Cement and Concrete Research 106 (2018) 1–11

Contents lists available at ScienceDirect

Cement and Concrete Research

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

Determination of mortar setting times using shear wave velocity evolution curves measured by the bender element technique

J. Zhu[a,b], J.N. Cao[b], B. Bate[c,*], K.H. Khayat[d]

[a] Jones Lang LaSalle, 1 Zhongxinsi Road, Futian District, Shenzhen 518048, China
[b] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO 65409, United States
[c] Institute of Geotechnical Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China
[d] University Transportation Center and the Center for Infrastructure Engineering Studies, Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Rolla, MO 65409, United States

ARTICLE INFO

Keywords:
Mortar
Early age
Shear wave velocity
Initial setting time
Final setting time
Bender element

ABSTRACT

Although identified as a good indicator to characterize freshly cast cementitious materials, shear wave velocity (V_s) alone has not been used successfully to determine the initial and final setting times (t_i and t_f). The challenge originates from the large V_s range that can vary from < 50 m/s to > 2000 m/s for cementitious materials at early age (typically < 24 h). To overcome these challenges, modifications to traditional bender element and to specimen geometry were made to obtain V_s *versus* time ($V_s(t)$) curves of six early age mortars at different water-to-cement ratios, some with chemical admixtures. Derivative methods were then proposed to obtain t_i and t_f. The peak time (t_{peak}') in the first-order derivative of $V_s(t)$ curves correlate well to the final setting time (R^2 = 0.979), while the peak time (t_{peak}'') of the second-order derivative of $V_s(t)$ curves correspond well to the initial setting time (R^2 = 0.950).

1. Introduction

Monitoring freshly cast cementitious materials (paste, mortar, and concrete) at early age (approximately the first 24 h) is desired in quality assurance and quality control (QA/QC), and for long-term performance prediction. Initial and final setting times are the two key parameters to characterize cementitious material properties of early age. Initial setting time denotes the time when a cementitious material is sufficiently rigid to withstand a certain pressure and the material starts losing its plasticity. Final setting time denotes the time when the developments of strength and stiffness start, and the plasticity is completely lost. Both setting times are useful parameters in the transportation, casting, and consolidation of cementitious materials and are key parameters for strength development at early age and for formwork removal [1,2].

The standard methods of measuring setting times are based on the penetration resistance test (ASTM C403) for mortar or concrete and the Vicat needle test (ASTM C191) for paste. Both tests are destructive laboratory tests. The isothermal calorimetry method was employed to determine setting times from heat evolution curves [3–8]. The above methods are at the specimen scale. The ultrasonic pulse velocity measurement [9,10] is widely used in the field due to its non-destructive nature and its sensitivity to the presence of air pockets, abnormalities, or defects. However, water in the concrete leads to a high V_p value (approximately 1490 m/s), which is on the same order of magnitude as that of the fresh cementitious material where V_p can vary from approximately 100 m/s in the fresh state to over 4000 m/s in the hardened state. Subsequently, P-wave velocity originating from the solid portion of the cement-based material during curing is shielded by water, which makes it a poor indicator of the curing process when used alone. Carette and Staquet [11] combined V_p and V_s results to determine setting time of mortars, and concluded that the P-wave is less sensitive to the setting process than S-wave. The hydraulic pressure method monitors the setting/hardening process using wall hydraulic pressure that are in contact with the concrete through the formwork (from hydrostatic to zero as the specimen cures from slump to fully hardening) [7,12]. Hydraulic pressure method can be implemented in the field. However, this method necessitates the use of high accuracy pressure sensors. Pore water pressure sensors in contact with concrete can then be used to evaluate the rate of setting.

Previous studies suggest that shear wave velocity (V_s) is a good indicator of the curing process of cementitious materials, such as mortars [11] and cement-soil mixtures [13,14]. This is because shear waves propagate primarily through the solid skeleton of a material and is not significantly influenced by the presence of water or air. In spite of its use in evaluating characteristics of *in-situ* soils and cemented soil in the laboratory, shear wave velocity alone is not commonly used to

* Corresponding author at: Institute of Geotechnical Engineering, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China.
E-mail address: batebate@zju.edu.cn (B. Bate).

https://doi.org/10.1016/j.cemconres.2018.01.013
Received 14 February 2017; Received in revised form 4 November 2017; Accepted 11 January 2018

monitor the early age properties of cementitious materials. This is because early-age cementitious materials have a larger range of stiffness variations during the curing process where V_s can vary from around 50 m/s in the fresh state to over 2000 m/s in the hardened stage. This is considerably greater than soils that normally vary from 30 m/s (kaolinite [15]) to 350 m/s (iron oxide-coated sand, [16]) under normal loading conditions (< 400 kPa). The quick stiffness (V_s) increment increases the resonant frequency of the specimen, which subsequently mandates the increment of the exciting frequency to ensure a good signal-to-noise ratio [17,18], reduces wavelength, and poses challenges in maintaining the wavelength ratio (R_d) requirement ($R_d > 2$) needed to minimize the near-field effect in < 24 h [19,20]. This is the major reason that existing studies using traditional piezoceramic material-based tools, such as the traditional bender element (BE) [21] and piezoelectric ring actuator [7], provide only partial V_s evolution data (< 15 h) for cementitious materials generally with longer curing process (normally > 24 h). However, in view of its advantages, such as *in-situ* and laboratory experimental capabilities and well-established approaches for soils, the bender element technique could be suitable to evaluate the stiffness of cement-based materials at early age.

This study aims at modifying the traditional bender element to obtain V_s evolution curves of mortar at early-age spanning from 0 to > 24 h. The study also seeks to determine the initial and final setting times based on V_s evolution results. The following objectives are proposed accordingly: (1) modify the geometry of mortar specimen and change the geometry, alignment and coating of a traditional bender element used for soils to cover V_s variations at early-age of cement-based materials; and (2) measure the evolution of shear wave velocity of mortar specimens at early age (up to 96 h) with the modified bender element testing system. Six mortar mixtures of different water-to-cement ratios (w/c), including one with a set accelerator and two with set retarders were prepared to embrace a broad range of setting times. The evolution of V_s with time was analyzed to evaluate setting times, which were compared to values measured by ASTM standard penetration resistance test. In addition, a calorimetry test-based method was also evaluated and used to correlate to setting times determined from penetration resistance test.

2. Materials

A Type I portland cement was used. Missouri River sand. A well graded river-bed sand was used. The sand was sieved through No. 4 sieve with D_{50} of 0.7 mm and C_u (coefficient of uniformity, D_{60}/D_{10}) of 2.74. The grain-size distribution of the sand is shown in Fig. 1 and is close to the lower limit of the specification for aggregate used to make masonry mortar (ASTM C144). Two chemical admixtures were introduced to alter the range of setting times: a hydration controlling admixture that retards setting times by controlling the hydration of the cement, and a non-chloride accelerating admixture that accelerates cement hydration.

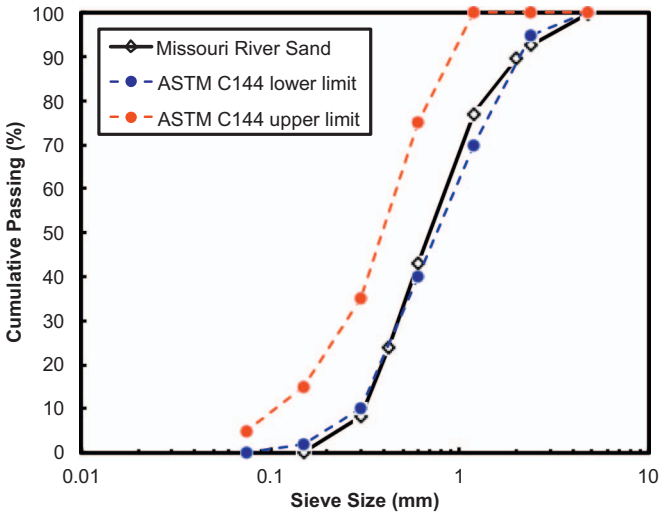

Fig. 1. Grain-size distribution of sand used in this study.

Table 1
Mixture proportioning of tested mortars.

Mixture	Mix 1[a]	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
w/c	0.50	0.43	0.37	0.43	0.43	0.43
Cement (kg/m^3)	673	713	751	713	713	713
Sand (kg/m^3)	1137	1203	1267	1203	1203	1203
Water (kg/m^3)	337	313	277	313	313	313
Set retarder (ml/100kgc)	–	–	–	195	–	220
Set accelerator (ml/100kgc)	–	–	–	–	1500	–
Unit weight (kN/m^3)	21.34	22.28	22.63	22.08	21.78	22.08

[a] Repeated three times to verify the repeatability of material properties.

3. Mixing design

Six mortar mixtures were used, as shown in Table 1. Mortar mixtures with w/c of 0.50, 0.43, and 0.37 are referred to as Mix 1, Mix 2, and Mix 3, respectively. The dosage rates of the admixtures (*i.e.*, set accelerator and set retarder) were selected based on the criteria in ASTM C 494: Normal variation of delaying in the initial setting time is between 1 and 3.5 h when using a set retarder, or between 1 and 3.5 h earlier when using an accelerator. Mix 4 and Mix 6, modified from Mix 2 (w/c of 0.43), contained 3 fl oz./cwt (fluid ounce/cement hundredweight) (195 ml/100kgc) and 3.4 fl oz./cwt (220 ml/100kgc) hydration controlling admixture, respectively. Mix 5 was modified from Mix 2 with w/c of 0.43, and incorporated 23 fl oz./cwt (1500 ml/100 kg) accelerating admixture. The procedure used for mixing mortar is in compliance with ASTM C 305. A mechanical mixer was used. In each test, a batch of 25 l of mortar was prepared, and 21 l was placed in the formwork.

4. Bender element testing system

A bender element (BE) testing system for measuring V_s of cementitious materials was used. The BE system consisted of three pairs of bender elements, a signal generation and acquisition system, and a wooden formwork measuring $0.61 \times 0.305 \times 0.14$ m^3 (length × width × height, inner geometry) (Fig. 2). The system was developed with modifications on a traditional bender element system. The details of each component and the rationale behind the corresponding modifications are discussed below.

5. Bender element test setup

Two-layered brass-reinforced piezo actuators were cut into bender element plates with dimension of $23 \times 11.5 \times 2$ mm^3 (length × width × thickness). This size is larger than typical sizes ranging from $12 \times 5 \times 0.5$ mm^3 to $20 \times 12.7 \times 2$ mm^3 [22] used in soil testing. The selected larger size is expected to enhance signal strength given the long travel distance in a large specimen and the initially paste-type materials (possibly weak signal due to the few contacting points for V_s propagation). A parallel-type connection was also adopted over series-type connection for stronger received signals [23].

From inside out, coatings of a bender element that is typically used for geotechnical applications follow the order of polyurethane, silver conductive paint, and epoxy coatings (Fig. 2b) [15,17,23,24]. Modifications were made to these coatings to accommodate testing of cementitious materials, which are corrosive with high pH. For the