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Investigation of influences of mixing parameters on acoustoelastic coefficient of concrete using coda wave interferometry

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Abstract. The stress dependence of ultrasonic wave velocity is known as the acoustoelastic effect. This effect is useful for stress monitoring if the acoustoelastic coefficient of a subject medium is known. The acoustoelastic coefficients of metallic materials such as steel have been studied widely. However, the acoustoelastic coefficient of concrete has not been well understood yet. Basic constituents of concrete are water, cement, and aggregates. The mix proportion of those constituents greatly affects many mechanical and physical properties of concrete and so does the acoustoelastic coefficient of concrete. In this study, influence of the water-cement ratio (w/c ratio) and the fine-coarse aggregates ratio (fa/ta ratio) on the acoustoelastic coefficient of concrete was investigated. The w/c and the fa/ta ratios are important parameters in mix design and affect wave behaviors in concrete. Load-controlled uni-axial compression tests were performed on concrete specimens. Ultrasonic wave measurements were also performed during the compression tests. The stretching coda wave interferometry method was used to obtain the relative velocity change of ultrasonic waves with respect to the stress level of the specimens. From the experimental results, it was found that the w/c ratio greatly affects the acoustoelastic coefficient while the fa/ta ratio does not. The acoustoelastic coefficient increased from 0.003073 MPa^{-1} to 0.005553 MPa^{-1} when the w/c ratio was increased from 0.4 to 0.5. On the other hand, the acoustoelastic coefficient changed in small from 0.003606 MPa^{-1} to 0.003801 MPa^{-1} when the fa/ta ratio was increased from 0.3 to 0.5. Finally, it was also found that the relative velocity change has a linear relationship with the stress level of concrete.

Keywords: acoustoelastic effect of concrete; acoustoelastic coefficient of concrete; coda wave interferometry; ultrasonic based stress monitoring

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1. Introduction

Stress states in concrete structures can be changed due to overloading, support settlements, corrosion of reinforcements, etc. Therefore, monitoring of the stress state is important and useful for condition assessment and health monitoring of concrete structures.

It is well known that the ultrasonic wave velocity in a solid medium changes with the stress state in the medium (Rose 1999). This stress dependence of the wave velocity is so called as acoustoelastic effect (Toupin and Bernstein 1961). Since the wave velocity is depending on the stress state of a solid medium, the stress state of the medium can directly be monitored from wave velocity measurements given that the acoustoelastic coefficient of the medium is known (Bray and Stanley 1997). Therefore, to develop an acoustoelastic based stress monitoring technique, the acoustoelastic coefficient of a subject material must be characterized in advance. Many efforts have been devoted to characterize the acoustoelastic coefficient of relatively homogeneous materials such as steel (Egle and Bray 1976, Cantrell and Salama 1991, Washer *et al.* 2002, Chaki and Bourse 2009). However, the acoustoelastic coefficient of concrete, a strongly heterogeneous material, has not been well understood yet.

A wave velocity change due to the acoustoelastic effect is very small since theoretically it relies on the higher-order terms of nonlinear stress-strain relation (Hughes and Kelly 1953). Accordingly, an accurate and precise measurement of the wave velocity is essential to detect a small change of the wave velocity from which the acoustoelastic coefficient of materials can be estimated. A conventional time-of-flight (TOF) method is commonly used for wave velocity measurements. The TOF method is accurate and reliable when it applies to relatively homogeneous materials such as steel. However, it may not be effective to apply it for the wave velocity measurement of complex heterogeneous materials since scattering of ultrasonic wave due to heterogeneity of the materials hinders accurate detection of wave arrival time in measured signals (Dai *et al*. 2013). A usual error of the TOF method used for the velocity measurement of concrete is higher than 1% (Popovics *et al.* 1998), while the velocity change due to acoustoelastic effect of concrete is often lower than 1%. Therefore, it is unreliable to use the TOF method for detection of the wave velocity change due to the acoustoelastic effect of concrete.

In 2009, it was successfully showed that the wave velocity change due to the acoustoelastic effect of concrete can be reliably detected using coda wave interferometry (CWI) technique (Payan *et al*. 2009). By exploiting coda wave of ultrasonic signals, CWI technique can precisely detect and quantify small temporal change of ultrasonic wave propagated through concrete (Shin 2014). After a success in 2009, research on the acoustoelastic effect of concrete using CWI has been rapidly growing. For examples, Schurr et al. showed that alkali-silica reaction (ASR) damage alters the acoustoelastic coefficient of concrete and they suggested to use the acoustoelastic coefficient for detection of ASR damage in concrete (Schurr *et al.* 2011). LiIlamand *et al*. investigated the effects of wave modes (compression and shear waves) and propagating directions (parallel and perpendicular to the loading direction) on the acoustoelastic coefficient of concrete (Lillamand *et al*. 2010). For more on CWI for concrete, refer to the state-of-the art paper (Planes and Larose 2013).

Basic constituents of concrete are water, cement and aggregates. The proportion of those constituents greatly affects mechanical, physical, and chemical properties of concrete (Mindess *et al.* 2002, Mehta and Monteiro 2006). Therefore, the proportion of the constituents may also be influential on the acoustoelastic coefficient of concrete. The water-cement (w/c) ratio and the fine-coarse aggregates (fa/ta) ratio are important parameters in mix proportion design. Moreover, those parameters also affect the behavior of ultrasonic waves in concrete. For example, the w/c ratio significantly affects the wave velocity of concrete, while the fa/ta ratio controls scattering of ultrasonic waves in concrete (Abo-Qudais 2005, Philippidis and Aggelis 2005). However, influences of those parameters on the acoustoelastic coefficient of concrete have not been reported.

In this study, the influences of those two mixing parameters on the acoustoelastic coefficient of concrete are investigated. Ultrasonic wave measurements are conducted in parallel with uni-axial compression tests on 6 groups (3 different w/c ratio groups and 3 different fa/ta ratio groups) of concrete specimens. CWI technique is used to detect and quantify the relative velocity change of ultrasonic waves. Experimental results are analyzed and the influences of the w/c and the fa/ta ratios on the acoustoelastic coefficient of concrete discussed.

2. Theoretical basis

2.1 Acoustoelastic effect of concrete

When compressive load is applied to concrete, bond cracks occur when the level of stress reaches about 30-40 (%) of compressive strength. After then, when the level of stress reaches about 60-70 (%) of compressive strength, mortar cracks, which bridge the bond cracks, are appeared in concrete matrix and developed further with stress increment (Mindess *et al.* 2002, Mehta and Monteiro 2006). Several papers have reported that, above the mortar cracking stress level, ultrasonic wave velocity decreases significantly with stress increment due to cracking effect (Liniers 1987, Popovics and Popovics 1991, Malhotra and Carino 2004). The papers also reported that the velocity maintains almost constant (or slightly increases) when the level is lower than the mortar cracking stress. For this reason, it was believed that, if the level of stress is lower than the mortar cracking stress, the stress state does not affect much on the wave velocity of concrete and can be ignorable (Malhotra and Carino 2004). In reality, although very small, the wave velocity changes with the stress state of concrete even when the level of stress is lower than the mortar cracking stress due to the acoustoelastic effect. For example, using coda wave interferometry technique, it has been shown that the velocity of concrete increases almost linearly until the compressive stress of concrete reaches the mortar cracking stress (Lillamand *et al.* 2010, Stahler *et al.* 2011, Shokouhi *et al*. 2012). It is worth noting that the velocity reduction above the mortar cracking stress level is not due to the acoustoelastic effect but the cracking effect (Shokouhi *et al*. 2010). Therefore, the acoustoelastic effect of concrete is effective only when the level of stress is lower than the mortar cracking stress.

The classical theory of ultrasonic wave propagation assumes a linear elastic behavior of solids (e.g., $\sigma = E\varepsilon$). Under this assumption, the material properties (e.g., elastic constants) of solid medium determine the wave velocity, which is independent of the stress state of the medium. For example, the wave velocity in isotropic solid medium can be expressed using the Lame's elastic constants (λ and μ) and the density (ρ_0) of the medium as

$$V_{ij} = \begin{cases} \sqrt{\dfrac{\lambda + 2\mu}{\rho_0}} & for \quad i = j \\ \sqrt{\dfrac{\mu}{\rho_0}} & for \quad i \neq j \end{cases} \tag{1}$$

where V_{ij} is the velocity of ultrasonic wave propagating in direction i and polarized in direction j (Rose 1999). However, when a solid material exhibits nonlinear elastic behavior, higher-order terms to describe nonlinear behavior should be included in the stress-strain relation (e.g., $\sigma = E\varepsilon(1+\beta\varepsilon)$) and in this case the wave velocity becomes stress dependent (Toupin and Bernstein 1961). Hughes and Kelly derived the following stress-velocity relationship of uni-axially loaded isotropic medium based on Murnaghan's theory of nonlinear elasticity as (Hughes and Kelly 1953, Murnaghan 1951)

$$\begin{cases} \rho_0 V_{11}^2 = \lambda + 2\mu + \dfrac{\sigma}{3K}\left[2l + \lambda + \dfrac{\lambda+\mu}{\mu}(4m + 4\lambda + 10\mu)\right] \\ \rho_0 V_{12}^2 = \rho_0 V_{13}^2 = \mu + \dfrac{\sigma}{3K}\left[m + \dfrac{\lambda n}{4\mu} + 4\lambda + 4\mu\right] \\ \rho_0 V_{22}^2 = \lambda + 2\mu + \dfrac{\sigma}{3K}\left[2l - \dfrac{2\lambda}{\mu}(m + \lambda + 2\mu)\right] \\ \rho_0 V_{21}^2 = \mu + \dfrac{\sigma}{3K}\left[m + \dfrac{\lambda n}{4\mu} + \lambda + 2\mu\right] \\ \rho_0 V_{23}^2 = \mu + \dfrac{\sigma}{3K}\left[m - \dfrac{\lambda+\mu}{2\mu}n - 2\lambda\right] \end{cases} \tag{2}$$

where σ is the normal stress in direction 1, (l, m, n) are the Murnaghan's third order elastic constants, and $K = \lambda + \dfrac{2}{3}\mu$. This stress-velocity relationship can be further generalized using the first order linearization as (Lillamand *et al*. 2010)

$$V_{ij}^{\sigma} = V_{ij}^{0}(1 + \theta_{ij} \cdot \sigma) \tag{3}$$

where V_{ij}^{σ} and V_{ij}^{0} are the stressed and the stress-free (or initial) wave velocities of a medium respectively, θ_{ij} is the acoustoelastic coefficient which depends on the Lame's and the Murnaghan's elastic constants. The stress-free velocity of a medium can be calculated using Eq. (1). It is obvious that the velocity is depending on the stress state (i.e., σ) in the medium. Eq. (3) can be re-written as

$$\sigma = \frac{1}{\theta_{ij}} \frac{V_{ij}^{\sigma} - V_{ij}^{0}}{V_{ij}^{0}} = \frac{1}{\theta_{ij}} \frac{\Delta V_{ij}}{V_{ij}^{0}} \tag{4}$$

Therefore, if the acoustoelastic coefficient (θ_{ij}) of a medium is known, the current stress state (σ) of the medium can be estimated by measuring the current and the initial wave velocities of the medium. This is the basic idea of the acoustoelastic based stress monitoring technique.

As shown in Eq. (4), the acoustoelastic coefficient of an interesting medium must be known in advance to monitor the stress state of the medium based on wave velocity measurements. Since the acoustoelastic coefficient of a material cannot be determined analytically, an experiment to establish the following velocity-stress relation should be performed. Rearranging Eq. (4) and introducing an index for relative velocity change (α_{ij}), the velocity-stress relation can be expressed as (Zhang *et al*. 2012)

$$\frac{\Delta V_{ij}}{V_{ij}^{0}} = \theta_{ij} \cdot \sigma = \alpha_{ij} \tag{5}$$

This suggests that the acoustoelastic coefficient (θ) can be determined by estimating the slope of $\alpha - \sigma$ relation. In this study, influences of two mixing parameters (the w/c and the fa/ta ratios) on the acoustoelastic coefficient of concrete is investigated.

2.2 Coda Wave Interferometry (CWI) technique

As shown in the previous section, theoretically the acoustoelastic effect relies on the higher order terms of nonlinear stress-strain relation. Accordingly, a velocity change due to the acoustoelastic effect is very small (e.g., 0.01-0.1% /MPa for concrete Planes and Larose 2013) so that a precise velocity measurement method must be applied to accurately estimate the acoustoelastic coefficient (θ) from the relative velocity change (α) measurements. CWI technique is useful for this purpose.

CWI was originally developed for detection and quantification of small temporal change between two seismic waves originating from the same source (Snieder *et al*. 2002). As originated from seismology, *coda wave* means a tail of seismogram after an earthquake. When ultrasonic wave propagates through a complex heterogeneous medium, multiple scattering occurs due to heterogeneities of the medium. Since these multiply scattered wave (i.e., coda wave) travelled longer distance than the directly propagated wave (i.e., ballistic wave), coda wave forms later part of ultrasonic signal while ballistic wave forms early part (Pacheco and Snieder 2006). Coda wave has more information on the medium than ballistic wave as it travelled longer distance and interacted more with the medium. Therefore, a small change in the medium, that is hardly detected in ballistic wave, becomes detectable in coda wave (Planes and Larose 2013). CWI utilizes a complex medium (e.g., concrete) as an interferometer of coda wave in order to detect small temporal change of a complex medium (Snieder *et al*. 2002). It has been proven that the CWI technique carried out on concrete can provide a precise evaluation of the wave velocity variation (0.001 %) (Larose and Hall 2009, Shin 2014). This confirms that the potential of the CWI as a promising technique for acoustoelastic based stress monitoring of concrete. Theory of the CWI technique is briefly given here. For more details on the theory of CWI, refer to the state-of-the-art paper by Snieder (2006).

Suppose that in a medium the wave velocity is perturbed with the perturbation dV, and the relative velocity change dV/V is the same at every location in the medium. The unperturbed travel time of the wave is given by

$$t = \int_P \frac{1}{V} ds \tag{6}$$

where P is wave path. The perturbed travel time to the first order in the velocity perturbation is given by

$$t + dt = \int_P \frac{1}{V + dV} ds = \int_P \left(\frac{1}{V} - \frac{dV}{V^2} \right) ds = \int_P \frac{1}{V} ds - \int_P \frac{dV}{V^2} ds \tag{7}$$

Since dV/V is assumed to be constant, Eq. (7) can be re-arranged using Eq. (6) as

$$dt = -\int_P \frac{1}{V} \frac{dV}{V} ds = -\frac{dV}{V} \int_P \frac{1}{V} ds = -\left(\frac{dV}{V} \right) t \tag{8}$$

According to Eq. (8), the travel time perturbation depends only on the arrival time of the wave, but is independent of the particular wave path. This indicates that the travel time perturbation increases linearly with the arrival time. Therefore, the travel time perturbation due to the acoustoelastic effect is more clearly identified in coda wave than ballistic wave as coda wave arrives later than ballistic wave.

Eq. (8) can be related with Eq. (5) as

$$\alpha = \frac{dV}{V} = -\frac{dt}{t} \tag{9}$$

To obtain α from coda wave in measured signals, two cross correlation based methods (the doublet and the stretching methods) are available. However, the stretching method is most widely used as it is more robust than the doublet method (Hadziioannou *et al*. 2009). The stretching method begins with measuring the reference (i.e., unperturbed wave signal; $u_0(t)$) and the object (i.e., perturbed wave signal; $u_p(t)$) signals (Larose and Hall 2009). When the medium is perturbed due to the acoustoelastic effect, the arrival time of the wave is perturbed with dt from the unperturbed wave. Therefore, the relationship between the unperturbed and the perturbed signals can be written as

$$u_p(t) = u_0(t + dt) \tag{10}$$

Using Eqs. (8) and (9), Eq. (10) can be re-written as

$$u_p(t) = u_0(t - \frac{dV}{V} t) = u_0[t(1-\alpha)] \tag{11}$$

This relation suggests that the value α can be estimated by stretching (or compressing) the unperturbed wave signal to match a perturbed wave signal. The quality of the match between the stretched unperturbed wave signal and the perturbed wave signal within time-window $[t_1, t_2]$, in which possesses coda wave, can be quantified with the following cross-correlation function as

3. Experimental program

3.1 Specimen preparation

Table 1 Mix Design of Test Specimens

Groups	w/c ratios (by weight)	fa/ta ratios (by volume)	Unit Contents (kgf/m^3)			
			Water (w)	Cement (c)	Fine Aggregates (fa)	Coarse Aggregates (ca)
WC40	0.4		165	412.5	899.6	934.2
WC45	0.45	0.5	165	366.67	920.4	954.45
WC50	0.50		165	330	933.4	969.3
FT30		0.3	165	366.67	551.2	1336.23
FT40	0.45	0.4	165	366.67	733.2	1145.34
FT50		0.5	165	366.67	920.4	954.45

In this study, the water-cement (w/c) ratio and the fine aggregate (fa/ta) ratio are selected to investigate the influences of those parameters on the acoustoelastic effect of concrete. Both the w/c and the fa/ta ratios are important parameters in mix proportion design and affecting not only material properties of concrete but also wave behaviors in concrete.

6 groups of concrete specimens (3 different w/c ratio groups and 3 different fa/ta ratio groups) are prepared and tested. The dimensions of all specimens are $20\times20\times40$ (cm^3). A mix design for each group is listed in Table 1. The mix design follows the Korean Concrete Institute (KCI) standard which is in accordance with American Concrete Institute (ACI) standard. It is worth noting that, in standard mix design, the w/c ratio is defined as a weight ratio between water and cement, while the fa/ta ratio is practically defined as a volume ratio between fine aggregate (fa) content and total aggregate (ta) content. As shown in Table 1, in WC groups, the w/c ratio (by weight) is varied from 0.4 to 0.5, while the fa/ta ratio (by volume) remains constant as 50%. On the other hand, in FT groups, the fa/ta ratio is varied from 30% to 50% while the w/c ratio remains constant as 0.45. The cement used is the Type I Portland cement. Well-graded river sands and crushed gravels are used as the fine and the coarse aggregates respectively. Nominal maximum size of the fine and coarse aggregates are 1 mm and 25 mm, respectively. After casting, all specimens were stored in temperature controlled water bath (controlled temperature : 21℃) and cured for 28 days. After the water bath curing, all specimens were removed from the water bath and remained in a dry room until test.

$$CC(\alpha_i)=\frac{\int_{t_1}^{t_2}u_0[t(1-\alpha_i)]u_p[t]dt}{\sqrt{\int_{t_1}^{t_2}u_0^2[t(1-\alpha_i)]dt\int_{t_1}^{t_2}u_p^2[t]dt}} \tag{12}$$

where α_i is a stretching parameter. The key parameter in the stretching CWI technique is the choice of a time window $[t_1,t_2]$. Determination of the size of the time window will be explained in Section 4.1. Finally, α can be found among all values of α_i that maximize the correlation coefficient as

$$\alpha = \max_{\alpha_i \in \Gamma} CC(\alpha_i) \tag{13}$$

where Γ is a domain of α_i (Larose and Hall 2009). In this study, the stretching method is used to obtain $\alpha - \sigma$ relation of concrete.

3.2 Test setup and procedures

In order to obtain the relative velocity change (α) with respect to the stress state of a concrete specimen, ultrasonic wave measurements are executed during the uni-axial compression tests on the specimens. The ultrasonic wave measurement setup and the uni-axial compression test setup are shown in Figs. 1 and 2. A pair of ultrasonic transducers with a central frequency 100 kHz (Model : Olympus V1011) was used for transmitting and receiving of ultrasonic waves. To minimize stress gradient in the test region of the specimen, both transducers were attached on the middle of two opposite sides of the specimen (see Fig. 2). Therefore, the direction of wave propagation (2 direction) is set to be perpendicular to the direction of loading (1 direction). Note that since the transducer used in this study generates compressional ultrasonic wave, the mode of the wave velocity becomes V_{22}. In order to ensure constant contact between the transducers and the surface of the specimen over the entire duration of the test, the transducers are tied with green duct tape as shown in Fig. 2. The input signal is 10 cycles of (hanning) windowed sine function with an oscillation frequency of 100 kHz. A waveform generator and a power amplifier are used to generate the input signal. The received signal is also amplified with a preamplifier and then digitized by a AD converter with a sampling rate of 1 μs and a duration of 2 ms. The digitized signals are saved in a personal computer for further signal processing.

The uni-axial compression tests on the concrete specimens are performed using a 1500 kN capacity hydraulic testing machine (INSTRON 1500HDX). The top and bottom surfaces of the test specimens are polished to avoid an imperfect contact with loading plates when the specimens are compressed, as well as to achieve two parallel faces. Load-controlled compression tests were performed on the specimens.

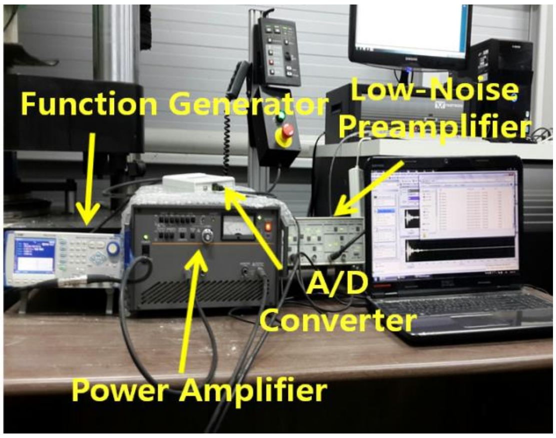


Fig. 1 Ultrasonic Measurement Setup

Fig. 2 Uni-axial Compression Test Setup

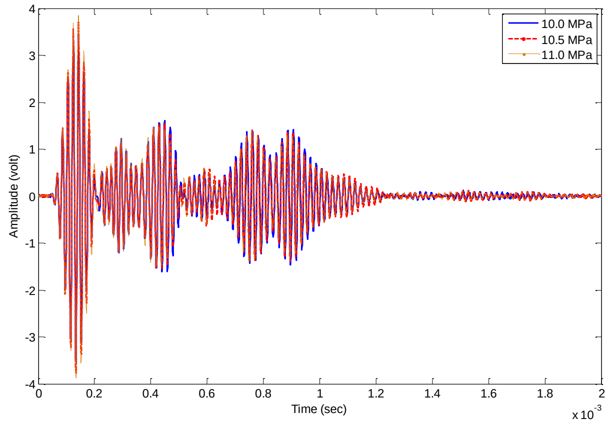
As described, the wave velocity in concrete increases linearly until the compressive stress of concrete reaches the mortar cracking stress (Lillamand *et al.* 2010, Stahler *et al.* 2011, Shokouhi *et al*. 2012). Thus, the test stress range is not important in the estimation of the acoustoelastic coefficient of concrete if the range is lower than the mortar cracking stress level. In this study, test stress range is set from 10 to 11 MPa with 0.1 MPa of load increment step, which is well below the mortar cracking stress level of the test specimens : this will be further discussed in Section 4.3. Ultrasonic measurements are performed at each loading step. The applied load is maintained constant during the ultrasonic measurement. After the measurement, the compressive load is slowly increased to the next step load and then the ultrasonic measurement is repeated.

4. Results and discussions

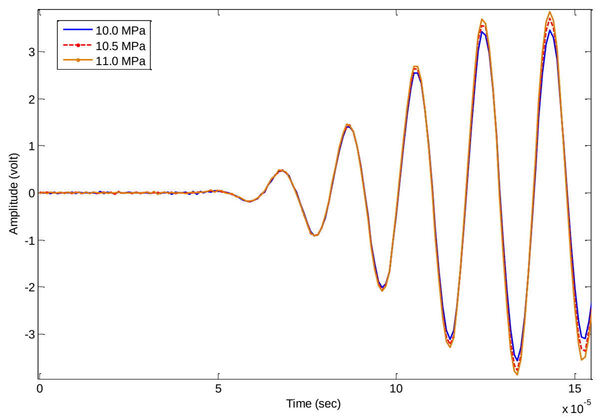
4.1 Coda wave analysis

Typical ultrasonic signals measured at different stress states (10.0 MPa, 10.5 MPa and 11.0 MPa) are shown in Figs. 3(a)-3(d). Note that similar wave behaviors are also observed for all other groups. As seen in Figure 3 (a), those three signals seem to be almost identical over the entire duration of the signals. However, notable phase changes of ultrasonic waves are clearly seen in the later part of the measured wave signals as shown in Figs. 3(c) and 3(d). In contrast, in the early part shown in Fig. 3(b), it is observed that the arrival of ultrasonic wave is not visibly discernible (almost identical) nevertheless of the different stress states. Therefore, it is confirmed that the conventional TOF method, which detects the flight time of the first arrival wave, is not an effective method to identify the acoustoelastic effect of concrete. The result also proves the validity of Eq. (8) and hence confirms the effectiveness of coda wave to identify the acoustoelastic effect of concrete.

In order to establish $\alpha-\sigma$ relation, α value for each load step must be obtained. In this study, the stretching CWI technique as provided in Eqs. (12) and (13) is used to obtain α values. The key parameter in the stretching CWI technique is the choice of a time window $[t_1, t_2]$ in which possesses coda wave. The start time of the window t_1 needs to be late enough to ensure the waves have been propagating for a long enough time to be sufficiently scattered. The propagation distance of the wave has been suggested to be (at least) 4 times larger than the length of the mean free path in order to be sufficiently scattered (Pacheco and Snieder 2005, Zhang *et al*. 2012). On the other hand, the end time of the window t_2 is limited by the signal quality (i.e., the signal-to-noise ratio) since the wave energy becomes increasingly dissipated for longer propagation times (Zhang *et al*. 2012). Therefore, t_2, which should be larger than t_1, is at least smaller than the duration of measured signal. As shown in Fig. 3(c), $[t_1, t_2] = [750\mu s, 1000\mu s]$ is chosen in this study. Because, the signal quality is relatively poor after 1100 μs in most cases: see Fig. 3(d). While 750 μs is about 5 times larger than the arrival time of the first largest wave component of the reference ultrasonic signal.

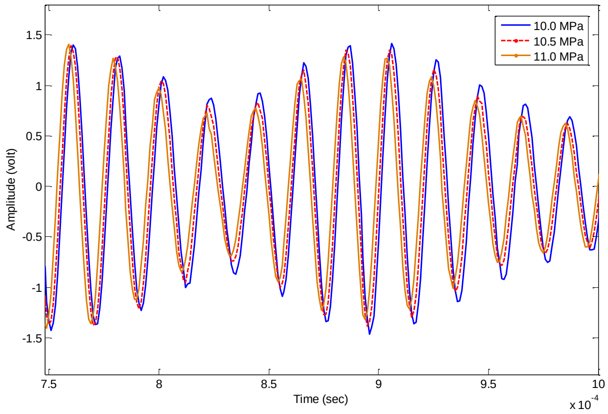


(a) Full Signals

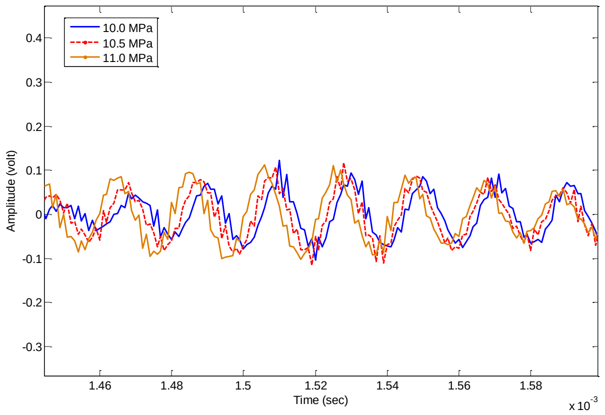


(b) Early Part (from 0 to 150 μs) of Full Signals

Continued-



(c) Later Part (from 750 to 1000) of Full Signals



(d) Later Part (from 1450 to 1600 μs) of Full Signals

Fig. 3 Measured Ultrasonic Signals at 3 Different Stress Levels (WC40 Case)

4.2 Influences of mixing parameters

The relative velocity change (α) with respect to the stress state of WC groups are shown in Fig. 4. It is noting that the ultrasonic signals measured at the stress level of 10 MPa were selected as the reference signals $u_0(t)$ for stretching CWI processing. It is clearly seen that, regardless of the w/c ratio, the α value increases as the compressive stress increases. However, it is also seen that the increasing trend is different with the w/c ratio. It tends that the higher the w/c ratio, the steeper the increasing trend. The acoustoelastic coefficients (θ), which are represented as slopes in Fig. 4, are estimated using linear regression analysis. Fig. 5 shows the estimated acoustoelastic coefficients with correlation coefficient (R^2) values. Correlation coefficients are larger than 0.98 for all cases, which indicates that the $\alpha - \sigma$ relation is linear. The estimated acoustoelastic coefficient varies from 0.003073-0.005553 MPa^{-1}, which falls into the published value for normal concrete (Planes and Larose 2013). It is obvious that the acoustoelastic coefficient is dependent on the w/c ratio, i.e., the higher the w/c ratio, the larger the acoustoelastic coefficient. This result suggests that the velocity variation due to acoutoeslatic effect is more pronounced if the w/c ratio of the concrete is relatively high.

On the other hand, Fig. 6 shows the $\alpha - \sigma$ relations of FT groups. Ultrasonic signals measured at the stress level of 10 MPa were also used as the reference signals. It is seen that, similar to WC groups, the α value increases as the compressive stress increases regardless of the fa/ta ratio. One distinction from the result of the WC group is that the acoustoelastic coefficient (θ) is not much changed with the fa/ta ratio. Fig. 7 shows the estimated acoustoelastic coefficients with R^2 values for FT groups. R^2 values are also very high (>0.97) for all cases. The estimated acoustoelastic coefficient varies from 0.003606-0.003801 MPa^{-1} for FT groups, and which is greatly narrower than that of the WC groups. The variation of the acoustoelastic coefficient for the WC groups is about 180% (0.005553/0.003073) while that for the FT groups is 5.4% (0.003801/0.003606). This indicates that the fa/ta ratio of concrete is less influential than the w/c ratio on the acoustoelastic behavior of concrete. The less-influential of the fa/ta ratio on the acoustoelastic coefficient gives a following insight on the acoustoelastic behavior of concrete. Figure 8 shows the reference signals for FT30 and FT50 cases. Different signal behaviors are observed in this figure. This difference in signal behavior mainly comes from the difference of the wave paths. In concrete, the aggregates act as wave scattering sources and thus their sizes and spatial distribution determine the scattering wave paths in concrete (Chaix *et al*. 2006). Therefore, if the sizes and the spatial distribution of the aggregates are fixed in concrete, ultrasonic waves identically introduced in the same position will propagate through the same paths in that concrete. In this case the behaviors of the ultrasonic waves will be almost identical as evidently shown in Fig. 3. In Fig. 3, it is seen that the signal shapes are almost identical excepting phase changes due to acoustoelastic effect. This suggests that the aggregate composition affects the scattering behavior (and hence the wave paths) of ultrasonic waves, but it does not affect the acoustoelastic behavior of concrete.

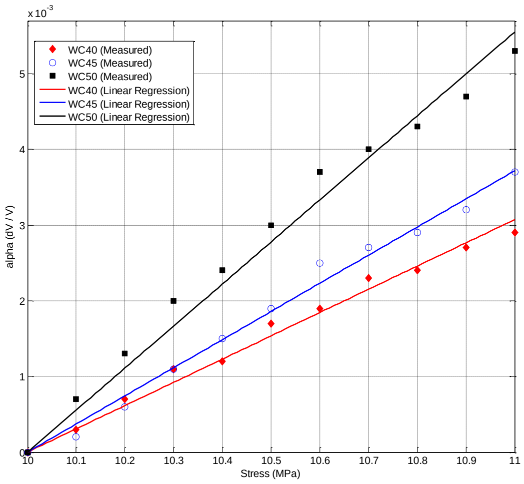


Fig. 4 Relative Velocity Changes of WC groups

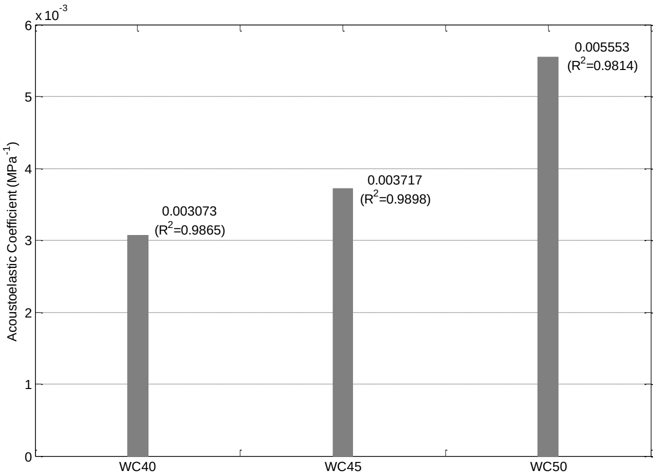


Fig. 5 Estimated Acoustoelastic Coefficients of WC groups

Finally, as shown in Figs. 5 and 7, the w/c ratio more affects the acoustoelastic behavior of concrete than the aggregate composition. It is well known that the strength of concrete depends largely on the w/c ratio but less on the aggregate composition (Mindess *et al.* 2002, Mehta and Monteiro 2006). Therefore, it may be possible to correlate the compressive strength of concrete with the acoustoelastic coefficient of the concrete. In fact, many mechanical properties of concrete relate with the compressive strength (Popovics 1998). Thus, it is reasonable to expect a relationship between the acoustoelstic coefficient and the compressive strength. The relationship between them is currently under investigation.

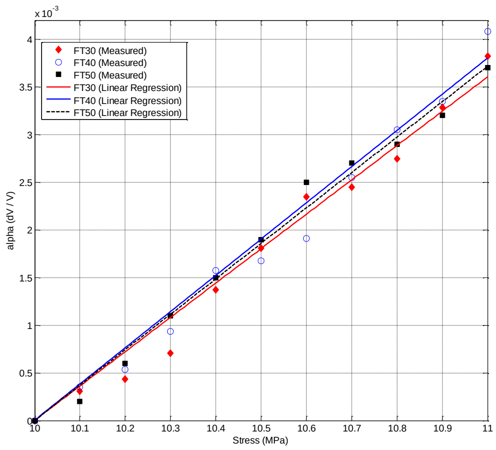


Fig. 6 Relative Velocity Changes of FT groups

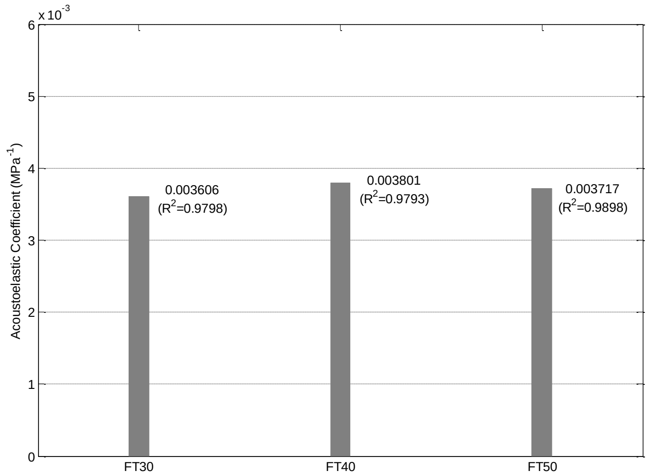


Fig. 7 Estimated Acoustoelastic Coefficients of FT groups

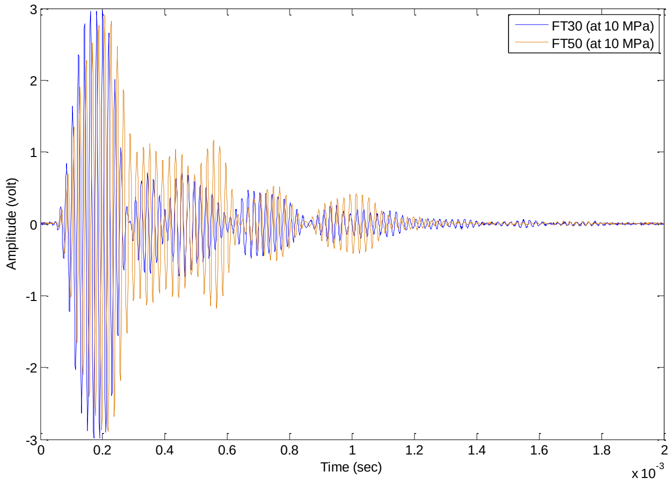


Fig. 8 Measured Ultrasonic Signals at Reference Stress Level (10 MPa) : FT30 and FT50 Cases

4.3 Linearity of acoustoelastic effect of concrete

As described in Section 3.2, since the wave velocity in concrete increases linearly with the stress, test stress range is not important in the estimation of the acoustoelastic coefficient of concrete if the range is lower than the mortar cracking stress level. In this section, the linearity of the acoustoelastic effect of concrete is discussed.

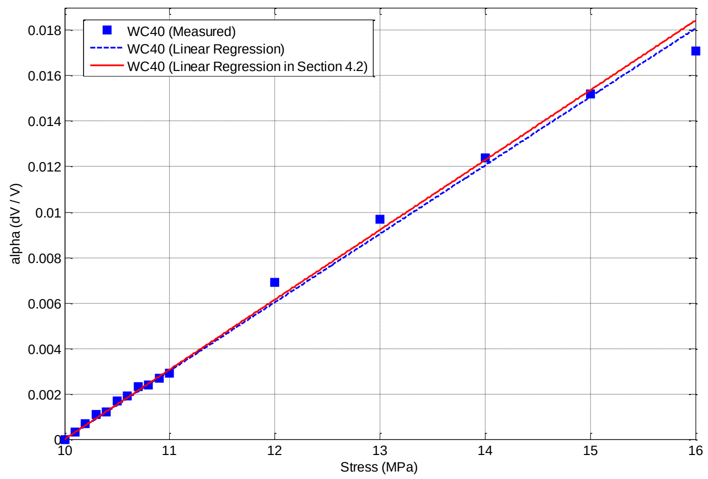


Fig. 9 Relative Velocity Changes for Stress Levels from 10-16 MPa (WC40 Case)

Additional tests to obtain the relative velocity changes for stress levels from 11 MPa to 16 MPa (1 MPa increment) were performed on WC40 specimen. Fig. 9 shows measured relative velocity changes for stress levels from 10 MPa to 16 MPa. Note that the data for 10 MPa to 11 MPa (0.1 MPa increment) are also presented in Fig. 9. It is observed that, even at the levels from 11 MPa to 16 MPa, the α value linearly increases as the stress increases. The estimated acoustoelatic coefficient for this case is 0.003013 MPa^{-1} (R^2=0.9948), and which is very close to 0.003073 MPa^{-1} obtained in Section 4.2. The deviation is about 1.8% (0.003013/0.003073). Though the additional test was stopped at the stress level of 16 MPa, this result is sufficient to verify the linearity of the acoustoelastic effect of concrete and confirms the reliability of the acoustoelastic coefficients estimated in this study.

5. Conclusions

This study presents the influences of the w/c and the fa/ta ratios on the acoustoelastic effect of concrete. The w/c and the fa/ta ratios are important parameters in mix design of concrete and affect wave behaviors in concrete. From the experimental study, it is confirmed that a phase change in ultrasonic waves due to compressive loading on the specimen can be more clearly identified in the late arrival coda wave than the early arrival ballistic wave. It is also confirmed that the relative velocity change of ultrasonic wave due to the acoustoelastic effect can be successfully detected and quantified using CWI technique. The relative velocity change (α value) increases linearly as the stress level of concrete increases. However, the acoustoelastic coefficient (θ), i.e., the slope in $\alpha-\sigma$ relation, is different with the mix proportions of concrete. Experimental results show that the w/c ratio greatly affects the acoustoelastic coefficient while the fa/ta ratio does not. The acoustoelastic coefficient sensitively increases as the w/c ratio of concrete increases. On the other hand, the acoustoelastic coefficient is insensitive to the fa/ta ratio of concrete. The fa/ta ratio affects the scattering wave paths in concrete while it does not affect the acoustoelastic behavior of concrete. The acoustoelastic coefficient estimated from the data for the stress levels of 11-16 MPa (1 MPa increment) is very close to that of 10-11 MPa (0.1 MPa increment). This result confirms the linearity of the acoustoelastic effect of concrete.

Finally, it is well known that the strength of concrete depends largely on the w/c ratio but less on the fa/ta ratio. Therefore, it may be possible to correlate the compressive strength of concrete with the acoustoelastic coefficient of the concrete. The relationship between them is currently under investigation.

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