Feasibility of Evaluating Acoustoelastic Coefficient of Concrete under Tensile Stress with One-Sided Ultrasonic Method

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Abstract. In this paper, an experimental study on the feasibility of evaluating acoustoelastic coefficient of concrete with one-sided ultrasonic pulse method under tensile stress is conducted. Tensile load cycles are imposed on prismatic concrete specimens and ultrasonic wave velocities are measured simultaneously. Acoustoelastic coefficients are obtained by linear fit of the test results and compared to correlate results in literature. The feasibility of evaluating acoustoelastic coefficient of concrete with one-sided ultrasonic method under tensile stress is discussed.

1. Introduction
Acoustoelastic coefficient plays an important role in Non-destructive evaluation (NDE) of concrete. Correlative experimental and theoretical studies have been conducted in many literatures as Refs. [1-4], for example, Lillamand et al. [1] and Bompan et al. [2] have studied compressive acoustoelastic coefficients by utilizing direct transmission ultrasonic devices, and Zhang et al. [3] have studied tensile acoustoelastic coefficients by utilizing thermally-compensated Coda Wave Interferometry. It can be found in these studies that two accessible surfaces at opposite sides of concrete specimens are required, however, such kind of requirement cannot always be satisfied in field measurement. For example, when concrete of basement structure needs to be diagnosed, it will be hard to access the surface which contacts to soil.

The purpose of this paper is to verify the feasibility of using one-sided ultrasonic method to evaluate acoustoelastic coefficient of concrete under tensile stress by experiment, for it has the advantages in the arrangement of measuring points when concrete components only have one accessible surface [5-7] and the possibility of conducting tensile stress evaluation in a relative simple manner and at low cost.

The section 2 gives details of experiment arrangement and section 3 gives test results of the experiment and summary of acoustoelastic coefficients evaluated with one-sided methods. Feasibility of evaluating tensile acoustoelastic coefficients is discussed in the section 4.

2. Experimental Materials
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2.1. Concrete Specimens
Dimensions of prismatic specimens and target tensile strength of concrete are chosen for the purpose of this study, and the mix designs of specimens are listed in in table 1.
### Table 1. Mix designs of concrete specimens.

| Number | Dimensions (mm) | Target tensile strength | Content (kg/m³) | 
|--------|----------------|-------------------------|-----------------|
|        |                |                         | Potland cement (grade 42.5) | Sand | Aggregates | Water to cement ratio |
| 1      | 150x150x550    | >1.7 MPa                | 213.4           | 823.8 | 1186.5     | 0.82               |
| 2      | 150x150x550    | >2.4 MPa                | 357.1           | 574.9 | 1164.1     | 0.49               |

To apply tensile stress on end sections, 16×250mm steel rods with screw treads are fixed with nuts at the ends of each mould before casting, as illustrated in figure 1. Regular concrete which contains 40 mm maximal size rubble aggregates is used and each specimen has been cured for at least 28 days before experiments.

2.2. Test Set-Up

Electro-acoustical transducers (emitters and receivers) with three different frequencies (20 kHz, 50 kHz and 100 kHz) are used for comparison, and distance between transducers’ inner edges is set to 400mm according to preliminary study, as illustrated in figure 2a. NM-4B multi-purpose portable ultrasonic test mainframe with oscilloscope display is used to measure longitudinal wave propagation velocity in specimen as well as its transmitting voltage is set to 500 V.

A specially designed fixture set is use to provide quantitative and stable fixing pressure on transducers, as illustrated in figure 2b. Preliminary study shows test results may be affected if the fixing pressure is lower than 30kPa, therefore, 70 kPa fixing pressure is chosen to be applied on the transducers.

WAW-300B computer-controlled electro-hydraulic servo universal test machine in Structural Engineering Laboratory of Zhejiang Sci-Tech University is used to provide tensile stress cycles on the specimens, as illustrated in figure 3. The amplitude of axial tensile stress is controlled to be less than the target concrete tensile strength in the experiment. For specimen No.1, stepwise stress level is set to 0, 0.2, ..., 1.4 MPa, and for specimen No. 2, stress level is set to 0, 0.4, ..., 2.4 MPa respectively.

Ultrasonic wave velocities are measured with fixed amplitude measuring method [8] while the specimens are stably stressed at preset level, and transducers with different frequencies are used in the specific force cycles as follows: 50kHz transducers for cycle 1-3, 20 kHz transducers for cycle 4-6, and 100 kHz transducers for cycle 7-9.

To avoid possible tensile failure of the specimens, foil strain gauges are also fixed on surfaces of the specimens to monitor tensile strain level in real time, as illustrated in figures 2a and 2b. DH3819 strain meter is used to collect strain data, and its sample rate is set to 1 Hz.

![Figure 1. Dimensions of specimen.](image1)

![Figure 2. Experimental set-up of one-sided ultrasonic method.](image2)
Figure 3. Tensile stress cycles imposed on specimens.

2.3. Data Processing

Murnaghan [9] has developed a third-order elastic constants (m, n, l) system to describe nonlinear elasticity for isotropic media. Based on the theory, Hughes and Kelly [10] has developed equations to describe acoustoelastic effects. By performing linearization at the first order, Lillamand [2], Zhang [11] and Bompan [3] have adopted the similar method in literature to calculated acoustoelastic coefficient, as shown in equation (1):

$$A_{ij} = \frac{V_{ij}^\sigma - V_{ij}^0}{V_{ij}^0 \sigma_{11}}$$  \hspace{1cm} (1)

where $i$ = the wave propagating direction; $j$= the wave polarized direction; $\sigma_{11}$ = the normal stress along direction 1; $V_{ij}^\sigma$ = the wave velocity corresponds to $\sigma_{11}$; $V_{ij}^0$ = the wave velocity corresponds to zero stress; $A_{ij}$ = the acoustoelastic coefficient.

To obtain the acoustoelastic coefficient by linear fit, the following data processing method is adopted in this paper: firstly, wave velocity of each loading step is measured 16 times, and then the 3 minimum and maximum values are dismissed before data processing; secondly, longitudinal wave velocity of each measurement is calculated via equation (2); lastly, average wave velocity of each load step is calculated via equation (3).

$$V_k = \frac{d}{t}$$  \hspace{1cm} (2)

$$\overline{V} = \frac{1}{10} \sum_{k=1}^{10} V_k$$  \hspace{1cm} (3)

where $d$ = the distance between inner edges of ultrasonic transducers; $t$ = the longitudinal wave propagation time; $V_k$ = the wave velocity of $k$th measurement; $\overline{V}$ = the average wave velocity of concerned load step.

3. Test Result and Discussion

3.1. Test Results of 50kHz Transducers

The 1-3 tensile stress cycles are imposed on each specimen and the corresponding curves of evaluated average wave velocities versus tensile stress of each specimen is portrayed in figure 4, where figure 4a is for specimen No. 1 and figure 4b is for specimen No. 2. The maximum strain of the specimens measured in the cycles is 73 $\mu$e and 83 $\mu$e respectively, which are lower than known ultimate tensile strain level of conventional concrete [11]. It can be seen in figure 4 that the first stress cycle of each specimen has the maximum wave velocity at the beginning. The phenomenon is known to be caused by the opening of new microcracks in the first tensile stress cycle [3]. However, when more tensile stress cycles are imposed on the specimens, crack development stabilizes due to Kaiser Effect [7, 12, 13].
3.2. Test Results of 20 kHz Transducers
The 4-6 tensile stress cycles are imposed on each specimen and the corresponding curves of evaluated average wave velocities versus tensile stress of each specimen is portrayed in figure 5, where figure 5a is for specimen No. 1 and figure 5b is for specimen No. 2. The maximum strain of the specimens measured in the cycles is 70 µe and 84 µe respectively.

![Figure 4](image4.png)
![Figure 5](image5.png)

**Figure 4.** Wave velocities versus tensile stress in 1-3 stress cycles.

**Figure 5.** Wave velocities versus tensile stress in 4-6 stress cycles.

It can be observed in figure 5 that the curves in the 4-6 cycles show rather clear trend of descending, which implies linear fit is more suitable in 4-6 cycles than in 1-3 cycles.

3.3. Test Results of 100 kHz Transducers
The 7-9 tensile stress cycles are imposed on each specimen and the corresponding curves of evaluated average wave velocities versus tensile stress of each specimen is portrayed in figure 6, where figure 6a is for specimen No. 1 and figure 6b is for specimen No. 2. The maximum strain of the specimens measured in the cycles is 68 µe and 85 µe respectively.

It can be observed in figure 6 that specimen No. 2 shows better pattern than specimen No. 1. A possible explanation for this phenomenon is high-frequency signals are easily attenuated in the concrete, especially when massive internal cracks are generated by tensile stress in the concrete with lower tensile strength.

3.4. Summary of the Acoustoelastic Coefficients
Bases on the upper test data and correlate acoustoelastic theory [1-3, 8, 9], acoustoelastic coefficients under tensile stress are evaluated by linear fit. The results are listed in table 2.

It can be seen in table 2 that the acoustoelastic coefficient in the first 3 tensile stress cycle is not suitable to be evaluated by linear fit (maximum $R^2$ coefficients < 0.52). This phenomenon can be explained by the opening of new microcracks in the specimens causes variation of acoustoelastic coefficients. In the 4-9 stress cycles, test results of the two specimens show different pattern: for
specimen No.1, it is still difficult to evaluate tensile acoustoelastic coefficients by linear fit (maximum $R^2$ coefficients < 0.56), which means the material is not at a stable status in these cycles, but for specimen No. 2, it appears the acoustoelastic coefficient are more suitable to be evaluated by linear fit (maximum $R^2$ coefficients > 0.8). Moreover, the 20 kHz transducer shows better adaptability than 100 kHz transducer when measuring acoustoelastic coefficients in the specimen with lower target strength.

![Wave velocities versus tensile stress in 7-9 stress cycles.](image1)

**Figure 6.** Wave velocities versus tensile stress in 7-9 stress cycles.

| Specimen number | Transducer frequency | Load cycle | $A_{11}$ | $R^2$ Coefficient of linear fit |
|-----------------|----------------------|------------|----------|--------------------------------|
| 1               | 50 kHz               | 1          | -0.366   | 0.111                          |
|                 |                      | 2          | -0.006   | -0.166                         |
|                 |                      | 3          | -0.436   | 0.386                          |
|                 | 20 kHz               | 4          | -0.390   | 0.190                          |
|                 |                      | 5          | -0.820   | 0.551                          |
|                 |                      | 6          | -0.522   | 0.345                          |
|                 | 100 kHz              | 7          | -0.112   | -0.074                         |
|                 |                      | 8          | -0.463   | 0.312                          |
|                 |                      | 9          | -0.183   | -0.100                         |
| 2               | 50 kHz               | 1          | -0.294   | 0.301                          |
|                 |                      | 2          | -0.710   | 0.573                          |
|                 |                      | 3          | -0.166   | 0.220                          |
|                 | 20 kHz               | 4          | -0.538   | 0.510                          |
|                 |                      | 5          | -0.579   | 0.847                          |
|                 |                      | 6          | -0.448   | 0.653                          |
|                 | 100 kHz              | 7          | -0.436   | 0.629                          |
|                 |                      | 8          | -0.402   | 0.729                          |
|                 |                      | 9          | -0.439   | 0.832                          |
| Cylindrical specimen in Ref. [3] 500 kHz | 3 | -0.130* | n/a |
| Cylindrical specimen in Ref. [2] 500 kHz | n/a | 0.130* | 0.99 |
| Prismatic specimens P1-P12 in Ref. [1] 250 kHz | >15 | 0.13-0.61 | n/a |

*The original value in literature is converted to the unit form in Ref. [1].

By comparing the acoustoelastic coefficients in literature, one can see that the absolute values in the 7-9 cycles are very close to the compressive acoustoelastic coefficients in Ref. [1]. It should be noted...
that the tensile acoustoelastic coefficient given in Ref. [3] has the smallest absolute value (0.13) which is very close to the compressive acoustoelastic coefficient given in Ref. [2]. Considering the crack opening process in concrete under tensile stress is much faster than that under compressive stress, or the material usually gets “softer” under tensile stress, the possible explanation to this phenomenon is the thermally-compensated Coda Wave Interferometry method adopted in Ref. [3] gives relatively low acoustoelastic coefficient under tensile stress than the direct transmission method and one-sided method.

4. Conclusion
In the study, direct tensile force is imposed on concrete specimens and wave velocities of each load step is measured. Acoustoelastic coefficients of each tensile stress cycle are evaluated and compared to correlate results in the literature. Feasibility of evaluating tensile acoustoelastic coefficient of concrete with one-sided ultrasonic method is found in the condition when the concrete has higher target strength and new microcracks stop opening in the material. The transducer with lower working frequency shows better adaptability of measuring acoustoelastic coefficients in the specimen with lower target strength. It also should be mentioned that the suggested experimental set-up in this paper only requires one accessible surface of concrete component, which provides convenience in field measurement.

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