Embedded Piezoelectric Pitch-Catch Sensing-based NDT Techniques for Concrete Strength Evaluation

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Recently, novel methods using piezoelectric materials to monitor the strength development of concrete during curing process have been reported. However, these methods showed some limitations to obtain an absolute concrete strength in real-world. In order to estimate the absolute strength of the concrete, the concrete strength monitoring method using embedded pitch-catched guided-wave propagation is proposed in this study. Because the wave signals are varied by the change of mechanical properties of structure, the strength of the concrete can be estimated. Moreover, to obtain the absolute strength of the concrete, specific strength equations are derived using the features extracted from the wave signal variations according to the strength development of the concrete. To verify the effectiveness of the proposed approach, a series of experimental studies using miscellaneous concrete specimens have been carried out. The guided-wave signal was measured by embedded piezoelectric sensors using a pitch-catch method. The propagation velocity was extracted from the each signal, and the strength estimation equation was derived from the relationship between velocity and measured compressive strength. Finally, further research issues will be discussed for real-world implementation of the proposed approach.

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EMBEDDED PIEZOELECTRIC PITCH-CATCH SENSING-BASED NDT TECHNIQUES FOR CONCRETE STRENGTH EVALUATION

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ABSTRACT: Recently, novel methods using piezoelectric materials to monitor the strength development of concrete during curing process have been reported. However, these methods showed some limitations to obtain an absolute concrete strength in real-world. In order to estimate the absolute strength of the concrete, the concrete strength monitoring method using embedded pitch-catched guided-wave propagation is proposed in this study. Because the wave signals are varied by the change of mechanical properties of structure, the strength of the concrete can be estimated. Moreover, to obtain the absolute strength of the concrete, specific strength equations are derived using the features extracted from the wave signal variations according to the strength development of the concrete. To verify the effectiveness of the proposed approach, a series of experimental studies using miscellaneous concrete specimens have been carried out. The guided-wave signal was measured by embedded piezoelectric sensors using a pitch-catch method. The propagation velocity was extracted from the each signal, and the strength estimation equation was derived from the relationship between velocity and measured compressive strength. Finally, further research issues will be discussed for real-world implementation of the proposed approach.

1 INSTRUCTION

Recently massive structures such as high-rise buildings or wide-span brides have been constructed world-widely. These structures are constructed with lots of mass concrete. It is hard to manage the construction process of these concrete structures because the strength of concrete during curing process is cannot measured accurately in construction site. Also concrete structures might be susceptible to brittle fracture if their curing process is inadequate. Therefore, to prevent these problems, it is essential to predict the absolute strength of the concrete nondestructively in real-time. In addition, continuous monitoring of the strength is important for reducing the construction time and cost because it can determine the appropriate curing time to achieve sufficient strength to progress to the next phase safely. Conventionally, the in-situ strength of concrete structures can be determined with high precision by performing strength testing and

material analysis on core samples removed from the structure but this method should destroy the concrete structure itself (Irie et al. 2008) Therefore, a range of methods based on the thermal, acoustical, electrical, magnetic, optical, radiographic and mechanical properties of the test materials have been developed to monitor the strength development without damaging the host structure (ACI Committee 228 2003, Lamond & Pielert 2006, Metha & Monterio 2006). Currently the most commonly used method for monitoring concrete strength is the hydration-heat based method. It is relatively inexpensive but does not produce accurate results. Therefore the reliable nondestructive strength estimation method is required in construction field.

Recently guided-wave method is studied to structural health monitoring technique. The guided-wave signal can monitor the structural health condition because it can represent the mechanical properties of host structure (Park et al. 2010, Kim et al. 2011). Especially, the guided-wave measurement using piezoelectric patch can sensitively monitor the local damage of structure. By utilizing this, this study proposed concrete strength estimation method using piezoelectric guided-wave signal. For this, the embedded smart sensor and strength estimation method using embedded smart sensor is developed.

2 DEVELOPMENT OF CONCRETE STRENGTH ESTIMATION SYSTEM

2.1 Development of embedded smart sensor

Piezoelectric materials, such as PZT(Lead Zirconate Titanate) or MFC(micro fiber composite), exhibit a piezoelectric effect, i.e. an applied mechanical stress generates a surface charge (direct effect), and conversely, an applied electric field produces mechanical strain (converse effect). This piezoelectric effect is given by the following Eq.(1):

$$\begin{aligned} S &= s^E T + dE \\ D &= dT + \varepsilon^T E \end{aligned} \tag{1}$$

where S is the mechanical strain, T is the mechanical stress, D is the dielectric displacement, E is the applied electric field, s^E is the mechanical compliance measured at a constant electric field, ε^T is the dielectric permittivity measured at constant stress, and d is the piezoelectric constant. Piezoelectric sensors, as shown in Figure 1, can be used as both actuators and sensors on account of their unique molecular structures that allow bidirectional electromechanical coupling between the electric field and strain (Liang et al. 1994).

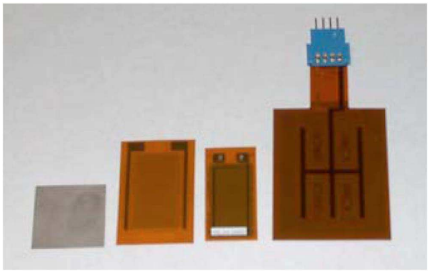

Figure 1. Piezoelectric sensors

To measure inside of strength, the PZT should embed into the concrete structure. However PZT cannot against the impact or other environmental damage inside of concrete because it can be easily fractured. Therefore to embed PZT into the concrete, the embedded smart sensor was developed.
The embedded smart sensor was manufactured using steel plate and PZT sensors as shown in Figure 2. The steel plate protects the PZT sensors from impact from concrete and other environmental condition and provides the wave path of guided-wave signal.

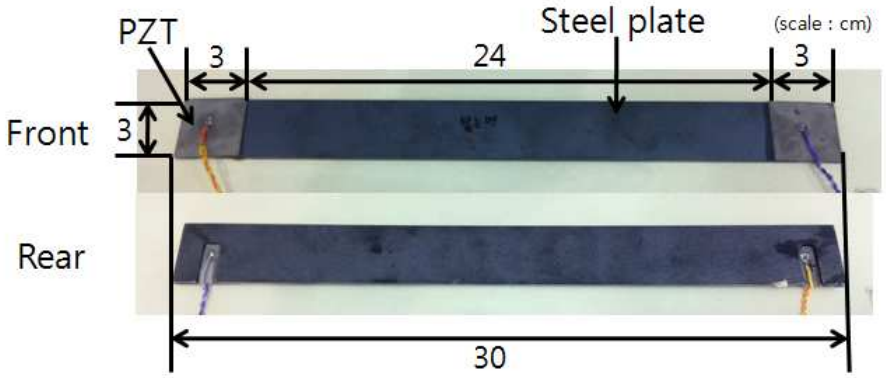

Figure 2. Embedded smart sensor

2.2 Development of Concrete strength estimation equation

The guided-wave is the combination of longitudinal wave (C_L) and transverse wave (C_T). The velocity of each wave is calculated by the elastic coefficient (E), Poisson's ratio (ν), and density (ρ) of host structure (Inman 2004).

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2}$$

$$C_L = \sqrt{\frac{E}{2\rho(1+\nu)}} \tag{3}$$

During the curing process, these variables are varied by changing of strength of concrete. Especially, the elastic coefficient is dominantly increased according to strength gain. Therefore the wave velocity is getting faster due to strength increase.
To estimate the concrete strength, the strength estimation equation was established using the relationship between strength of concrete and velocity of wave propagation using linear regression method as shown in Eq. (4).

$$S = aV_w + b \tag{4}$$

Where S is the strength of concrete (MPa), V_w is the wave propagation velocity, and a and b is the estimation coefficient derived by experimental study.

3 EXPERIMENTAL STUDY

3.1 Experimental setup

Test specimen was the Φ90x30cm unreinforced concrete and the embedded smart sensor was embedded as shown in Figure 3. The guided-wave signal was measured by NI-PXI DAQ system. The guided-wave was actuated using 140kHz Morelet wavelet based tone-burst signal because it can propagated through the steel plate of embedded smart sensor under the concrete media.

Test was performed at 2, 3, 4, 5, 7, 10, 11, 14, 21, 28 day after cast. The guided-wave signal was measured each test day and to measure actual strength of concrete, the compressive strength test was performed same time using standard concrete cylinder which casted same concrete and time with test specimen.

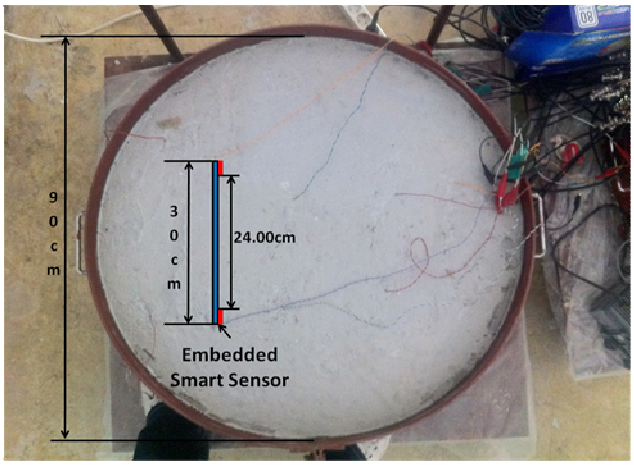

Figure 3. Test specimen

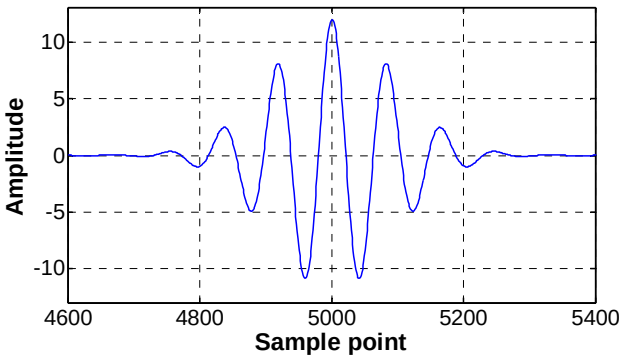

Figure 4. Input signal

3.2 Test results and establish strength estimation equation

The representative guided-wave results are shown in figure 5. The travel time of the peak with maximum amplitude is getting shorter according to the strength gain of host structure. The packet approached time was extracted and the wave propagation velocity of each test day was calculated. As shown in Table 1, the wave propagation velocity was linearly increased due to the strength development.

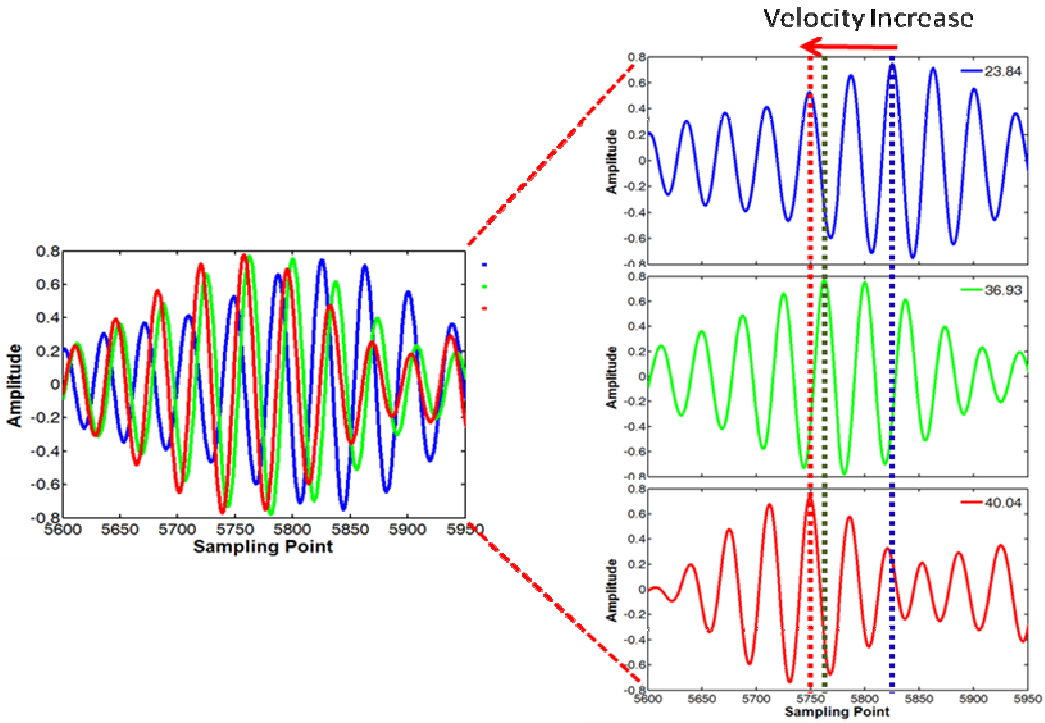

Figure 5. Wave propagation velocity variation

Table 1. Test result

Curing Age	*Strength (MPa)*	*Packet approached sampling point*	*Propagation velocity(m/s)*
2	10.29	5858	1398.601
3	23.84	5825	1454.545
4	26.57	5792	1515.152
5	30.01	5777	1544.402
7	35.67	5764	1570.681
10	36.93	5762	1574.803
11	37.65	5759	1581.028
14	40.04	5756	1587.302
21	42.99	5751	1597.87
28	43.9	5748	1604.278

$$S = 0.149V_w - 197 \qquad R^2 = 0.9552 \tag{5}$$

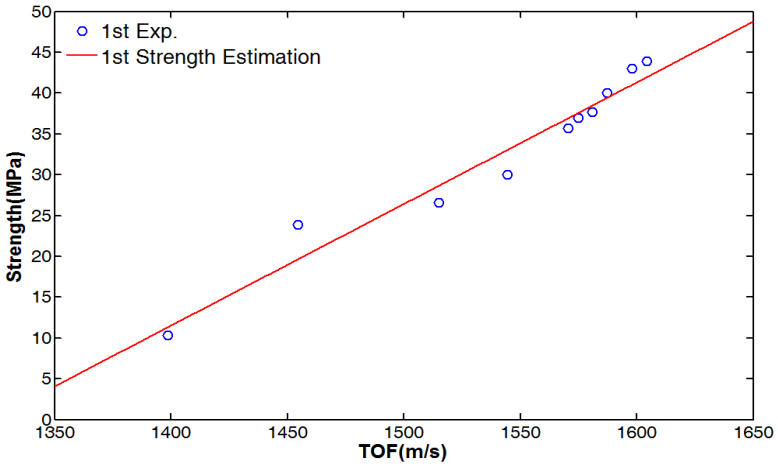

Figure 6. Linear regression result

The strength estimation equation was established by linear regression using wave velocities and the strength as shown in figure 6. And Eq. (5). It is found that the strength estimation has high accuracy through high R-squared value. Therefore it is confirmed the strength estimation system using guided-wave velocity can be the one of strength estimation method.

4 CONCLUSION

This study proposed a real-time concrete strength estimation system using embedded smart sensor. To estimate the absolute strength of concrete continuously during its curing process, the guided-wave methods, which are normally used to detect structural damage nondestructively, was applied. To embed piezoelectric sensor into the concrete, the embedded smart sensor was developed using steel plate. The steel plate protects the piezoelectric sensor and provides the wave path. The guided-wave velocity varied according to the strength development of host concrete structure during curing process. The experimental results showed that the wave propagation velocity is linearly increased due to strength development. The strength estimation equation with high accuracy was established by the linear regression method using wave velocities and measured compressive strength of specimen. Overally, it is confirmed that the concrete strength estimation equation using the embedded smart sensor can be used effectively to obtain the absolute strength of the concrete structures.

ACKNOWLEDGEMENTS

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