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Monitoring early age property of cement and concrete using piezoceramic bender elements

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Abstract
Ultrasonic waves are commonly used for non-destructive evaluation of concrete structures. For fresh concrete, ultrasonic waves have also been used to monitor concrete setting and strength development at early ages. However, the conventional ultrasonic test set-up typically needs access to the two opposite sides of concrete structures, which is not always possible for *in situ* field testing. In this paper, embedded piezoceramic bender elements are proposed to measure ultrasonic shear (S) waves in fresh cement paste, mortar and concrete. The shear wave velocities are obtained from B-scan images of a collection of recorded signals over time. Experimental results indicate that the shear wave velocity is closely related to the setting time, and this relationship is independent of air void content and w/c of cement pastes. The low cost bender elements can also be of use to monitor the setting of fresh concrete and the long term evaluation of hardened concrete.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The quality and durability of concrete structures are mainly determined by the early age properties of concrete, including setting times and workability. Many studies have reported the potential application of ultrasonic waves to determine the initial setting time of cement and concrete [1–6]. However, there remain many unanswered questions about this technique, which limit its applications to field testing. Firstly, the effects of air voids on ultrasound measurements are not well understood. It has been noticed that the ultrasonic longitudinal (P) wave velocity is significantly affected by air void content in cement paste, mortar and concrete [2]. There is no clear criterion to determine cement or concrete setting time based on the P wave velocity. To eliminate air void effects, de-aired cement paste samples were used in many studies [2, 4, 7]. However, using de-aired samples is unrealistic in practice. Secondly, the conventional ultrasonic test set-up uses two commercial ultrasonic transducers and needs access to two opposite sides of the sample, which is not suitable for *in situ* field testing.

Shear wave propagation has been found to be related to solid microstructural development in cement pastes during the hydration process [8, 9]. In those studies, due to high attenuation shear waves could not be observed until the initial setting time was reached. In a recent study by the authors [10], shear waves have been successfully detected by a pair of commercial shear wave transducers at very early ages in cement pastes, about 30 min after cement hydration starts. Findings from this study indicate that the shear wave velocity correlates well to the initial setting time of cement pastes. The shear wave velocity V_S at the initial setting time (by the Vicat test) is around 300 m s^{-1}, independent of air void content in cement pastes.

Piezoceramic sensors (PZT) have recently been used to monitor early age concrete properties [11, 7]. Song *et al* [11] developed 'smart aggregates' using PZT sensors and embedded these smart aggregates in concrete structures during casting. The sensors were used to monitor concrete strength development from day 1 to day 28. However, no information was reported about the performance of the sensors in fresh concrete before the initial setting. Qin and Li [7] used PZT

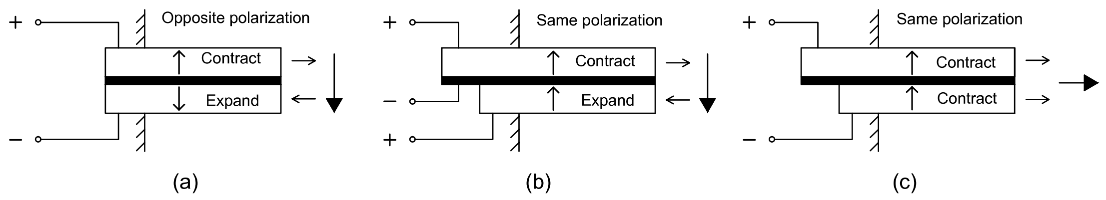

Figure 1. Typical bender structure and wiring details: (a) series-connection bender, (b) parallel-connection bender and (c) series-connection extender.

sensors to monitor P wave velocity and electrical impedance change in de-aired cement paste. In that study, the thickness mode resonance of a PZT sensor was used to generate P waves in materials. In fresh cement pates, however, due to the large impedance mismatch between the PZT sensor and cement paste, the energy transmitted to the cement paste is very limited. Therefore it will be difficult to obtain reliable ultrasonic wave signals in materials with high attenuation, such as air-entrained cement pastes and concrete at early ages.

In this paper, the authors propose using piezoceramic bender elements to monitor the setting and hardening processes of cement pastes and concrete during early ages. Cement pastes with different water to cement ratios (w/c) and air void content were investigated. The measured shear wave velocities from bender element tests were compared to those from conventional ultrasonic tests. Experimental results show that the bender elements are especially effective in measuring shear wave propagation in fresh cement paste, mortar and concrete. Due to the low cost and small size of the sensors, the embedded bender elements provide an inexpensive but powerful tool to monitor the setting process of cementitious materials. After concrete hardens, the sensors can also be used for health monitoring purposes to evaluate mechanical properties of the surrounding concrete.

2. Description of bender elements

2.1. Working principle of bender elements

Piezoceramic bender elements, also called bimorphs, were first used to measure shear wave velocity of marine sediments by Shirley and Hampton in 1978 [12]. The small thickness of bender elements needs relatively small forces to drive the sensor and allows large displacement generated in materials with low acoustic impedance [12], such as sediments and soils. Since then, this technique has been quickly adopted in the soil mechanics research field to evaluate small strain shear moduli in laboratory soil samples [13–19]. Similarly, bender elements could be used to monitor shear wave propagation in fresh cement paste and concrete, since they have low stiffness and acoustic impedance at very early ages. However, to the authors' best knowledge, there has been no study reporting application of benders to fresh cement or concrete.

A bender element typically consists of two layers of thin piezoceramic sheets bonded to a center shim. The center shim, usually made of metal (brass or steel) or composite materials, is used to reinforce the thin piezoceramic sheets. The structure of bender elements is shown in figure 1 [15]. The typical thickness of a bender ranges from 0.5 to 1.0 mm. The piezoceramic sheets are polarized in the thickness direction. When a voltage is applied to two surfaces of a ceramic sheet, the sheet expands/contracts in the thickness direction, i.e. along the axis of polarization. At the same time, the sheet contracts/expands in the transverse direction. Bending deformation is produced by a bender element when one layer expands while the other layer contracts. The tip deflection of a bender is proportional to the applied voltage and the square of the length of the bender [20].

Based on polarization and wiring configurations, bender elements can be classified into two types: series- and parallel-connected benders, as shown in figure 1. In a series-connected bender, the two ceramic sheets have opposite polarization directions. Two wires are connected to the outside electrode of each sheet. When a voltage is applied across two layers, the voltage on each layer is one-half the total voltage applied. In each sheet, the voltage direction is the same but the polarization is opposite, which produces a bending motion. In a parallel-connected bender, the two sheets have the same polarization direction. Three wires are needed, with two attached to the outside electrodes and one attached to the center shim. Opposite voltages are applied to each layer of the ceramic sheet and generate a bending motion. A study by Lee and Santamarina [21] indicated that a bender generates strong in-plane shear waves in front of the bender and out-of-plane P waves in the close region of the bender. The shear waves propagate in the plane of the bender with particle vibration in the out-of-plane direction. The large tip deflection of a bender causes shear motion of the matrix material, and therefore preferentially generates stronger shear waves than P waves.

An interesting feature of a bender element is that it can be easily converted into an extender by exchanging the wiring pattern. In figure 1(c), two sheets in a bender have the same polarization direction and use a series connection, i.e. two wires are connected to the outside electrodes on each sheet. Because both sheets have the same polarization and voltage, extension/contraction occurs in the thickness/longitudinal directions. This type of connection has been proven effective to generate P waves in materials [15].

2.2. Preparation of bender elements

Parallel-connected benders, manufactured by Omega Piezo Technologies, Inc., were used in this study. The dimensions of the benders are $L \times W \times T = 40$ mm $\times$ 20 mm $\times$ 0.6 mm and 45 mm $\times$ 10 mm $\times$ 0.6 mm. The $W = 20$ mm bender was used as the source and the $W = 10$ mm benders were used as receivers. Because the benders were used in a conductive environment, electrical insulation and

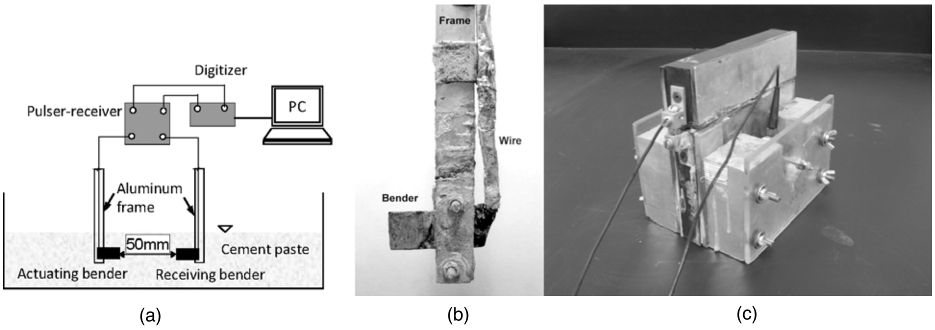

Figure 2. Test set-up for cement hydration monitoring. (a) Set-up using the bender elements, (b) picture of bender element and (c) set-up using ultrasonic transducers.

waterproofing are needed. A detailed description of sensor preparation procedures is given by Jung [17]. First, three wires were soldered to the electrodes on the bender. During soldering, one should take care to avoid overheating, which will cause depolarization of piezoceramics. Then, five layers of polyurethane coatings (M-coat A by VISHAY) were applied to the surfaces of benders. Each layer of coating should be fully air dried before applying the next layer. Finally, to reduce electromagnetic interference (cross-talk) between the source and receiver benders, a thin layer of silver paint was applied to the bender surface to provide electrical shielding. A grounding wire was connected to the silver paint at one end and connected to the earth ground at the other end.

3. Experimental set-ups

3.1. Materials and sample preparation

Ordinary Type I/II Portland cement was used in all tests. Six cement paste mixtures were prepared according to the proportions shown in table 1. The mixture compositions were selected to span a wide variety of air contents and two water/cement ratios (w/c = 0.4 and 0.5). For each w/c, three mixtures with different air contents were prepared. Air voids were introduced into the pastes by using an air-entraining agent (AEA) with three different doses (0, 0.05 and 0.2% by cement weight). A previous study by the authors [10] showed that the actual air void content in cement paste increases with AEA doses, and varies in the range of 0.2%–5% (by cement paste cross-section area) for the AEA doses used in this study. To investigate the possibility of applying benders to field testing, tests were also performed on fresh mortar and concrete specimens using bender elements. The w/c for mortar and concrete were 0.5 and 0.57, respectively. All tests were started about 30 min after mixing water with cement.

3.2. Test set-up using bender elements

Two bender elements were used to measure shear waves in cement paste, as shown in figure 2. One end of each bender was clamped onto an aluminum frame, and the frame was placed in a plastic box (300 mm × 150 mm × 100 mm). The mixed cement paste was poured into the plastic box to 60 mm height to cover the benders. The benders were about 10 mm below the cement paste surface. One bender was used as the actuator (source) and another one was the receiver. The source bender was driven by a 100 V square wave pulse generated from a pulser-receiver (Panametrics 5077PR). The receiving bender was connected to the pulser-receiver with a gain of 40 dB. The amplified receiving signals were then digitized by an NI-PXI 5101 high speed digitizer at a sampling rate of 10 MHz and transferred to a computer. Because ultrasonic waves have high attenuation in fresh cement pastes, to improve the signal-to-noise ratio, 150 signals were averaged and saved. Tests were run for 6 h for all specimens.

Table 1. Cement pastes and setting times.

w/c	AEA[a]	Initial set (Hr)	Final set (Hr)
0.4	0	3.9	4.6
0.4	0.05	4.1	4.6
0.4	0.2	4.2	5.1
0.5	0	4.4	5.6
0.5	0.05	4.5	6.3
0.5	0.2	5.2	6.2

[a] Per cent of cement weight.

3.3. Test set-up using ultrasonic transducers

For comparison purposes, cement pastes with the same mix design were also monitored using the ultrasonic transducer set-up. Figure 2 illustrates the test set-up. A U-shape rubber container with two Plexiglas plates formed a cement paste mold and a pair of ultrasonic transducers were installed on both sides of the sample coupled through the Plexiglas plates. To reduce direct transmission of ultrasonic waves through the rubber mold, a layer of foam tape was inserted between the rubber and Plexiglas plate. The specimen thickness in this set-up was about 25 mm. The actual thicknesses of samples were measured after the ultrasonic testing. The ultrasonic transducers used in this study were a pair of 500 kHz shear wave transducers (Panametrics V151). Configurations of the pulser-receiver and data acquisition were similar to the bender element set-up.

3.4. Vicat tests

To determine setting times of cement pastes, the Vicat-needle tests were carried out in accordance with ASTM C191 [22]. The measured setting times were correlated with acoustic

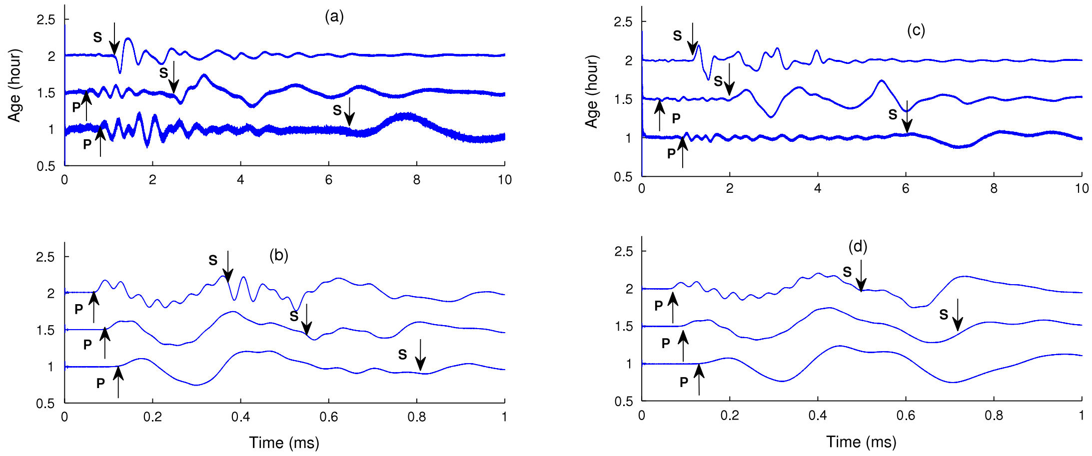

Figure 3. Shear wave signals measured in two fresh cement paste specimens (w/c = 0.4, AEA = 0.05 and 0.2%) before 2 h by bender elements ((a) and (c)), and shear wave transducers ((b) and (d)). Signals in (a) and (b) were from cement paste with AEA = 0.05%, and (c) and (d) from cement paste with AEA = 0.2%. Shear wave and P wave arrivals are marked with arrows. Shear wave arrivals were determined from B-scan images as described in section 4.2.

parameters obtained from bender element and ultrasonic tests. In the Vicat test, a 300 g needle with a diameter of 1 mm was released into a cement paste specimen that was from the same batch as in the corresponding ultrasound test. The initial setting time corresponds to a needle penetration of 25 mm and the final setting time is reached when the needle does not leave a complete impression in the paste surface [22]. The cement paste specimen was kept in a sealed container with relative humidity consistently maintained higher than 50% except during tests.

4. Results and discussion

4.1. Shear wave signals in cement pastes

Figure 3 shows the normalized time domain signals measured in fresh cement pastes (w/c = 0.4, AEA = 0.05% and 0.2%) by benders and shear wave ultrasonic transducers. The signals in the bender test show strong shear wave pulses and clear arrival times. Relatively strong P waves are also observed in the signals recorded at 1 h age. With the progress of cement hydration, the relative amplitude of shear waves increases and shear waves dominate the signals. In all signals from the bender test, the shear wave velocity can be easily calculated based on the arrival time. However, in figures 3(b) and (d) showing signals measured by the shear wave transducers, there are no clear shear wave arrivals due to interference of P waves and directly transmitted waves through the set-up device. Although a foam layer was used between the Plexiglas plates and the rubber mold, the direct waves transmitted through the rubber mold were still stronger than the shear waves through cement paste, because the fresh cement paste has very low shear modulus and high attenuation to shear waves. The shear wave arrivals marked in the figure were determined from B-scan images method that will be described in section 4.2.

Comparison of figures 3(a) and (c) indicates that the P wave propagation is sensitive to air void content. The P wave in cement with 0.2% AEA has a much lower amplitude than in the paste with 0.05% AEA, which means that air voids in fresh cement paste significantly attenuate P waves. This result agrees with previous studies.

4.2. B-scan images of signals in cement pastes

Because cement hydration and microstructural development is a continuous process, the ultrasonic wave velocity in fresh cement paste also develops continuously. Therefore the ultrasonic wave arrival time will show a trend of gradual decrease with hydration age, and it could be easier to identify from a series of signals than from a single signal. In this study, a B-scan image is formed by stacking up a series of normalized ultrasonic wave signals recorded at different ages, with the x-axis representing the time of signals (unit: millisecond) and the y axis for the age of cement pastes (unit: hour). The brightness of the grayscale images represents the amplitude of signals, with bright colors for positive amplitudes, and dark colors for negative amplitudes. Because the amplitudes of ultrasonic wave signals at later ages are several orders higher than that at early ages, each signal was first normalized by its maximum amplitude, so that all signals have the same normalized peak amplitude, 1.0. The following results indicate that the B-scan imaging is an effective method to identify different wave modes propagating through the cement pastes.

Figure 4 shows two B-scan images of ultrasonic wave signals through cement paste (w/c = 0.4, AEA = 0.05) measured by the bender elements. It can be seen that the P wave and shear wave signals were detected immediately when the monitoring test started. At very early ages (0–2 h), although the signals in figure 4(a) contain some noise, the P and S wave arrivals can be clearly identified. After 2 h, the shear wave dominates the signals and have much higher amplitude than the P wave. The experimental data verifies that the bender elements are effective in generating and measuring shear waves in fresh cement pastes.

For the same cement paste (w/c = 0.4, AEA = 0.05), the B-scan image of signals measured by the shear wave ultrasonic

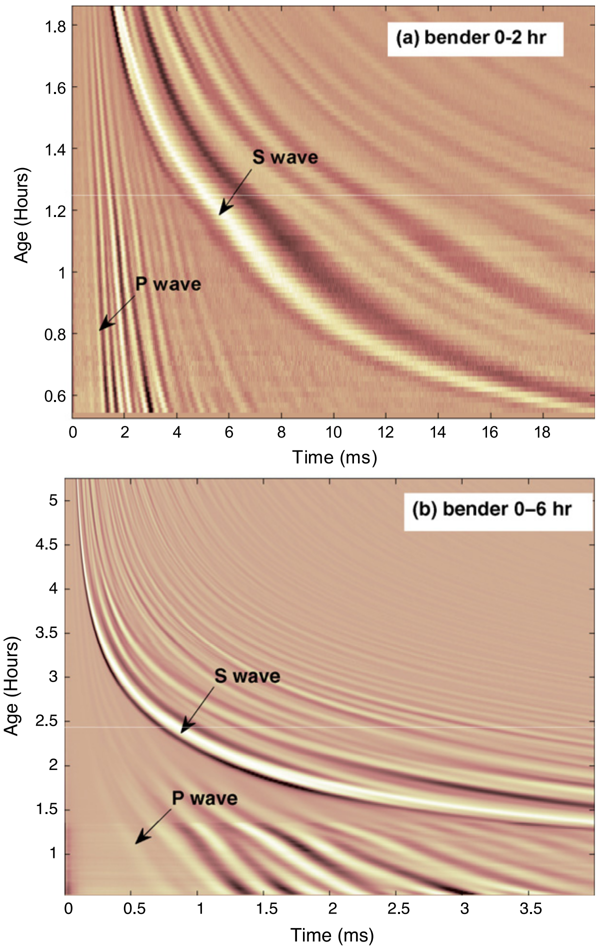

Figure 4. B-scan images showing wave propagation in cement paste (w/c = 0.4, AEA = 0.05) measured by bender elements. (a) 0–2 h and (b) 0–6 h.

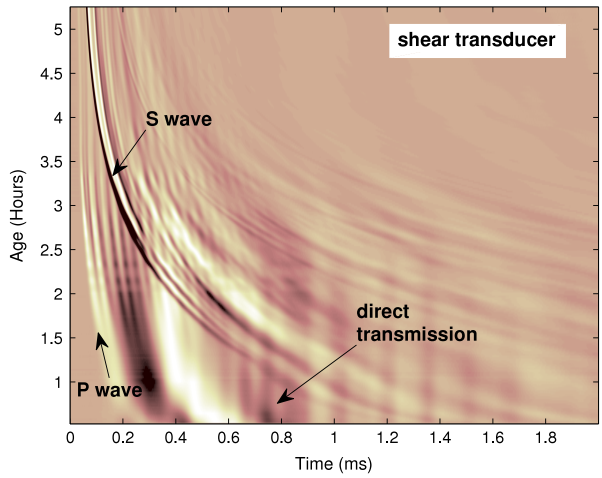

Figure 5. B-scan images showing wave propagation in cement paste (w/c = 0.4, AEA = 0.05) measured by shear wave transducers.

transducers is shown in figure 5. In addition to P and S waves that are marked in the image, there are strong direct transmission waves through the test set-up at early ages (0–3 h). At very early ages, the direct transmission wave is stronger and faster than the shear waves in the cement paste, which makes it difficult to identify the arrival time of shear waves from a single signal. However, with the aid of B-scan images and the trend of shear wave velocity development, the shear wave arrivals can still be identified.

4.3. Shear wave velocity

The arrival time of P wave is usually determined by detecting the first signal point that exceeds a predetermined threshold. However, this method does not work well for the shear wave because it arrives later than the P waves. In addition, the threshold method may give erroneous results on noisy signals, especially at early ages. In this study, we used a digitizing tool to directly obtain shear wave arrival times from B-scan images. The velocity was calculated by dividing the wave path over the travel time of the wave through specimens. The actual wave travel time t through a cement paste was determined by subtracting the zero time t_0 of the test system. The t_0 for shear wave measurement in this study was 4 μs in the ultrasonic tests and 1 μs in the bender tests. Figure 6 shows the shear wave velocities measured from all cement pastes using the benders and 500 kHz shear wave transducers. Solid lines in the figure represent shear wave velocities measured in the w/c = 0.4 cement pastes, while the dashed lines are for w/c = 0.5 pastes. By comparing these two figures, we can see that these two types of tests gave very similar results, although there are minor differences between these curves. Both figures show that the shear wave velocity decreases with the increase of air void content and w/c. This conclusion agrees with previous findings by the authors [10].

Setting times for all mixtures are also marked on velocity curves in figure 6. As seen in the figure, although the cement pastes have different mixtures and setting times, the shear wave velocities at the initial setting times are very similar for all specimens. This is because both the shear wave and Vicat tests measure the mechanical property of the solid frame in cement pastes, in which the shear wave velocity is directly related to the shear modulus of the solid frame, while the Vicat test measures shear resistance of cement pastes. Therefore, the shear wave velocity and setting time show strong correlation between them. In this study, the shear wave velocities at initial settings are around 320 m s^{-1} in the bender tests and 300 m s^{-1} in the shear transducer tests. The small difference between these results may be because the cement pastes in these two set-ups have slightly different curing conditions. In the shear wave transducer set-up, a small volume of cement paste was sealed in the container to avoid drying shrinkage. In the bender test set-up, a relatively large volume of cement paste was needed and tested in a plastic container with a large surface open to the air. Although the container was covered by a plastic sheet, cement paste in the bender test had a much larger air contact area than in the ultrasonic test set-up. Therefore, the specimens in the bender tests may have a slightly earlier setting time than in the ultrasonic tests.

5. Application of bender elements to mortar and concrete

Section 4 shows that the bender elements are very effective for measuring shear wave velocity in cement pastes. In mortar

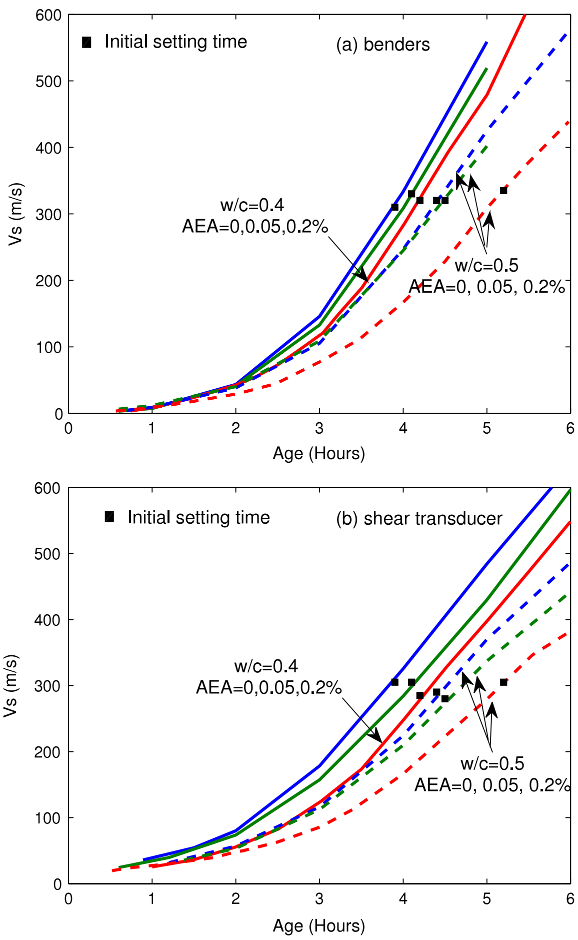

Figure 6. Shear wave velocities and setting times for all cement pastes measured by (a) bender elements and (b) shear wave transducers.

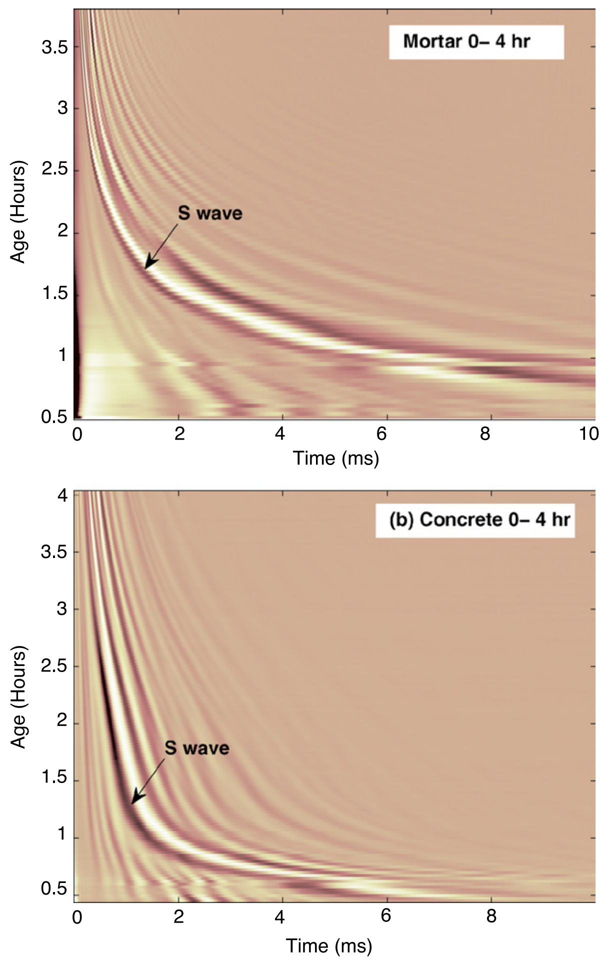

Figure 7. B-scan images showing wave propagation in (a) mortar and (b) concrete.

and concrete, the fine and coarse aggregates cause strong scattering of ultrasonic waves in fresh mixes. In addition, inclusion of aggregates also induces more air voids during mixing than in cement paste. Therefore, mortar and concrete exhibit high attenuation for ultrasonic waves at early ages, which makes it difficult to accurately measure wave velocity using conventional ultrasonic transducers. However, our study indicates that the bender elements are also very effective for shear wave measurements in mortar and concrete. Figure 7 shows B-scan images of signals obtained from fresh mortar and concrete specimens measured by bender elements. Both images show clear shear wave arrivals at very early ages, immediately after the tests started. These test results show the potential of bender elements to be used in construction practice to monitor concrete setting and hardening processes.

6. Bender elements in hardened concrete

In hardened concrete, bender elements cannot generate large tip deflections due to confinement by surrounding hard concrete. However, the bender can be converted to an extender by exchanging the wiring pattern, as shown in figure 1(c). The extender is effective for P wave generation and measurement.

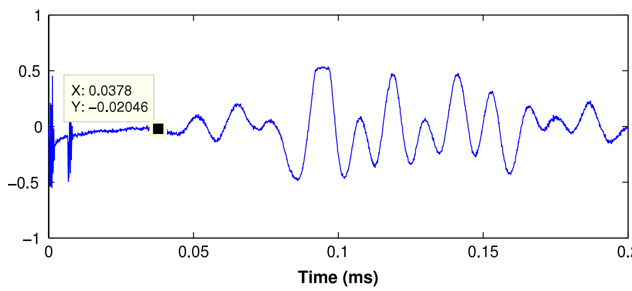

Figure 8. A signal measured by embedded bender elements in a hardened concrete slab. The sensor spacing is 150 mm.

This concept has been proposed and verified by Lings and Greening [15]. In this study, two benders were embedded in a concrete slab, with the sensor spacing of 150 mm. One month after the concrete was cast, signals were measured by the embedded benders using the extender wiring. Figure 8 shows the measured signal with the P wave arrival time marked. The P wave arrival at 37.8 μs gives the P wave velocity of 3968 m s^{-1} in the concrete slab. This result agrees well with the P wave velocity of 4010 m s^{-1} measured by a pair of 54 kHz ultrasonic transducers using the ultrasonic pulse velocity (UPV) method.

7. Conclusions

In this paper, bender elements were proposed to generate and receive shear waves in fresh cement and concrete. The shear wave velocity reflects the solid frame development in a cement paste matrix, and can be used to monitor the setting and hardening processes of cementitious materials. In addition, the low cost bender elements embedded in concrete structures can be used for long term monitoring of mechanical properties of concrete. Therefore, the study presented in this paper shows the potential to use bender elements as low cost *in situ* sensors to monitor setting time and long term performance of concrete structures. Specifically, the following conclusions are obtained from this study:

(1) The shear wave velocity measured at the initial setting time in fresh cement pastes is around 320 ± 10 m s^{-1}. This result is not affected by air void content in cement pastes. Shear wave velocity development may be used to monitor setting, hardening and strength development of concrete at early ages.
(2) The piezoceramic bender elements provide an inexpensive but effective way to generate and measure shear wave velocity in fresh cementitious materials.
(3) Due to the small size and low cost, the piezoceramic sensors can be embedded in concrete during construction. The embedded sensors not only monitor concrete setting and hardening processes, it also shows potential for long term performance monitoring in hardened concrete.

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