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

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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

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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.