of the material. Conventional testing methods for fresh concrete and mortar include slump cone test, flow table test, penetration needle test, and hydration temperature measurement. All these are tests useful in designing the concrete mix. However, an online test of concrete as it is being poured in the formwork is critical for monitoring of its quality. Between the various non-destructive test (NDT) methods, ultrasonic testing has emerged as a promising technique.

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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 wave pulse velocity experiments have been reported for characterising the setting and early hydration of cement based materials [3–10]. More recently, the ultrasonic wave reflection and transmission method has been reported in monitoring the setting behaviour of concrete [11–23]. With the development and easy availability of piezoelectric patches, researchers have embedded them in concrete to investigate concrete quality [24–26]. However, ultrasonic waves attenuate very rapidly in fresh concrete. This limits the applicability of the technique in large structures.

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 deep 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. It would be very useful to develop a non-destructive and in-situ method for evaluating development of bond between reinforcing steel and concrete that can be related to its setting properties. Some experimental investigations exist for utilising ultrasonic embedded waveguides for monitoring concrete [27] and mortars [28,29]. The ultrasonic signals can be more effective when the proper wave structure for the specific problem is chosen. The authors in their prior research have established that specific ultrasonic guided wave modes are effective in monitoring the core and surface areas of waveguides [30]. By studying the modal displacement and energy distribution functions specific modes can be identified that are sensitive to surface changes [30,31]. 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 [32]. In this paper the concept is extended to the monitoring of phase change process of concrete.

The early age property of concrete varies greatly due to functional necessities. For example if the concrete is used at a site where there is limitation of allowable noise, vibration of concrete may be infeasible and it may be worthwhile to design Self-Compacting Concrete (SCC). SCC is able to flow under its own weight, completely filling formwork and achieving full compaction, even in the presence of congested reinforcement. Due to its superior properties the design of SCC has been standardised with a series of excellent investigations. Although hardened SCC is expected to have the same engineering properties and durability as traditional vibrated concrete, its initial rheology is very different. Therefore, a technique for discerning the phase change process must be calibrated for varying workabilities.

In this investigation, the ultrasonic modal excitation technique is applied to monitor the development of bond between steel and the surrounding concrete with two dramatically different workabilities. Comparison of guided wave technique regards to the established procedures of penetration depth and ultrasonic pulse velocity measurements is attempted. The methodology developed in this study has the ability to be developed into an in-situ and non-invasive technique for monitoring various types of freshly poured concretes.

2. Guided waves in reinforcing bars placed in concrete

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. The velocity-frequency relationships of guided waves can be displayed as dispersion curves [33,34]. For a cylindrical system like reinforcing bar, waves propagate in three modes due to dispersive effect of boundaries i.e. longitudinal (L), flexural (F) and torsional (T) modes. The modes are numbered according to the format used by Disperse [34], which closely follows that defined by Silk and Bainton [35].

Specific guided wave modes can be excited selectively by choosing a frequency bound. Longitudinal waveforms have axial and radial displacements but no angular displacements and can be produced by coupling a compressional transducer parallel to the axis of the bar [36,37] or by using angled transducers on the sides [38]. In the present investigation, longitudinal modes which are less attenuative than the flexural and torsional modes and also easier to excite were chosen. They were generated through ultrasonic probes of different frequencies attached at the end of the bar by means of a holder assembly. 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 concrete and the steel [39]. Thus, the steel–concrete interface can be characterised by the ultrasonic technique [30–32,37–44].

As concrete sets and hardens, the bond between the reinforcing bar and the surrounding concrete improves. This should increase leakage of the energy of waves into the surrounding concrete and cause signal attenuation. Contrary to the techniques that apply the ultrasonic waves on concrete, when it is passed through the steel bar the signal attenuates due to hardening. To test this hypothesis, an experimental program has been undertaken.

3. Experimental investigations

3.1. Sample details

RC slab specimens of dimension 100 mm × 300 mm × 300 mm are prepared with two different mixes (Table 1). The mixes for conventional vibrated concrete (CC) having a moderate slump and SCC with high slump with proportions as shown in Table 1. The workability properties of prepared SCC mixes are given in Table 2. The prepared SCC mix satisfied the standardised workability requirements for SCC and were further used for studying the bond development and setting properties of SCC. An ambient temperature of 30 ± 2 °C was noted throughout the experiment. One 25 mm diameter plain mild steel bar of 500 mm length was placed at the centre of cross-section of the slab at the time of casting. The bar projected out by 100 mm on each side of slab (Fig. 1). Although ribbed bars that offer mechanical bonding between the bar and the concrete are more popular in construction, in this investigation plain bars were used to avoid such mechanical bonding and to observe how the different concretes setting phenomenon influences the interfacial bond only.

3.2. Selection of excitation modes

An ultrasonic testing system consisting of a pulser-receiver device, ultrasonic transducers, data acquisition card and display device was used (Fig. 2). Guided longitudinal waves were produced in the embedded bars by keeping the transducers at the two ends of the bars. Transducers (Contact Type, Karl Deutsch Make) were attached at the two projected ends of the bar in the concrete beams. One transducer acts as transmitter and the other acts as receiver. They were held in place at the two ends of the bars by means of a holder and a coupling gel between the bar and the transducer. The holders maintained a constant pressure between the transducer and the bar.

Driven by the pulser (DPR 300), the compressional transducers generates an ultrasonic spike pulse that propagates through the embedded bar in the form of longitudinal waves. The excitation signal consisted of a compressive spike pulse. The pulse transmitted at the other end of the bar was recorded on the receiving transducer. The ultrasonic signatures were taken at regular one hour intervals till the signals vanished and were not measurable.

The selection of excitation frequencies for testing was done using the software Disperse [34]. They were also validated by experimentally confirming the signal fidelity. The modes that are easily distinguishable and have lowest signal attenuation were selected [39,44]. For bars embedded in concrete, which is a layered waveguide system, leakage plays an important role. Frequency regions with lowest