초기 재령 콘크리트의 모니터링을 위한 개선된 레일리파 속도 측정 기법

Improved Rayleigh Wave Velocity Measurement Technique for Early-age Concrete Monitoring

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ABSTRACT

A modified one-sided measurement technique is proposed for Rayleigh wave (R-wave) velocity measurement in concrete. The scattering from heterogeneity may affect the waveforms of R-waves in concrete, which may make the R-waves dispersive. Conventional one-sided techniques do not consider the scattering dispersion of R-waves in concrete. In this study, the maximum energy arrival concept is adopted to determine the wave velocity by employing its continuous wavelet transform. Experimental study was performed to show the effectiveness of the proposed method. The present method is applied to monitor the strength development of early-age concrete. A series of experiments were performed on early-age concrete specimens with various curing conditions. Results reveal that the proposed method can be effectively used to measure the R-wave velocity in concrete structures and to monitor the strength development of early-age concrete.

Keywords: Rayleigh Wave Velocity Measurement in Concrete, One-sided Technique, Wavelet Transform, Nondestructive Curing Monitoring

1. Introduction

Ultrasonic wave-based nondestructive testing and evaluation (NDT & E) methods have been developed for over 60 years and have been successfully applied to many civil infrastructures in the context of safety assessment of existing structures. Especially the impact-based one-sided technique (IBOST) has been frequently used, when the opposite sides of the tested members are inaccessible for through-thickness tests, or the sizes are too large for pulse-echo tests [1,2,3]. Recently efforts toward the accurate one-sided measurement of the longitudinal wave (L-wave) velocity in concrete have been shown significant improvement [3]. However, there were few improvements for one-sided velocity measurement for Rayleigh waves (R-waves) in concrete. Most of the

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previous researches for one-sided R-wave velocity measurement, which requires a fair long distance either between the source and the receiver or between the receivers in order to maintain the homogeneous condition and to ensure stable R-wave velocity measurement [1,2].

A new distance-insensitive technique for one-sided R-wave velocity measurement is developed for concrete structures in this study. The maximum energy arrival concept is adopted to determine the time of flight of R-waves. Continuous wavelet transform (CWT) is employed to this end. Experimental study is performed to show the effectiveness of the proposed method. The proposed method for R-wave velocity measurement is applied to monitor the strength gain of the early-age concrete during the curing. A series of experiments for various curing conditions was performed to relate the R-wave velocity to the strength gain of early-age concrete. The results show that the R-wave velocity and strength gain has a strong relationship.

2. Improved R-wave Velocity Measurement Technique

Since most of the energy generated by an impact is transmitted by R-waves, the maximum energy arrival may be closely related to the carrier R-wave arrival. This concept gives possibility of using a cross correlation method to calculate the maximum energy arrival time. However, the correlation works well only if the signals obtained by the two receivers are similar in shape [4]. In other words, it is valid only for non-dispersive waves. In this study, CWT is used to calculate the maximum energy point considering its merit for robustness of time-frequency tiling. Since the time-frequency tiling of CWT can be varying, it is very effective to calculate the maximum energy arrival point for dispersive signals. CWT can be expressed mathematically as follows [5],

$$W(a,t)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}s(\tau)g(\frac{\tau-t}{a})d\tau \qquad a\neq 0 \tag{1}$$

where $g(t)$ is a mother wavelet, and a is a scale parameter. $W(a,t)$ is a wavelet coefficient for a given time domain signal $s(t)$.

With CWT, a wavelet coefficient can be obtained by correlating the time domain signal with a dilated (or scaled) mother wavelet (sometimes called the basis). Dilation is a process of changing the size of the time-frequency tiling and is a key feature of CWT.

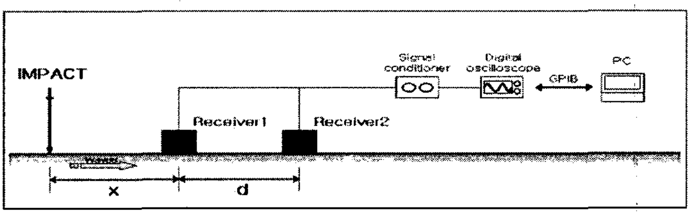

Figure 1. Experimental Set-up for IBOST

Referring the experimental setup shown in Figure 1, the R-wave velocity can be determined from the maximum energy points of the signals from two receivers as,

$$C_R = \frac{d}{\Delta T} \tag{2}$$

where d is the known distance between two receivers, and ΔT is the time of flight of the maximum energy point between two receivers, which is obtained from

$$\Delta T = (t|a_1)_2 - (t|a_1)_1 \tag{3}$$

where $(t|a_1)_1$ is the time of maximum value occurrence in the near receiver's wavelet coefficient $W_1(a,t)$ for a scale a_1 (which is the scale of near receiver's maximum value occurrence), and $(t|a_1)_2$ is the time of maximum value occurrence in the far receiver's wavelet coefficient $W_2(a,t)$ for the scale a_1. Note that the far receiver's maximum energy point should be determined at given scale a_1 which is the scale of the near receiver's maximum energy point.

3. Experimental Study for R-wave Velocity Measurement

A series of experiments were conducted on two concrete specimens of different compositions to demonstrate the effectiveness of the proposed method. Detailed descriptions of the specimen can be found in Table 1. Nominal coarse aggregate size of the concrete specimen is ranged in 20-25 (mm). The concrete specimens were cured in room conditions for 24 hours after vibrating compaction. Then the molds were stripped and they were placed in a curing room with controlled humidity and temperature for 28 days. Compressive strengths were evaluated at the 28th day. The experimental set-up, as shown in Figure 1, consists of an impact source (air-gun), two receiving miniature accelerometers (PCB 353), a signal conditioner, and a digital oscilloscope connecting to a personal computer with GPIB interface system [3]. The transient signals are digitized with 2500 points using a sampling rate of 0.04 μs. In this study, several cases of the distance between two receivers are considered to investigate the distance effect. The distance between the source and the near receiver is set to be 50 mm.

Table 1. Specimen Descriptions

Materials	Dimensions (cm)			Compositions	Ages (Days)	Compressive Strength
	Width	Length	Height	(w:c:fa:ca)*		(MPa)
Concrete 1	40	40	15	0.38:1:1.55:2.11	28-40	49
Concrete 2	40	40	15	0.69:1:2.67:4.05	28-40	26

* (c:cement, w:water, fa:fine aggregates, ca:coarse aggregates, ratios by mass)

One-sided velocity measurements were taken for all the tests. For each test, ten repeated measurements were carried out to remove background noise effect. Five different cases for the spacing (d) between Receivers 1 and 2 were considered for concrete specimens, i.e., 50, 70, 100, 130, and 200 (mm). Two conventional IBOST methods for R-wave velocity measurement are considered for comparison. IBOST 1 denotes a group velocity approach which uses the time difference between the first significant peaks in the time domain signals from two receivers. This approach was applied by Sansalone [1] and Popovics [3]. IBOST 2 is the cross-correlation method that uses the time lag of the maximum correlation between the two signals as applied by Wu [2]. The Gabor mother wavelet is applied here, which is most widely used owing to its simple structure [6]

Figures 2 and 3 show the R-wave velocities estimated from the tests with various spacings between two receivers. It shows that the proposed method gives results much less sensitive to the spacing than the other conventional methods. Particularly, if the spacing is shorter than 130 mm, the proposed method gives more consistent estimates than the conventional methods. The results suggest that the proposed method is superior over the conventional methods, because the maximum deviations among 50 sets (10 measurements each for 5 spacing cases) of the results are notably less than those of the conventional methods.

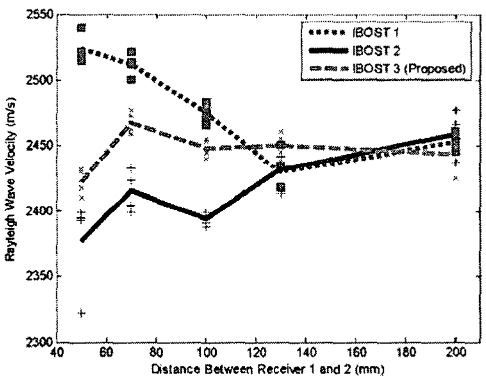

Figure 2. Rayleigh Wave Velocities (Concrete 1)

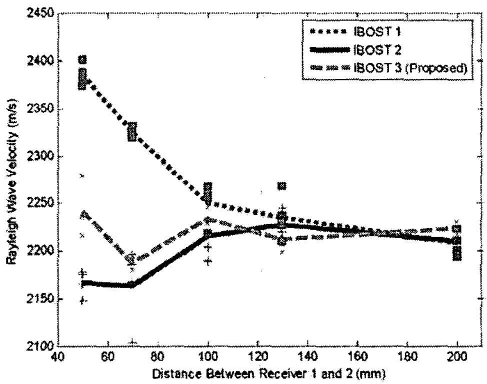

Figure 3. Rayleigh Wave Velocities (Concrete 2)

3. Application for Nondestructive Concrete Strength Gain Monitoring

As an application of the new proposed method, R-wave velocity using the IBOST3 analysis scheme is applied to monitor the compressive strength of early-age concrete. Though there are many factors influencing the strength gain of early-age concrete, only differences in curing condition are considered in this study. To this end, three batches of concrete with an identical mixture design were prepared with Type I Portland cement as binding matrix, natural sand as fine aggregate, and crushed gravels of 25mm nominal maximum size as coarse aggregate. The target design strength was 48 MPa. Three rectangular specimens (A, B, C) for different curing conditions were prepared for R-wave velocity measurements as shown in Table 2.

Table 2. Descriptions of Rectangular Specimen for Velocity Measurement

Groups	Dimensions (cm)			Compositions (w:c:fa:ca)*	Curing Condition	28th Day Compressive Strength (MPa)
	Width	Length	Height			
Concrete A					Water Bath Cured (Controlled Moisture and Temperature)	52
Concrete B	40	40	15	0.38:1:1.55:2.11	Air Cured with Plastic Sheet Covering (Controlled Temperature)	47
Concrete C					Air Cured (Uncontrolled)	38

* (c:cement, w:water, fa:fine aggregates, ca:coarse aggregates)

Immediately after mixing, 21 cylinders with a diameter of 100 mm and a height of 200 mm were prepared according to the Korean Concrete Code (KS F 2403) from each batch for the compressive strength tests at 7 different ages. Compressive strengths were determined at the ages of 2, 5, 7, 10, 15, 21 and 28 days following the code (KS F 2405). The compressive strengths on the final 28th day for different curing conditions are listed at Table 1. The R-wave velocity measurements were conducted on the rectangular specimen of each group and the compression tests were conducted on the cylinder specimens of each group at 7 different ages. For Group A, the tests for R-wave velocity and strength were made no less than 3 hours after removal from the water-bath in order to ensure constant moisture content.

As shown in Figure 4, it can be observed that the R-wave velocities of all groups increase as the curing age increases. The R-wave velocity rapidly increases until the 7th day, then it slowly increases to the final values for Groups A and B, while the R-wave velocity increases rapidly until 10th day for Group C. Similar trends can be observed for the compressive strength against the curing age in Figure 5.

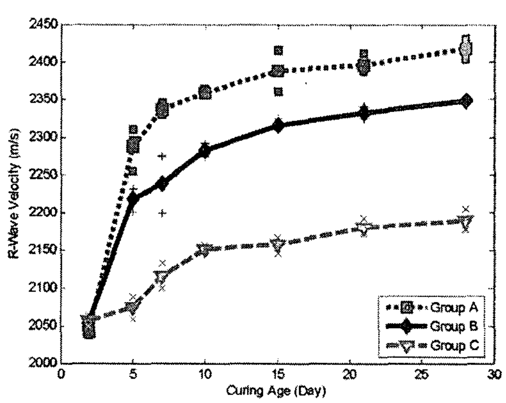

Figure 4. R-wave Velocities vs. Curing Ages

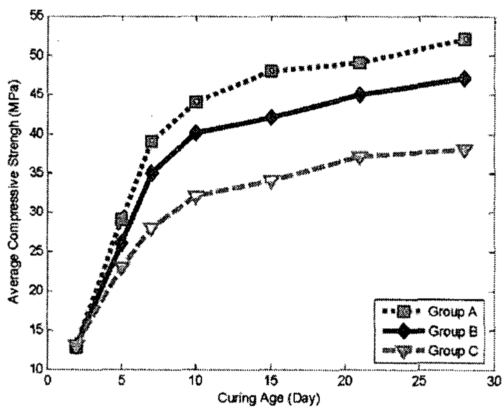

Figure 5. Compressive Strengths vs. Curing Ages

The above results indicate that the R-wave velocity may be used an indicator of the strength gain of the early-age concrete with proper curing conditions such as Groups A and B. Particularly, the results of Group B suggest that the R-wave velocity measurement may be directly applied in practice, because the curing condition for Group B is very similar to the real field condition. It can be observed that the final strength and R-wave velocity of each group are significantly different depending on the curing condition. For Group C, 27% significant reduction of the compressive strength and 11% of the R-wave velocity are observed compared with Group A. On the other hand, for Group B, less significant reductions are observed with 8% in the strength and 5% in the velocity. Similar results were reported on the effect of the curing conditions to the final strength of concrete by Price [7].

5. Conclusions

In this study, an improved technique is proposed for one-sided R-wave velocity measurement in concrete and, it is applied to monitor the strength gain of the early-age concrete. By using the continuous wavelet transform, the proposed method can effectively consider the scattering effects in the R-wave velocity measurement. It has been found from the experimental study that the proposed method gives R-wave velocity less-sensitive to the distance between two receivers, while the performance of the conventional methods strongly depends on the distance. Thus, the present method may be effectively applied to nondestructive testing for concrete structures. From the strength gain monitoring experiment, it can be concluded that the R-wave velocity may be used as a monitoring index for the strength development of the early-age concrete. It has been found that the R-wave velocity increases rapidly within the 7^{th} day, then it increases slowly to the final value for the properly cured concrete.

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