Monitoring of the Hardening Process of Ultra High Performance Concrete (UHPC) based on Guided Wave Propagation

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ABSTRACT

In this study, the hardening process of ultra high performance concrete (UHPC) was monitored non-destructively using a single embedded sensor system. The propagating characteristics of guided waves obtained from the sensing system were analyzed to estimate the setting time and the strength development of UHPC. Since the boundary conditions of the embedded sensor system continuously change during the hardening process of concrete materials, the hardening process can be monitored based on the measured characteristics of the propagating waves. To understand the variations in wave propagation, the modes for the guided waves were decomposed. The strength development of UHPC, with and without short-fiber reinforcement, was estimated using the variation of patterns of the decomposed wave modes. Based on the proposed methodology, which measures the propagation and variation of the guided waves, it is possible to estimate the time of phase transition and the strength development of UHPC.

1. INTRODUCTION

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. To generate and propagate waves with little attenuation, a steel coupon with attached ultrasonic sensors was embedded in concrete. 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.

2. TEST PREPARATION

2.1. Preparation of specimens

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. 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. The UHPC mixtures were poured into 50 mm cubic molds, without any subsequent vibration, for traditional compression testing.

2.2. Preparation of embedded sensors

In this study, Navy II type APC 850 PZTs were used, which have characteristics of high sensitivity and large displacement, because the PZT transducer were embedded in UHPC with large damping effects. The distance between the pairs of collocated PZTs were determined such that signals from the direct path of PZTs could not be contaminated by reflected signals from side and end boundaries of the steel coupons. Since thick transducers tend to generate ultrasonic waves in the direction of thickness of the steel coupons, thin PZTs were used to generate guided waves along the surface of the coupons. Each steel coupon with the PZTs, which is an embedded sensor system, was installed in each UHPC casting. The data acquisition system was composed of a controller, an arbitrary waveform generator (AWG), a high-speed signal digitizer (DIG) and multiplexers (MUX). Using the 16-bit AWG, a tone-burst signal with a ± 10 peak-to-peak voltage and a driving frequency of 100 kHz was generated and exerted to the PZTs. The time signals from the PZTs were acquired at the DIG with the sampling frequency of 5 MHz. Additionally, the MUXs were used to automatically switch PZTs with one channel of the DIG. The measured signals were stored and processed in the controller.

2.3. Estimation of time-of-flight of guided waves using a mode decomposition method

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 characteristics(Rose, 2014). The propagating characteristics, such as wave velocity, depend on material properties of the medium, especially density and Lamé constants of the medium. Therefore, the propagating characteristics change according to the strength development of UHPC. To effectively analyze the propagating characteristics, the Lamb wave should be decomposed into its S_n and A_n modes. In the previous study by Kim and Sohn (Kim & Sohn, 2006), mode decomposition was based on consideration of the different phases of two modes using the polarization characteristics of piezoelectric transducers (PZT, lead zirconate titanate). This approach was adopted herein to monitor the hardening process of UHPC.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Monitoring of phase transition of UHPC

For a practical issue, setting of concrete is important because initial and final setting times are related to the limit of handling and the beginning of mechanical strength development. According to ASTM C403 (ASTM, 2010), the values of the penetration resistance specified in the standard at the initial and final setting are 3.5 MPa and 27.6 MPa, respectively. The penetration resistance was compared to the attenuation characteristics of the A_0 mode. Since the amplitude of initial wave packets occurred and decreased as UHPC hardening, the initial setting time was difficult to observe using the wave characteristics. Hence, only the estimation of the final setting time is considered using the attenuation characteristics of the A_0 mode in this study. The characteristics of the A_0 modes decomposed from the signals of the control specimen are representatively described with the results of the penetration resistance, as shown in Figure 1. For the UHPC samples considered in this study, it takes about 11 hours to reach the final setting time after casting according to the penetration resistance. The amplitude of the decomposed A_0 mode is reduced and approaches zero when the age of UHPC reaches the final setting time, as shown in Figure 1. Then, the amplitude of the A_0 mode increases and the velocity becomes higher as UHPC hardens after the final setting.

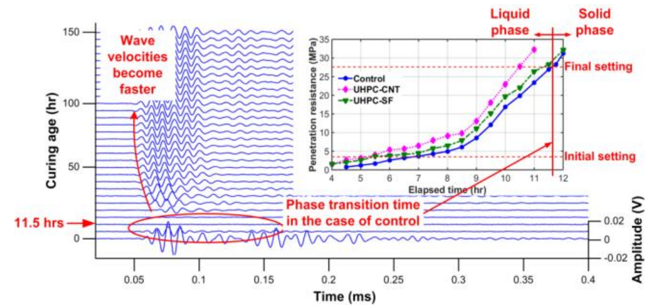

Figure 1. Trend of the variation of the decomposed A_0 mode during the curing process and the penetration resistance test according to ASTM C403 (the wave signals are measured in the control specimen)

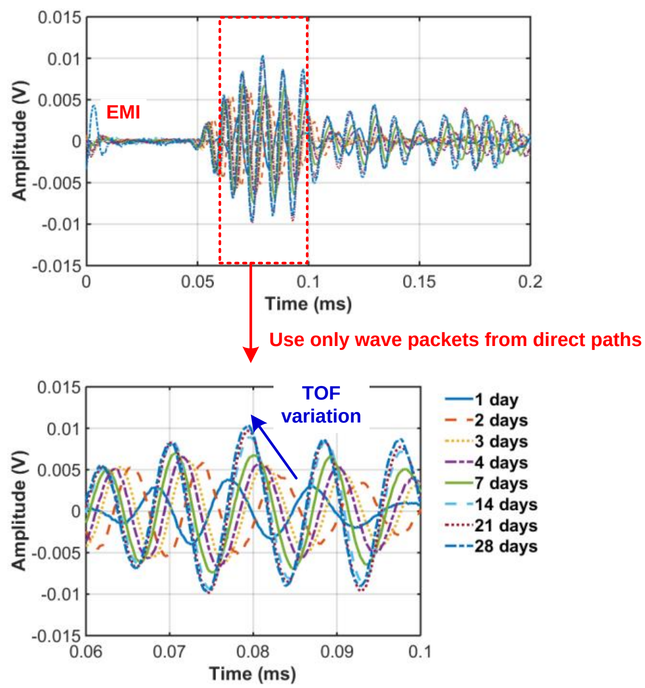

Figure 2. TOF variation according to the strength development of the UHPC (the signals obtained from the control specimen)

3.2. Estimation of strength development

After final setting, strength development of UHPC was monitored by observing the variation of the time-of-flight (TOF) of the A_0 mode. In this study, only the wave packets of the A_0 mode from the direct paths between the PZTs were used to determine the TOF. The packets from side and end boundaries can be superposed and cancel each other out, such that they are not effective in estimating TOF. Since the wave velocity becomes higher when the elastic modulus of the medium increases, TOF is reduced as strength of the UHPC increases. Patterns of TOF variation are shown in Figure 2. The signals were obtained from the control case, representatively, at the curing ages when destructive compression tests are typically performed. As expected, the value of the TOF decreased according to the strength development of UHPC. The TOF was significantly reduced during the early age of the hardening process, but changed slowly after about 7 days of curing. This pattern meets expectations for the hardening process of concrete materials. This feature was also observed in the signals from the UHPC-CNT and UHPC-SF cases. Therefore, the hardening process of UHPC can be simply monitored by tracing the TOF of the decomposed modes of ultrasonic waves.

4. CONCLUSIONS

In this study, the hardening process of UHPC was monitored using the characteristics of individual modes of Lamb waves, which were obtained from an embedded sensor system based on pairs of collocated PZTs. The hardening process was monitored before and after the phase transition of UHPC using a single embedded sensor system. Three UHPC mixtures were prepared based on their type of reinforcement: UHPC series without any reinforcement, with CNT, and with steel fibers. Two features were extracted from the individual Lamb wave modes: the amplitude attenuation and the time-of-flight (TOF). The individual Lamb wave modes, S_0 and A_0 modes, were decomposed using the phase characteristics of the Lamb waves and the polarization characteristics of the PZTs embedded into UHPC specimens. The setting time was estimated by tracing the pattern of the amplitude attenuation of the A_0 mode. Only the final setting time was estimated. In all cases, the amplitude of the A_0 modes disappeared about 1.5 hours earlier than the final setting time estimated by the traditional penetration resistance test when the patterns of the signals were directly compared to the penetration resistance. The final setting of UHPC could be decided by tracing the amplitude attenuation of the guided wave as well as the traditional penetration resistance.

Strength development was monitored based on the characteristics of the change of the TOF. Decomposed A_0 modes were also used to estimate the compressive strength of UHPC. Since only the decomposed modes were considered, the TOF could be easily traced without any interference from other modes and reflections. The TOF values decreased rapidly during the early age of the hardening process, but reduced slowly after about 7 days for the three mixture cases. This pattern was similar to the curves obtained from the destructive compression test. However, the TOF values were similar in each case although the mixture portions were different in terms of reinforcement type. It may be that the TOF depends only on the change of mechanical properties due to the chemical reaction during the hardening process of UHPC.

ACKNOWLEDGEMENT

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2014R1A2A1A11054299 and NRF-2015R1D1A1A01059291). This research was also sponsored by a grant from R&D Program of the Korea Railroad Research Institute, Republic of Korea.

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