Construction and Building Materials 72 (2014) 248–255

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Monitoring setting and hardening process of mortar and concrete using ultrasonic shear waves

Shukui Liu [a,b], Jinying Zhu [b,*], Saamiya Seraj [b], Rachel Cano [b], Maria Juenger [b]

[a] School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] Department of Civil, Architectural, and Environmental Engineering, The University of Texas of Austin, Austin, TX 78712, USA

HIGHLIGHTS

- Shear waves are used to monitor the setting process of mortar and concrete.
- Bender elements are effective to generate shear waves in fresh mortar and concrete.
- Shear wave velocity at setting times show high consistency in mortar.
- Shear velocity correlate well with penetration resistance in mortar.

ARTICLE INFO

Article history:
Received 14 May 2014
Received in revised form 31 July 2014
Accepted 23 August 2014

Keywords:
Setting time
Mortar
Concrete
Shear waves
Bender elements
Early age

ABSTRACT

Ultrasonic wave methods have been extensively investigated for monitoring the setting and hardening process of cementitious materials. However, the commonly used P wave velocity parameter is affected by air voids in the material in the fresh state. In addition, the conventional ultrasonic wave velocity test setup typically needs access to both sides of a structural member, which is not always possible for in-situ field testing. The ultrasonic shear wave reflection method measures the acoustic property of the near surface material only. In this paper, ultrasonic shear waves, measured by embedded piezoceramic bender elements, are used to monitor the setting and hardening process of mortar and concrete. Experimental results from mortar and concrete mixtures with different water to cement ratios show a clear relationship between the shear wave velocity and the penetration resistance (ASTM C403), which indicates that the shear wave velocity is a more reliable indicator than the P wave velocity for in-situ monitoring of the setting and hardening process of cementitious materials.

1. Introduction

Setting times are important parameters for determining form removal and surface finishing during the construction of concrete structures and pavements. Typically, the initial and final setting times are regarded as the times when concrete transforms from the fluid to solid state and starts to gain strength, respectively. Conventionally, the penetration test according to ASTM C403 is used to determine setting times by measuring penetration resistance of mortar mixtures or mortar sieved from concrete [1]. However, this method is not suitable for in-situ field testing and continuous monitoring of the early age properties of concrete. During the past two decades, many studies have shown the possibility of using ultrasonic waves to monitor setting times and to characterize early age properties of cementitious materials [2–8]. Since the 1980s, extensive effort has been focused on finding the correlation between the compression wave (P wave) velocity and the time of setting of cementitious materials [3–6]. Various criteria have been proposed for setting time determination based on features on the P wave velocity curve with age [9,5,10]. However, these criteria do not give consistent conclusions. Recent studies have indicated that the P wave velocity in cement pastes is sensitive to the presence of air voids [4,11], which limits the application of P wave velocity measurement methods in practice. An alternative would be to use shear waves. Shear wave velocity is closely related to the stiffness (shear modulus) of solid skeleton formed by cement hydration product, and its measurement is less sensitive to the presence of air voids than P wave measurement [11].

In spite of these advantages of shear wave measurement [8,11–13], the high attenuation of shear wave prevents reliable measurement of shear wave velocity in concrete before setting [8]. The shear wave reflection method [7,14–16] provides a solution by measuring shear wave reflection on a specimen surface through a

* Corresponding author.
E-mail address: jyzhu@mail.utexas.edu (J. Zhu).

http://dx.doi.org/10.1016/j.conbuildmat.2014.08.044
0950-0618/

buffer material (metal, or PMMA etc.). However, the shear wave reflection method measures the material property near the test surface only, while the cementitious mixtures on the surface may have different properties from the interior material due to bleeding, drying and shrinkage. A solution to this problem is to use embedded sensors, e.g. piezoelectric bender elements, to generate and measure shear waves in soil sediment, fresh cement and concrete [13,17–21]. Compared to ultrasonic transducers that use piezoelectric elements vibrating in thickness mode, the bender elements allow relatively large transverse deformation of the surrounding material (mortar and concrete in this study), and effectively generate shear waves of low frequencies. This allows the shear waves to propagate through fresh concrete with less attenuation than typical ultrasonic transducers generate. The embedded bender elements may stay in concrete after the setting time test and can be used as ultrasonic sensors for long-term monitoring of the quality of concrete [13,22].

Zhu et al. [11,13] investigated shear wave propagation in fresh cement pastes using bender elements, and their findings showed strong correlation between shear wave velocity and initial/final setting times in cement pastes. Although these studies demonstrated feasibility of applying bender elements to fresh mortar and concrete, more quantitative studies are needed to investigate if a similar relationship exists for mortar and concrete. Thus, in this paper, we extended the previous experimental study to mortar and concrete mixtures with various mix designs. The P wave and shear wave velocities were monitored until final set. Correlation between shear wave velocity and penetration resistance was obtained on mortar mixtures and mortar sieved from fresh concrete. We also investigated the performance of bender elements by comparing the results with those obtained from commercial ultrasonic transducers. By using different mixture designs, we evaluated the effects of different water to cement ratios (w/c) and aggregate sizes and types on these ultrasonic measurements.

2. Experimental investigation

In this experimental study, three mortar and five concrete mixtures were tested. The setting time of each mixture was measured with a penetrometer, according to ASTM C403. For the mortar mixtures, three different ultrasonic test setups (bender elements, commercial shear wave transducers and commercial P wave transducers) were used. Each setup was able to monitor the ultrasonic P wave and shear wave velocity simultaneously. To address the high attenuation problem of ultrasonic waves in concrete, the bender element setup was used to measured shear waves, and the P wave transducers setup was used to monitor P waves in concrete mixtures. In the mortar sieved from the concrete mixtures, the shear wave transducer setup was used to monitor P wave and shear wave velocity simultaneously.

2.1. Materials

Table 1 shows details of all eight mixtures investigated in this study. Three mortar mixtures with different w/c were used to investigate the effect of w/c on setting time. Out of the five concrete mixtures, three were used to investigate the effects of w/c on setting time. The coarse aggregate volume fraction was kept the same for these mixtures, while the w/c ratio was varied from 0.41 to 0.68. The coarse aggregate used for these mixtures was River Gravel (R) from Capitol Aggregates (Texas), with a relative density of 2.60, and a maximum size of 25.4 mm. The other two concrete mixtures had the same w/c of 0.5 and were used to investigate the effect of coarse aggregate size on setting time and wave velocities. The coarse aggregate used for these two mixtures was dolomitic limestone from Bridgeport, Texas, with a relative density of 2.65. For the "large aggregate" (L) concrete mix, the maximum aggregate size was larger than 19.1 mm, while the "small aggregate" (S) mix used a maximum aggregate size of 12.7 mm.

Type I Portland cement was used in all eight mixtures. The fine aggregate used for both the mortar and concrete mixtures was Colorado River sand from Webberville, Texas, with relative density of 2.62. The standard procedure described in ASTM C192 [23] was followed to make these mixtures.

2.2. Penetration resistance measurements

The setting times of the mortar and concrete mixtures were obtained by measuring the resistance of the mixtures to penetration by standard needles (HM 570 penetrometer, Gilson Company, Inc) at regular time intervals, as described by ASTM C403 [1]. The initial and final time of set correspond to penetration resistance values of 3.5 MPa [500 psi] and 27.6 MPa [4000 psi], respectively, and are determined from a plot of penetration resistance vs. elapsed time. For the concrete mixtures, the mixtures for measuring the time of set were prepared by wet-sieving the fresh concrete through a 4.75-mm sieve. For mortar mixtures, no sieving was required.

2.3. Test setup using bender elements

A pair of bender elements was used to generate and measure shear waves in both mortar and concrete mixtures, as shown in Fig. 1. The terminal end of each bender was clamped onto an aluminum frame, which was placed in a wooden box with dimensions of 300 mm × 150 mm × 100 mm. The mixed mortar or concrete was poured into the wooden box to 90 mm height to cover the bender elements. The bender elements were about 75 mm below the mortar/concrete surface, which was covered by a layer of plastic film to reduce moisture evaporation.

During the test, one bender element was used as the actuator while the one served as the receiver. The actuating bender element was driven by a 100 kHz, 200 V square wave pulse generated from a pulser–receiver (Panametrics 5077PR), and the receiving bender element was connected to the pulser–receiver with a gain of 40 dB. The amplified receiving signals were then digitized by an NI-PXI5133 digitizer at a sampling rate of 10 MHz and transferred to a computer. Since ultrasonic waves have high attenuation in fresh mortar and concrete, 200 signals were averaged in each measurement to improve the signal-to-noise ratio. All mixtures were monitored until the time of final set as determined by the procedures of ASTM C403.

2.4. Test setup using commercial ultrasonic transducers

For comparison purposes, mortar and concrete mixtures from the same batch were also monitored using two types of commercial ultrasonic transducers: shear wave transducers and P wave transducers. Fig. 1(c) and (d) illustrates the test setups. Each setup comprises of a U-shape rubber container with two Plexiglass plates. The difference between the container for the P wave transducers and that for the shear wave transducers is the thickness of the sample holder. The larger container, with a sample holder of 109 mm thick, was used to test mortar and concrete mixtures using a pair of 500 kHz P wave transducers (Panametrics V101). The container with a specimen holder thickness of 27 mm was used for mortar and the mortar sieved from concrete mixtures using a pair of 500 kHz shear wave transducers (Panametrics V151). A smaller specimen thickness was used with the shear wave

Table 1
Concrete and mortar mixture designs and setting times.

w/c	Mixture type	Test setups	Coarse aggregate type	Coarse aggregate volume (%)	Sand volume (%)	Initial setting (min)	Final setting (min)
0.40	Mortar	B, P, S	–	–	62.3	171	257
0.45	Mortar		–	–	61.6	189	272
0.50	Mortar		–	–	60.8	236	327
0.50	Concrete	B, P, S (mortar sieved from concrete mixtures)	"Large" Dolomitic Limestone (L)	43.4	28.9	239	315
0.50	Concrete		"Small" Dolomitic Limestone (S)	43.4	28.9	226	309
0.41	Concrete		River Gravel (R)	40.1	26.9	287	391
0.53	Concrete		River Gravel (R)	40.1	29.9	314	413
0.68	Concrete		River Gravel (R)	40.1	32.3	323	442

B: bender elements; P: P wave transducers; S: shear wave transducers.

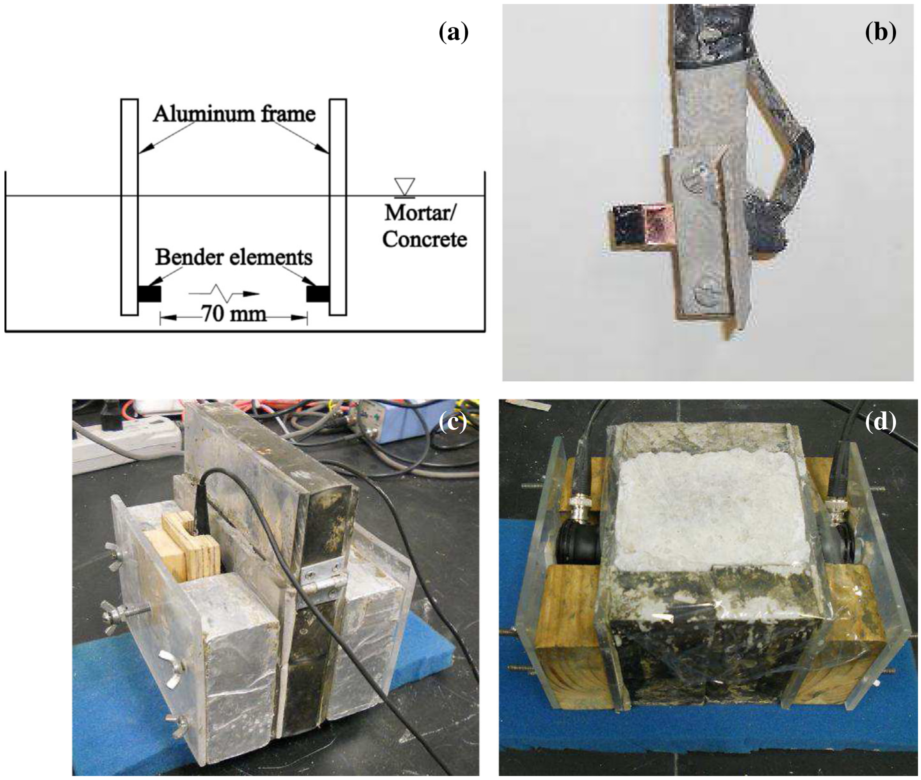

Fig. 1. Test setups: (a) setup using bender elements, (b) picture of bender element, (c) setup using shear wave transducers and (d) setup using P wave transducers.

transducers because shear waves have very high attenuation in fresh mortar. The actual thicknesses of mixtures were measured after the ultrasonic testing. In order to reduce the direct transmission of ultrasonic waves through the rubber mold, a layer of foam tape was inserted between the rubber and Plexiglass plate. Configurations of the pulser–receiver and data acquisition were similar to the bender elements setup.

2.5. Data processing of ultrasonic signals

Since the ultrasonic wave velocity in fresh mortar and concrete varies continuously, it is easier to identify the ultrasonic wave arrival time from a series of time-domain signals than from a single time-domain signal. In this study, images were formed by stacking up a series of normalized ultrasonic signals recorded at different ages, with the *x*-axis representing the time of signals in millisecond and the *y*-axis representing the age of mortar or concrete in hours. Since the amplitudes of ultrasonic signals at later ages are several orders higher than at early ages, each signal was first normalized by its maximum amplitude so that all signals have the same normalized peak amplitude.

The velocity was calculated by dividing the wave path over the travel time of the wave through mixtures. The actual wave travel time t through a mortar or concrete mixture was determined by subtracting the zero time t_0 of the test system. The t_0 in this study was 2 μs for P wave measurement and was 4 μs for shear wave measurement in the ultrasonic tests, and was 1 μs in the bender test.

Fig. 2 shows example images of ultrasonic signals in a mortar mixture ($w/c = 0.45$) measured by bender elements, shear wave transducers and P wave transducers, respectively. The signal amplitudes are normalized and the color scale is set as $[-1, 1]$. P and shear waves can be identified in these images. However, at very early ages (<1.3 h), the signals are very noisy, and arrival times of P and shear waves cannot be easily determined from the images. In addition, in Fig. 2(b) and (c), the very early age parts of the images are dominated by equally spaced wide pulses that do not change shape with ages. Further investigation indicated that these pulses are direct transmission waves through the containers. The weak signal and high level of noise make it difficult to identify the arrival time of P waves and shear waves from a single signal. However, with the aid of images, the trend of the wave arrivals and development can still be identified. It is noticed that both the bender elements and the shear wave transducers detect shear waves at earlier ages than P wave transducers, and the signals from shear wave transducers and bender elements have much higher amplitudes than those from the P wave transducers. However, the P wave transducers give strong and clear P wave arrivals.

3. Experimental results and discussion

3.1. Mortar mixtures

3.1.1. P and shear wave velocities

P and shear wave velocities in mortar mixtures measured from the bender elements setup are shown in Fig. 3, with initial setting times measured from the ASTM C403 penetration tests marked on the velocity curves. The values of setting times are shown in Table 1. The P wave velocity curves are well above the shear wave velocity curves due to the high velocity of the P waves. As seen in Fig. 3, although the mixtures have different w/c and setting times, the shear wave velocities at initial setting times for all mixtures are similar with an average of 388 m/s. The good agreement between shear wave velocity and penetration resistance results at setting times indicates that both the shear wave velocity and penetration resistance tests measure the shear property of the solid framework in mortar. On the contrary, the P wave velocities at initial setting times show greater variability, which is consistent with previous studies [11,13,24].

3.1.2. Effects of test setups and w/c on P and shear wave velocities

Fig. 4 shows both P wave and shear wave velocities measured by three different types of setups in the same batch of mortar mixtures with $w/c = 0.5$. It can be clearly seen that the three shear wave velocity curves, measured from the three different setups, agree with each other very well, while the P wave velocity curves show larger spread. There are several reasons that could contribute to such a deviation in P wave measurements. First, the P wave has a shorter arrival time than the shear wave. A small error in arrival time reading tends to cause large error in velocity calculation. Second, as discussed earlier, previous research has found that the ultrasonic P wave velocity is affected by air voids in early age

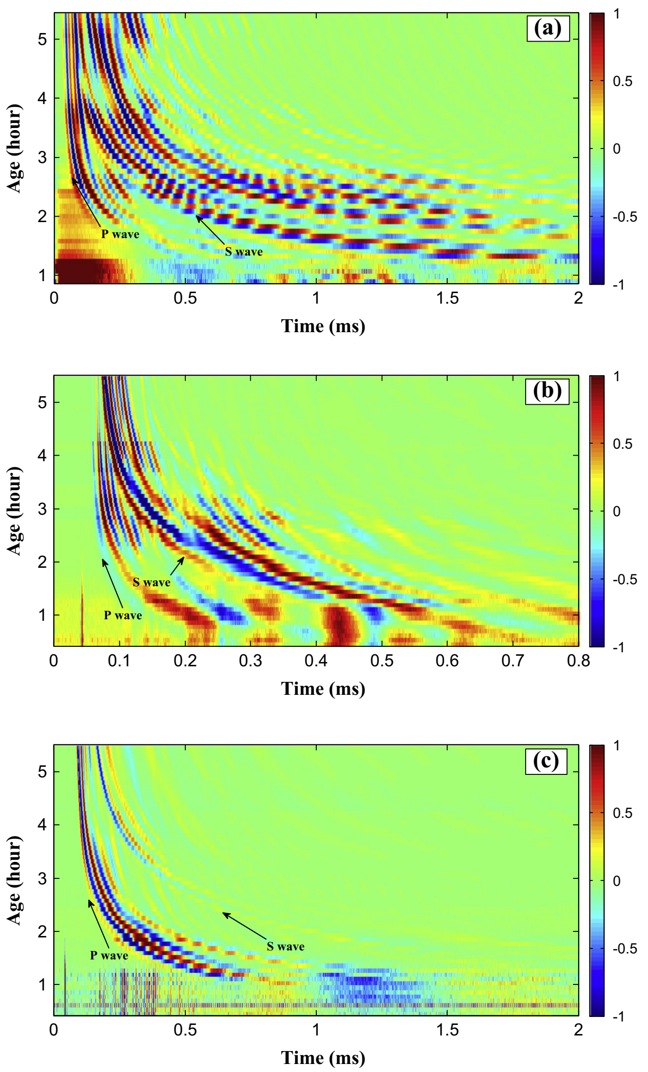

Fig. 2. Ultrasonic signal images obtained from a mortar mixture (w/c = 0.45) measured by: (a) bender elements, (b) shear wave transducers and (c) P wave transducers.

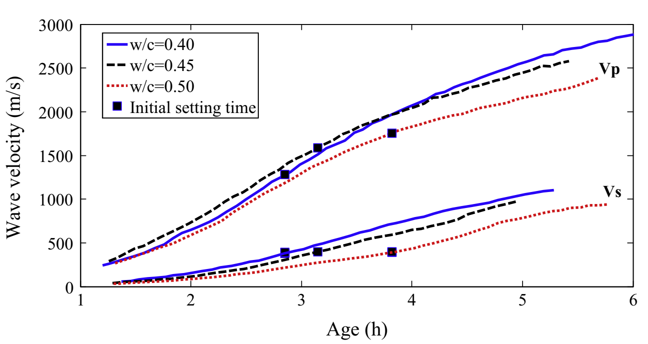

Fig. 3. Ultrasonic P wave and shear wave velocities measured in mortar mixtures.

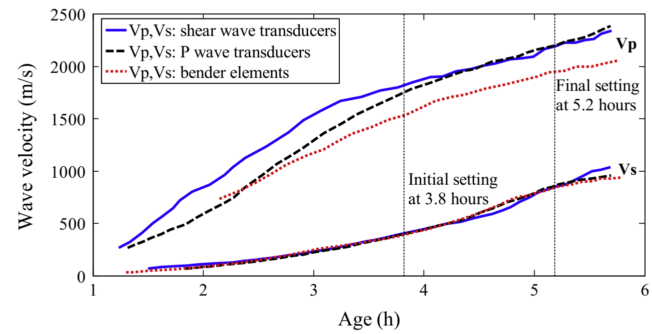

Fig. 4. Ultrasonic P and shear wave velocities in mortar (w/c = 0.5) measured by different types of transducers.

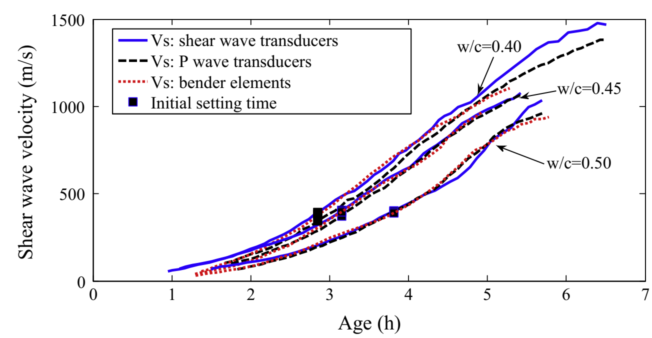

Fig. 5. Shear wave velocities in mortar mixtures with different w/c measured by different types of transducers.

Table 2
Ultrasonic wave velocities measured at initial and final setting times.

Mixtures	P wave velocity (m/s)		Shear wave velocity (m/s)	
	Initial setting	Final setting	Initial setting	Final setting
Mortar	1563 ± 164	2131 ± 120	392 ± 10	847 ± 12
Sieved concrete	1672 ± 98	2033 ± 102	508 ± 16	855 ± 19
Concrete	2674 ± 268	3355 ± 217	678 ± 76	1020 ± 186

cement pastes. Furthermore, research by Zhu et al. [11] has also found that one percent of air voids in fresh cement paste will reduce the P wave velocity from 1500 m/s to about 200 m/s. The mortar mixtures in the three setups may have slightly different air contents, which in turn may affect the P wave velocity.

To further address the influence of different w/c as well as different test setups on shear wave velocity measurement, shear wave velocities in mortar mixtures with different w/c from all three test setups are shown in detail in Fig. 5, with the initial setting times marked on the curves. For all mortar mixtures, the average shear wave velocity at initial setting times is 388 m/s in the bender element tests, 399 m/s in the shear wave transducer tests, and 372 m/s in the P wave transducer tests. It is noticed that the shear wave velocities measured by P wave transducers are slightly lower than those measured by the other two setups. As explained previously, the P wave transducers are not very effective for shear wave excitation and measurement. The weak shear wave amplitude tends to give later arrival time readings, and causes lower velocity. There is also a slight difference between the results of bender element tests and shear wave transducer tests. This may be because the mortar samples in these two setups have slightly different curing conditions. In the shear wave transducer test setup, a small volume of mortar was sealed in the container to avoid drying shrinkage, while in the bender element test setup, a relatively large volume of mortar was tested in a wooden container with a large surface open to the air. Although the container was covered by a plastic sheet, the mortar mixtures in the bender elements tests had a much larger air contact areas than in the shear wave transducer tests, which may cause a slightly earlier setting

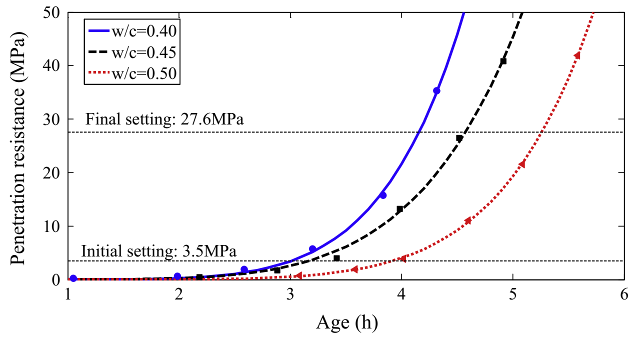

Fig. 6. Penetration resistance of mortar mixtures with different *w/c*.

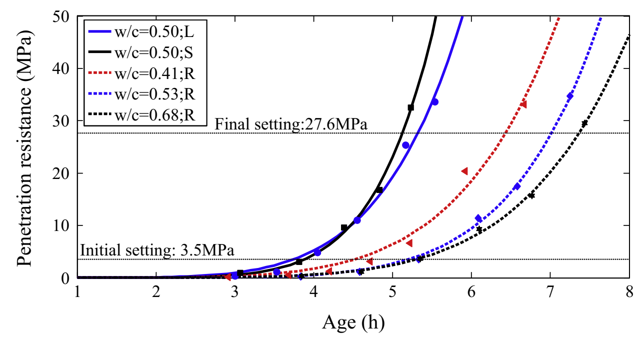

Fig. 9. Penetration resistance of mortar sieved from concrete mixtures.

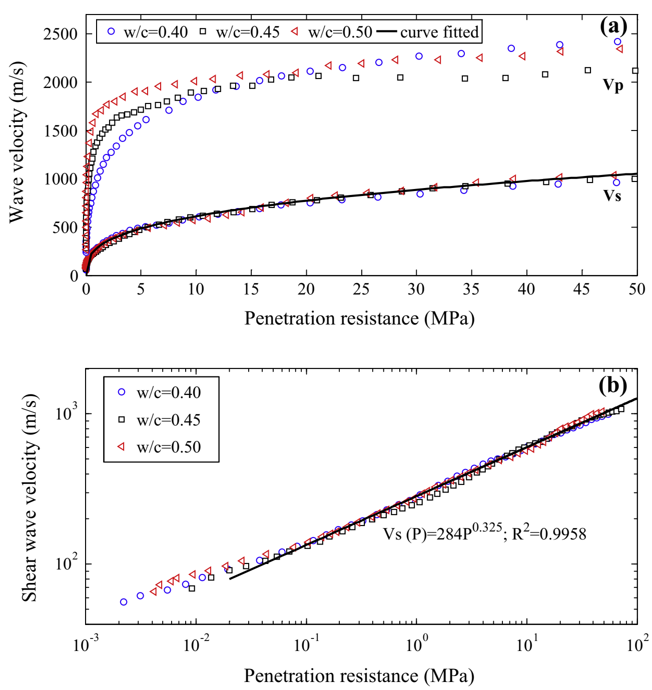

Fig. 7. Correlation between P and shear wave velocities and penetration resistance on mortar mixtures with different *w/c* in: (a) linear scale and (b) logarithm scale (shear wave velocity only).

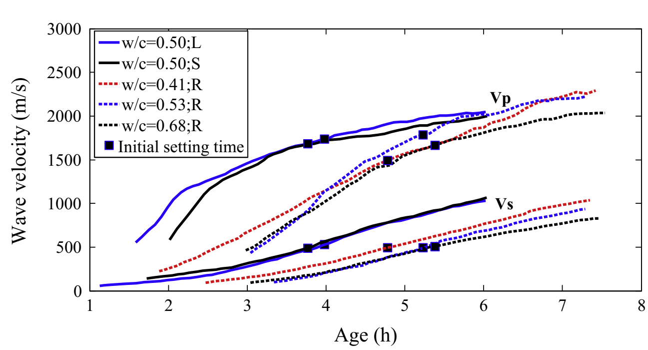

Fig. 8. Ultrasonic P and shear wave velocities in sieved concrete mixtures.

time in bender element tests compared to shear wave transducer tests. Despite these differences, the variation of the shear wave velocity at initial setting is still much smaller than the variation in P wave velocity at initial setting. The average velocities and their standard deviations are shown in Table 2.

3.1.3. Correlation between shear wave velocity and penetration resistance

Fig. 6 shows the penetration resistance measurements vs. age for mortar mixtures with different *w/c*. The initial and final setting times correspond to the penetration resistance values of 3.5 MPa [500 psi] and 27.6 MPa [4000 psi], separately. It is clearly seen that the initial and final setting times (detailed in Table 1) increase significantly as the *w/c* increases.

Since both the shear wave and penetration resistance tests measure the shear property of the solid frame in mortar, it is assumed that a unique relationship between the shear wave velocity and the penetration resistance exists. Fig. 7 plots the shear wave velocity vs. penetration resistance based on the data presented in Figs. 5 and 6. Each data point is an average of the data obtained from three different test setups. The penetration resistance data points in Fig. 7 were calculated by interpolating the equations in Fig. 6 at ages when shear wave velocities were measured. As seen in Fig. 7(a), a clear correlation is observed between the shear wave velocity and the penetration resistance, even though the mortar mixtures have different *w/c*. Fig. 7(b) shows the shear wave vs. penetration resistance data in logarithm scale. This correlation can be well represented by a power function. Since there were very few shear wave velocity data points for Vs < 100 m/s, the data points for Vs > 100 m/s were used to obtain a fit line. A very good correlation is obtained with a correlation coefficient $R^2 > 0.99$. For comparison, the P wave velocity vs. penetration resistance is also shown in Fig. 7(a). Although the data for each mixture shows a power function trend, the data from different mixtures do not show a unique correlation with the penetration results. The strong correlation between shear wave velocity and penetration resistance measurements is attributed to the fact that both measurements are directly related to the shear properties (modulus and resistance) of the solid frame in fresh mortar, while P wave velocity is also affected by the property and air voids in the fluid phase of mortar. Since setting times are determined by the penetration resistance test, the shear wave velocity is a more reliable parameter for setting time monitoring than the P wave velocity.

3.2. Mortar sieved from concrete mixtures

Five concrete mixtures of different designs were prepared, as shown in Table 1. Penetration resistance measurements were taken on mortar mixtures sieved from fresh concrete according to ASTM C403 [1]. The shear wave transducer setup was used to monitor P and shear velocities of the mortar sieved from concrete mixtures.

Fig. 8 shows development of P wave and shear wave velocities vs. age measured on sieved concrete (mortar) mixtures. It can be seen that all mixtures have similar shear wave velocities with an

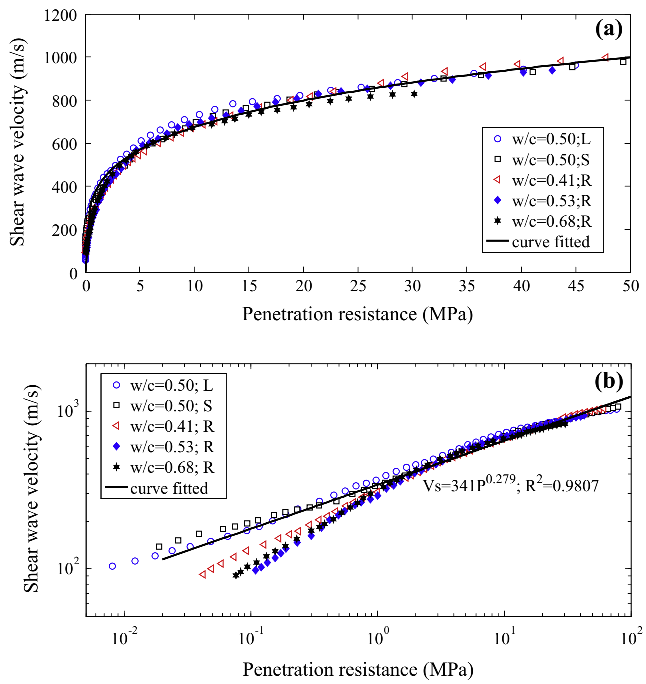

Fig. 10. Correlation between shear wave velocity and penetration resistance on mortar sieved from concrete mixtures in: (a) linear scale and (b) logarithm scale.

average of 508 m/s at initial setting times, although these mortar mixtures were sieved from concrete mixtures with different coarse aggregate sizes, different coarse aggregate types, and different *w*/*c*. The P wave velocities at initial setting times show large variance among different mixtures. This finding agrees with what was observed in the mortar tests discussed in the previous section.

The penetration resistance measurements vs. age for mortar sieved from concrete are presented in Fig. 9. It is clearly seen that the initial and final setting times increase significantly as the *w*/*c* increases in the concrete mixtures with river gravel as coarse aggregate. While in the concrete mixtures with dolomitic limestone as coarse aggregate, despite the fact that the two mixtures have different sizes of coarse aggregates, the initial and final setting are similar. This is because the two mixtures have the same *w*/*c*. In addition, the penetration resistance tests were performed on the sieved mortar samples, with most of the coarse aggregates from the concrete mixtures sieved out, thus the coarse aggregates have little influence on the setting time of these two mixtures.

The measured shear wave velocities were correlated to the penetration resistance (see Fig. 9) of the mortar sieved from concrete mixtures, and are presented in Fig. 10 in linear and logarithm

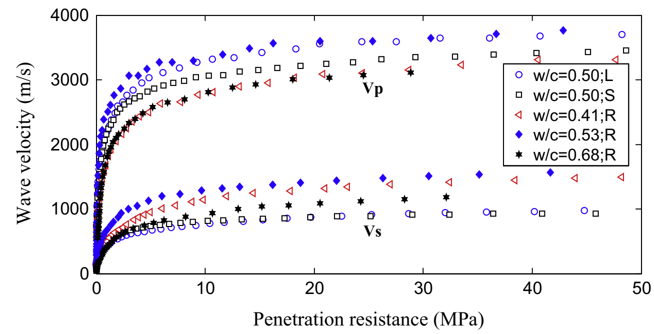

Fig. 12. Correlation between P and shear wave velocities and penetration resistance of different concrete mixtures.

scales. The data at very early age (Vs < 100 m/s) show large scattering, especially between the concrete using dolomitic limestone and river gravel aggregates. For Vs > 100 m/s, a clear correlation is obtained between the shear wave velocity and penetration resistance for all mortar mixtures sieved from concrete, with R^2 of 0.9807.

3.3. Concrete mixtures

The P wave and shear wave velocities measured from fresh concrete mixtures are shown in Fig. 11, with the setting times marked on the curves. The P wave velocity was measured by the P wave transducer setup, and shear wave velocity was measured by the bender element setup. It is noticed that both the P wave and shear wave velocities in concrete at setting times are much higher than those measured from mortar mixtures, and they also show much greater scatter. The velocities at setting times and standard deviation are shown in Table 2. It is reasonable to conclude that the large variance in measured data is caused by the heterogeneous nature of concrete. Coarse aggregates typically have much higher velocities than cement paste and mortar, and the velocity also varies

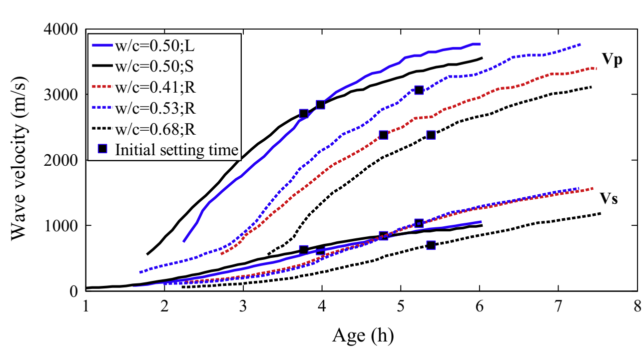

Fig. 11. Ultrasonic P wave and shear wave velocities measured in concrete mixtures.

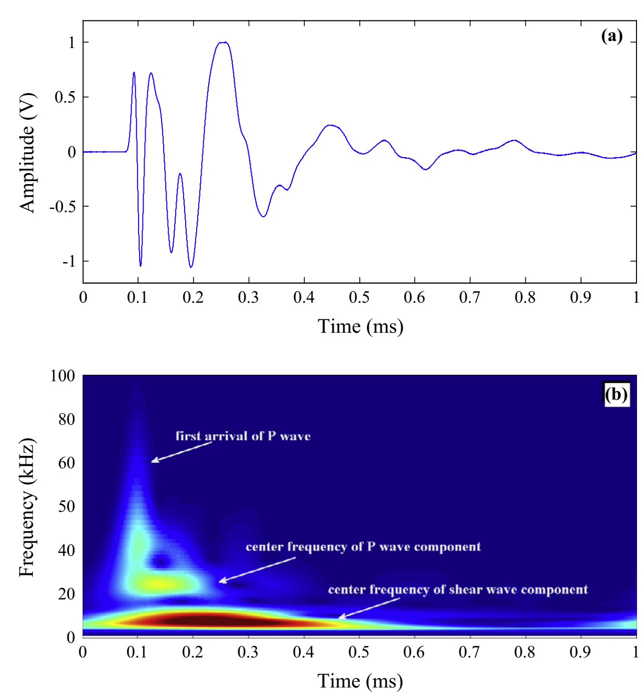

Fig. 13. (a) Time domain signal and (b) corresponding wavelet image of concrete mix (*w*/*c* = 0.50, "small" gravel).

significantly for different types of coarse aggregates. In addition, the actual coarse aggregate content in each concrete mixture might be different due to the small volume of concrete used in ultrasonic tests. Therefore, ultrasonic velocities measured on concrete mixtures are higher than those measured on the mortar sieved from the same batch of concrete, and the test results also show larger variance.

Fig. 12 shows the P wave and shear wave velocities measured on concrete mixtures vs. penetration resistance (see Fig. 9) of the sieved mortar mixtures. Unlike the mortar tests, there is no unique relationship between shear wave velocity measured in concrete and penetration resistance measured on sieved mortar, although the data from each mixture still show similar power function trends. It is because presence of coarse aggregates in concrete strongly affects both P wave and shear wave velocities, while the penetration resistance measured on sieved mortar is not affected. This study demonstrates the challenges for in-situ monitoring of fresh concrete using ultrasonic wave velocity methods, and indicates that there is no simple correlation between wave velocities and penetration resistance measurements for concrete with different mix designs.

3.4. Discussion

The measured ultrasonic wave velocities and standard deviations are listed in Table 2 for all mortar and concrete mixtures. For mortar mixtures and mortar sieved from concrete, the shear wave velocity at setting shows very small variance among mixtures with different *w*/*c*. The relative standard deviation of the velocity at setting times is 2–3%. There is a strong correlation between the shear wave velocity and penetration resistance throughout the entire monitoring period, as shown in Figs. 7 and 10. A previous study [25] indicated that the penetration resistance is fundamentally related to the shear modulus in cement pastes, while the shear wave velocity is also related to the shear modulus. Our experimental study further validates this theory and extends it to mortar mixtures. It should be noted that both the shear wave velocity and penetration measurements are affected by fine and coarse aggregate content and size. Therefore, the shear wave velocities at initial setting time are different for the designed mortar and mortar sieved from concrete. However, factors governing the hydration process of cement, such as *w*/*c*, will affect the shear wave velocity and penetration resistance in a similar way, which are related by the fundamental parameter shear modulus.

It is also noted that the P wave velocity measured in concrete at initial setting time is significantly higher than published values [9], and the P velocity difference (2674 vs. 1672 m/s) between concrete and sieved mortar mixtures is also much larger than the shear wave velocity difference (678 vs. 508 m/s). One possible reason is the high frequency of the ultrasonic waves used in this study. The P wave velocity was measured by using a pair of 500 kHz ultrasonic transducers. Fig. 13 shows a time domain signal measured at the initial setting time in concrete (*w*/*c* = 0.50, ''small'' dolomitic limestone) and its wavelet analysis result. The first arrival P wave contains high frequency components above 60 kHz, followed by P wave components with center frequencies around 20 kHz, and shear waves with center frequencies around 6.5 kHz. In the high frequency range, the ultrasonic wave propagates through the mortar matrix and coarse aggregates, and the total travel time of waves can be calculated by the ray theory. In this case, the P wave velocity will increase linearly with the volume of coarse aggregates.

In low frequency (long wavelength) range, the wavelength can be larger than the coarse aggregate size. In this case, concrete should be treated as an effective medium, and the wave velocity is related to the stiffness of the effective medium. Fresh concrete before setting can be modeled as a mortar suspension with coarse aggregates, where the Reuss theory [26] that describes an equal-stress model applies. According to the Reuss theory, the compliance of an effective medium is the volume weighted average of each component. Since the mortar matrix has much higher compliance than the coarse aggregates, the effective compliance of fresh concrete will be dominated by that of the mortar matrix. Therefore, the resulting wave velocity in fresh concrete will be close to the velocity in mortar matrix. From this point of view, using low frequency waves may reduce the effect of coarse aggregate variation at early ages.

4. Conclusions

In this study, ultrasonic tests were used to monitor the setting process in fresh mortar and concrete mixtures. It is shown that a clear correlation exists between the shear wave velocity and penetration resistance for mortar mixtures. Shear waves can be effectively measured in fresh mortar and concrete using bender elements. Specifically, the following conclusions can be drawn from this study:

1. The shear wave velocities measured at initial setting time are 392 ± 10 m/s in mortar, 508 ± 16 m/s in mortar sieved from concrete, and 678 ± 76 m/s in concrete, respectively. The shear wave velocities obtained at the initial and final setting times show higher consistency than the P wave velocities in mortar mixtures with different *w*/*c*, which implies that it is more reliable to correlate the setting times with the shear wave velocity rather than with the P wave velocity.
2. There is a clear correlation between the shear wave velocity and the penetration resistance measured on early age mortar mixtures through the entire process. This relationship is not affected by the *w*/*c* of the mixture.
3. Unlike in mortar tests, there is no unique correlation between P wave or shear wave velocity in concrete and penetration resistance measurements. It is because that wave velocities are strongly affected by coarse aggregates, while the penetration test is performed on sieved mortar samples, which is not affected by coarse aggregates.
4. Ultrasonic wave velocities in fresh concrete are also affected by frequencies and coarse aggregates. In the high frequency range, the velocity is greatly affected by coarse aggregate content. In low frequency range, the coarse aggregates affect wave velocities to a lesser degree.

Acknowledgements

This study was partially supported by the Texas Department of Transportation (TxDOT), United States, Research Project 0-6717 and by the China Scholarship Council.

References

[1] ASTM C403. Standard test method for time of setting of concrete mixtures by penetration resistance. Am Soc Test Mater 2008.
[2] Trtnik G, Gams M. Recent advances of ultrasonic testing of cement based materials at early ages. Ultrasonics 2014;54:66–75.
[3] Keating J, Hannant DJ, Hibbert AP. Comparison of shear modulus and pulse velocity techniques to measure the build-up of structure in fresh cement pastes used in oil well cementing. Cem Concr Res 1989;19:554–66.
[4] Sayers CM, Dahlin A. Propagation of ultrasound through hydrating cement pastes at early times. Adv Cem Based Mater 1993;1:12–21.
[5] Lee HK, Lee KM, Kim YH, Yim H, Bae DB. Ultrasonic in-situ monitoring of setting process of high-performance concrete. Cem Concr Res 2004;34:631–40.
[6] Qin L, Li Z. Monitoring of cement hydration using embedded piezoelectric transducers. Smart Mater Struct 2008;17:55005.
[7] Rapoport JR, Popovics JS, Kolluru SV, Shah SP. Using ultrasound to monitor stiffening process of concrete with admixtures. ACI Mater J 2000;97:675–83.

[8] Voigt T, Grosse CU, Sun Z, Shah SP, Reinhardt HW. Comparison of ultrasonic wave transmission and reflection measurements with P- and S-waves on early age mortar and concrete. Mater Struct 2005;38:729–38.
[9] Robeyst N, Gruyaert E, Grosse CU, De Belie N. Monitoring the setting of concrete containing blast-furnace slag by measuring the ultrasonic P-wave velocity. Cem Concr Res 2008;38:1169–76.
[10] Van der Winden NGB. Ultrasonic measurement for setting control of concrete. In: Reinhardt HW, editor. Testing during concrete construction. Chapman Hall; 1991. p. 122–37.
[11] Zhu J, Kee S-H, Han D, Tsai Y-T. Effects of air voids on ultrasonic wave propagation in early age cement pastes. Cem Concr Res 2011;41:872–81.
[12] D'Angelo R, Plona TJ, Schwartz LM, Coveney P. Ultrasonic measurements on hydrating cement slurries: onset of shear wave propagation. Adv Cem Based Mater 1995;2:8–14.
[13] Zhu J, Tsai Y-T, Kee S-H. Monitoring early age property of cement and concrete using piezoceramic bender elements. Smart Mater Struct 2011;20:115014.
[14] Stepisnik J, Lukac M, Kocuvan I. Measurement of cement hydration by ultrasonics. Am Ceram Soc Bull 1981;60:481–3.
[15] Valič MI. Hydration of cementitious materials by pulse echo USWR method, apparatus and application examples. Cem Concr Res 2000;30:1633–40.
[16] Trtnik G, Valič MI, Turk G. Measurement of setting process of cement pastes using non-destructive ultrasonic shear wave reflection technique. NDT E Int 2013;56:65–75.
[17] Shirley DJ, Hampton LD. Shear-wave measurements in laboratory sediments. J Acoust Soc Am 1978;63:607–13.
[18] Chaney R, Demars K, Brignoli E, Gotti M, Stokoe K. Measurement of shear waves in laboratory specimens by means of piezoelectric transducers. Geotech Test J 1996;19:384.
[19] David Suits L, Sheahan T, Leong E, Yeo S, Rahardjo H. Measuring shear wave velocity using bender elements. Geotech Test J 2005;28:12196.
[20] Lee J-S, Santamarina JC. Bender elements: performance and signal interpretation. J Geotech Geoenviron Eng 2005;131:1063–70.
[21] Jung MJ. Shear wave velocity measurements of normally consolidated kaolinite using bender elements. Master's Thesis, Univ Texas Austin; 2005.
[22] Kee S, Zhu J. Surface wave transmission across a partially closed surface-breaking crack in concrete. ACI Mater J 2014;111:35–46.
[23] ASTM C192. Standard practice for making and curing concrete test specimens in the laboratory. Am Soc Test Mater 2007:1–8.
[24] Juilland P, Flatt RJ, Lootens D. Pragmatic (and) scientific characterization of the early ages properties of cementitious materials. Creep, Shrinkage and Durability Mechanics of Concrete and Concrete Structures. Taylor & Francis; 2008. p. 305–8.
[25] Lootens D, Jousset P, Martinie L, Roussel N, Flatt RJ. Yield stress during setting of cement pastes from penetration tests. Cem Concr Res 2009;39:401–8.
[26] Hill R. The elastic behaviour of a crystalline aggregate. Proc Phys Soc Sect A 1952;65:349–54.