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Monitoring the hardening process of ultra high performance concrete using decomposed modes of guided waves

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HIGHLIGHTS

- Single embedded sensor is used to monitor early and longer-term hardening process of UHPC.
- Features of the hardening process are extracted from single Lamb wave mode.
- Attenuation and wave velocity of the Lamb mode serve as bases for strength estimation.
- The effects of carbon nanotube (CNT) and steel fiber additions are demonstrated.

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ABSTRACT

In this study, the hardening process of ultra high performance concrete (UHPC) was monitored nondestructively using a single embedded sensor system and the characteristics of guided waves, especially the Lamb wave. Lamb wave propagation depends on the material properties of the medium and boundary conditions. Since the boundary conditions of the embedded sensor system continuously change during the hardening process of concrete materials, the measured characteristics of the propagating waves also vary. To understand the variations in wave propagation, the Lamb modes were decomposed using the polarization characteristics of piezoelectric sensors, which were used to measure wave responses. Additionally, a traditional penetration resistance method was adopted to estimate the time for phase transition of UHPC. The decomposed Lamb modes were compared to measurements of penetration resistance. The strength development of UHPC, with and without short-fiber reinforcement, was estimated using the variation of patterns of the decomposed Lamb modes after the phase transition. Based on the proposed methodology, which measures the propagation and variation of the Lamb waves, it is possible to estimate the time of phase transition and the strength development of UHPC.

1. Introduction

Concrete is the most widely used construction material with its numerous engineering merits such as low cost and controllable workability. For sophisticated concrete structures, e.g., high-rise buildings and nuclear power plants, quality control of the casted concrete is a critical factor affecting construction staging and long-term performance in service. Unlike prefabricated concrete elements in factories, the quality control of field casted concrete is challenging because curing environments are not usually under control. Therefore, to verify proper strength development of concrete, traditional coring methods have been applied since the destructive testing methods are reliable and straightforward. However, such methods are often impractical for in-situ concrete structures because they require frequent coring of specimens and time for testing. Additionally, the cored spaces typically need to be filled.

To overcome drawbacks of such traditional methods, various nondestructive testing (NDT) methods have been proposed to estimate the mechanical performance of concrete during its hardening process. NDT methods for determining in-place strength can be classified into two main categories, according to their use of:

1) maturity calculations based on the monitoring of temperature, which influences cement hydration and thus the hardening of concrete [1–7]. The temperature can be easily measured using fiber optic sensors or thermocouples. Although such methodologies have been successful in esti-

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mating strength development for a variety of purposes, they typically rely on complex relationships between maturity and strength that are difficult to apply for in-situ conditions. Additionally, the amount of heat generated by hydration increases rapidly within the early stages of the hardening process; at later ages, however, heat generation slows, which complicates longer-term strength estimations. Furthermore, many approaches require user intervention to acquire pointwise, rather than a continuous, monitoring of property development.

2) measurements of other physical properties, from which strength can be estimated. The physical properties of concrete change tremendously during the hardening process [8]. Physical-property-based methodologies, based on the characteristics of ultrasonic waves or electromechanical impedance for example, have been successfully applied in a variety of applications. The characteristics of the ultrasonic waves or the electromechanical impedance are frequently used to nondestructively monitor the strength development process of concrete materials [9–23]. However, the amplitude of propagating ultrasonic waves is rapidly attenuated due to high damping effects within large scale concrete structures. Also, dispersion characteristics of the ultrasonic waves complicate the analysis of the characteristics of the propagating waves.

This study involves the real-time monitoring of property development using an ultrasonic wave-based technique, which achieves high signal-to-noise ratio and low attenuation of the measured signals. This is accomplished by utilizing piezoelectric transducers attached to an embedded steel plate. The sensors introduce and record Lamb waves, a form of ultrasonic guided wave.

Ultra high performance concrete (UHPC) has superior material properties such as compressive strength higher than 150 MPa and compact microstructure that promotes high durability. Various research has been carried out to characterize their exceptional material properties including tensile behavior [24], impact resistance [25] and durability [26]. Based on their superior mechanical properties, numerous applications of UHPC have been successfully implemented, including many uses within bridge components [27–30].

In this study, characteristics of ultrasonic guided waves were considered to monitor the strength development of UHPC. Two stages of investigation were conducted. In the first stage, the relationship between phase transition of UHPC (from liquid phase to solid phase) and the attenuation of waves was investigated. After the phase transition, the change of wave velocities of the decomposed Lamb wave modes was monitored. The modes of the Lamb wave measured from the embedded sensors were decomposed individually based on their phase characteristics. The strength development of UHPC was then monitored by observing the change in wave velocities of the individual Lamb wave modes, which depend on the mechanical properties of the medium and surrounding materials. The reinforcement of UHPC, with either steel fibers or carbon nanotubes, was also investigated using the proposed method. The experimental results demonstrate the ability of the proposed method to monitor property development from the early stages, during the transition from a gel to solid, well into the strength development stage.

2. Test preparation

2.1. Mixture design

The mixture proportions of UHPC used in this study are given in Table 1. The three mixtures differ mainly in the type of reinforcement considered, i.e. a control case is prepared without any reinforcement; UHPC-CNT is reinforced with carbon nanotubes (CNT), and UHPC-SF is reinforced with steel fibers. A commercially available multi-walled CNT was adopted in this research, which is pre-dispersed in the water with concentrations of 2.0 wt% (DT-CNTS-2DI, Ditto technology Co.). CNT are often added to concrete for the purpose of electromagnetic shielding. Since the CNT possess electromechanical properties, including piezoelectric properties [31,32], potential interference with the measurement of wave data is of interest. Brass coated smooth steel fibers were used in the UHPC-SF mixture. Each steel fiber is 19.5 mm long with a diameter of 0.2 mm and has a minimum tensile strength of 2450 MPa.

Each of the three UHPC mixtures was prepared using a similar process. First, silica fume and all sands were blended in a laboratory mixer for approximately five minutes. Then, cement and silica powder were added and mixed together for another five minutes. Water and superplasticizer were then gradually added into the dry mixture while the mixer was operating. After adding liquid components, the mixture become fluid usually within five minutes. Once the mixture started to show adequate consistency, the mixing process is completed for the Control and UHPC-CNT cases. For the UHPC-SF series, high strength steel fibers were added into the mixer by hand and allowed to disperse within the mixture. The CNT were pre-dispersed within the mixing water before the mixing for the UHPC-CNT series.

The UHPC mixtures were poured into 50 mm cubic molds, without any subsequent vibration, for traditional compression testing. The casted specimens were covered with plastic sheets and stored at ambient temperature for 24 h prior to demolding. Compressive strength at 24 h was tested immediately after the demolding. Compressive strength at 48 h was tested after an additional 24 h of exposure to the laboratory environment. The other demolded specimens were submerged in a water tank at 20 °C without any special curing process such as heat or pressure treatment. Compressive strength was tested in a dry condition at the designated ages, after 24 h of drying in the laboratory environment.

2.2. Estimation of time of flight (TOF) of guided waves using a mode composition method

The characteristics of guided waves were used in this study to monitor the strength development of UHPC. Lamb waves can be generated under traction-free boundary condition. An important phenomenon of the Lamb wave is its dispersion characteristics: the wave propagates in symmetric (S_n) and anti-symmetric (A_n) modes, although a single input is applied to the medium. The subscript ‘n’ stands for the order of modes. The fundamental modes, S_0 and A_0 modes, were used in this study to simplify the analysis of the wave characteristics. The two modes have different wave velocities and have different phases because of the dispersion

Table 1
Mix design of UHPC (proportions by weight).

Materials	Control	UHPC-CNT	UHPC-SF
Cement	1	1	1
Silica Fume	0.25	0.25	0.25
Silica Powder	0.25	0.25	0.25
Sand A[†]	0.315	0.315	0.306
Sand B[‡]	0.735	0.735	0.714
Superplasticizer[§]	0.011	0.011	0.011
Water	0.22	0.22	0.22
Fiber (vol.%)	0	0	1.0
CNT	0	0.00025	0

[†] dmax = 0.25 mm.
[‡] dmax = 0.60 mm.
[§] Solid content.