Center for Transportation Infrastructure and Safety

Using Shear Wave Velocity to Monitor the Curing Process of Self-Consolidating Concrete by Bender Element

by

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16. Abstract

The evaluation of the curing process of a fresh concrete is critical to its construction process and monitoring. Traditionally stress sensor and compressive wave sensor were often used to measure concrete properties. Bender element (BE) test, a nondestructive test measuring shear wave velocity (Vs) was widely used in geotechnical engineering. Maximum shear modulus is the ratio of shear stress to shear strain. It used in determination of elastic settlement and stiffness. The use of bender elements to detect stiffness change through shear wave velocity is a non-destructive test. BE test was used to monitor the curing process of fresh self-consolidating concrete in this study.

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MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

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Project content

Introduction

The evaluation of the curing process of a fresh concrete is critical to its construction process and monitoring. Traditionally stress sensor and compressive wave sensor were often used to measure concrete properties. Bender element (BE) test, a nondestructive test measuring shear wave velocity (V_s) was widely used in geotechnical engineering. Maximum shear modulus is the ratio of shear stress to shear strain. It used in determination of elastic settlement and stiffness. The use of bender elements to detect stiffness change through shear wave velocity is a non-destructive test. BE test was used to monitor the curing process of fresh self-consolidating concrete in this study.

Measuring methods of shear wave velocity

A traditional method of evaluating the safety of a structure is by testing samples removed from the structure. Nondestructive in situ evaluation is far more convenient and cost effective. Recent advances in computer and other electronic technologies have created a plethora of opportunities to measure the condition of a structure. The National Science Foundation (NSF) has contributed by funding the research ideas in this area. These efforts have been concentrated in the general approaches using (1) acoustic signals, (2) electromagnetic, (3) radiography, (4) fiber optics, (5) Radar and radio frequency, (6) optics, and (7) piezoelectric ceramic. Many methods exist for non-destructive evaluation ranging from acoustics to optical. Most of these methods measured damage indirectly by measuring sound, light, intensity of electromagnetic field, displacements, or temperature. Some methods are considerably simpler to apply than others because they do not require a special setup such as embedding the sensor during construction, which constrains their applications to new structures. Other methods are effective because of their cost effectiveness. In each of the particular methods, opportunities exist for groundbreaking research. [1]

Elasticity modulus and Poisson's ratio could be determined with the primary wave and shear wave velocities together with the density of the material. P-wave is widely used in material property characterization by ultrasonic pulse velocity (UPV), which is one of the non-destructive tests. However, shear waves are much slower and difficult to determine. Therefore, fewer researchers focus on the application of S-wave in concrete material.

Shear wave is a type of elastic wave; it also called secondary wave or S-wave. Shear wave moves through elastic media and the main restoring force comes from shear effects.

The measuring methods of shear wave velocity could be Bender Elements test (Santamarina et al., 2005 and Zhu et al., 2011), Hilbert Transformation (Recep, 2009), Resonance Analyzer Test (An et al., 2009) etc. [2-7]

This study is based on bender elements test.

Fabrication of bender elements

Bender elements are convenient shear wave transducers. It used to be applied in geotechnical engineering due to optimal soil-transducer coupling and compatible operating frequency. There are various aspects of bender element installations including: electromagnetic coupling prevention, directivity, resonant frequency, detection of first arrival and near field effects. [2]

The essential material of bender elements is piezoceramics. Two layer brass reinforced piezo actuators are used in this study. Normal fabrication process of bender elements have been discovered, but various testing objects should have various type bender elements. This study focused on concrete-testing bender elements.

Fabrication of bender element needs the following devices and materials.

Fig. 1 Devices and materials

1. Soldering tin
2. Nylon cap

3. Heat-shrink tube
4. Sandblaster
5. Pliers
6. Coaxial cable
7. Driller
8. Multimeter
9. Polyurethane
10. Soldering flux
11. Soldering machine
12. Hair dryer
13. Epoxy
14. Primer and PVC cement
15. Mackintosh
16. Nylon bag

Generally, there are 12 processes of fabricating bender elements.

1. Smooth the edges of piezoceramics by sandblaster.

Fig. 2 Smoothing

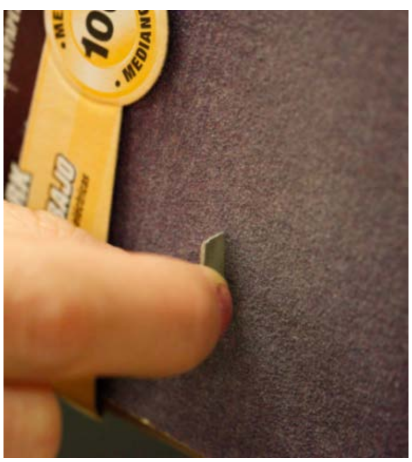


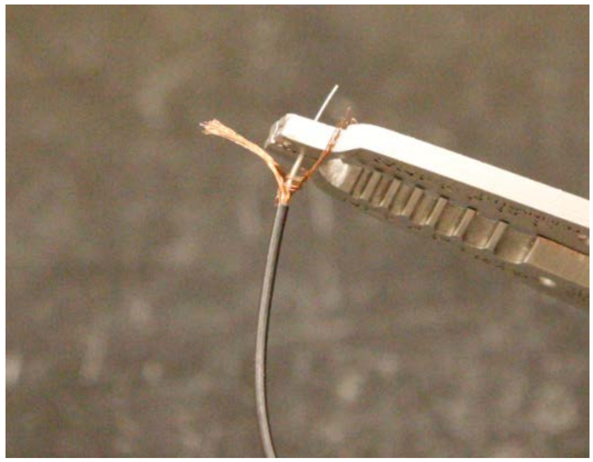
Fig. 3 Removing external plate

2. Use driller to remove a few area of external plate on one side of piezoceramics.

   Expose the internal plate.

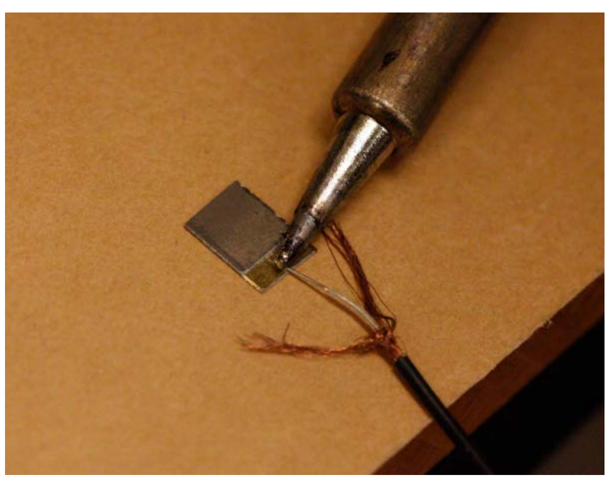
3. Remove outer shield from both ends of coaxial cable. Separate the inner core from the copper mesh at both ends; divide copper mesh into two branches at one end. Remove the end of inner core shield.

Fig. 4 Removing outer shields



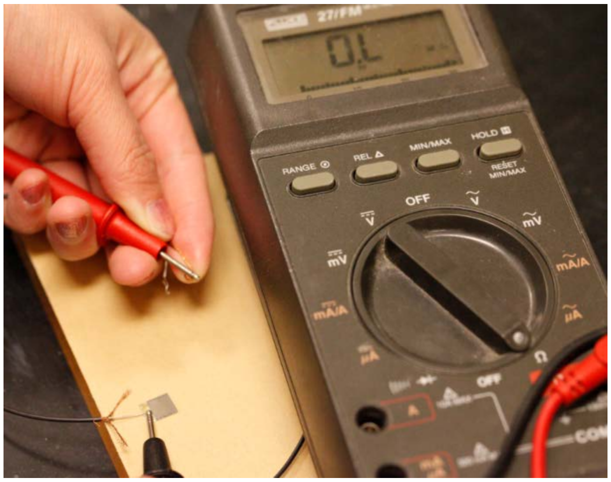
4. Solder the end of the cable with piezoceramics. Solder inner core with internal plate and copper mesh with external plates. Prevent inner core or soldering tin from touching external plates. Be very careful when using the soldering flux to prevent electromigration.

Fig. 5 Soldering



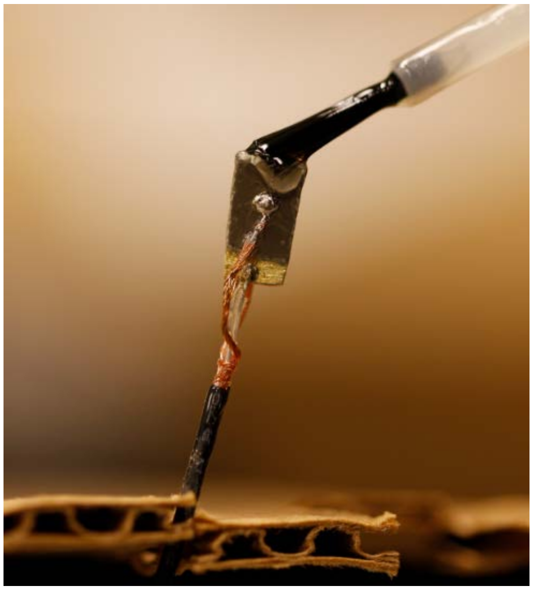
5. Check if the core-to-shield resistance is infinite with a multimeter. The circuits must open circuit. If not, check the previous processes correct or not.

Fig. 6 Checking circuit



6. Coat the entire piezoceramics and the exposed portion of the coaxial cable with low viscosity polyurethane. Let it air dry for several hours and then coat with the second layer. The coating layers are for water-proof.

Fig. 7 Coating with polyurethane



7. Coat the piezoceramics and the end shield of the coaxial cable with PVC cement, which has higher moisture resistance and better mechanical bond by means of both roughing up the surface of the transducer and using Oatey purple primer. Compared to epoxy, one of the advantages of coating with PVC cement is its flexibility and maintained integrity during vibrations. Compared to polyurethane, coating integrity remained high when in contact with fresh concrete over a certain time. [8] More important, PVC cement has good chemical resistance, which is essential for testing fresh concrete and a longer worklife.

Fig. 8 Applying primer

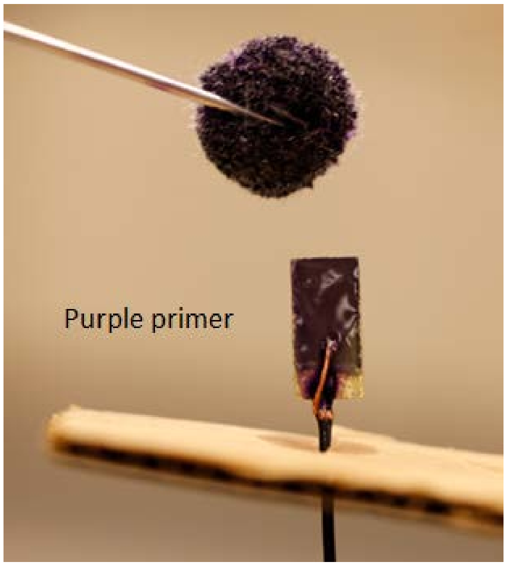
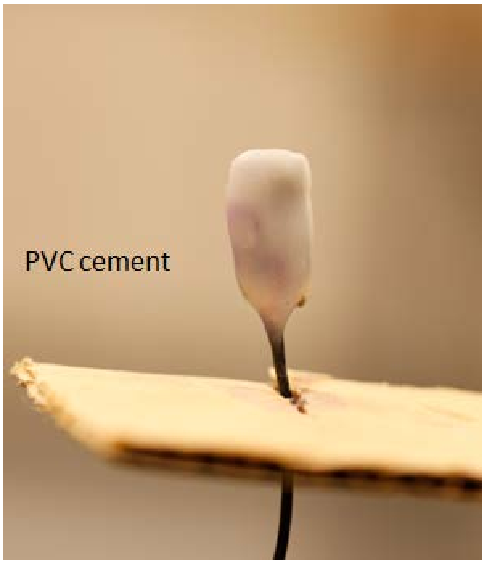
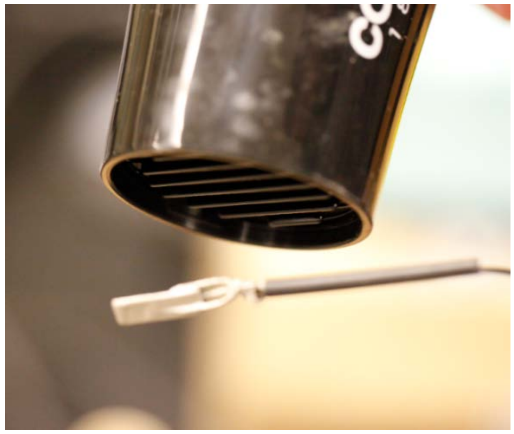


Fig. 9 Coating with PVC cement



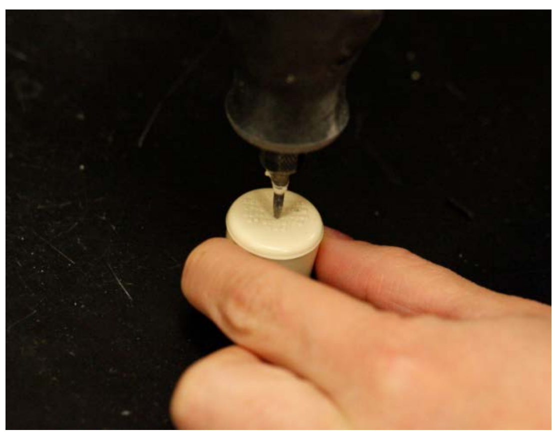
8. Using heat-shrink tube to reinforce the connections between coaxial cable and piezoceramics. The tube could shrink by using a hair dryer.

Fig. 10 Tube shrinkage



9. Drill a hole at the center of the nylon cap. Make sure the diameter of the hole is the same with the shrinking tube to prevent leakage of PVC cement. Slide the piezoceramics inside the nylon cap.

Fig. 11 Drilling



10. Mounting bender elements by a nylon cap with diameter of 13/16 inch. Fill in the cap with sand and PVC cement. The use of sand can save time of air dry and some PVC cement. Let it air-dry for a few days until the core-to-shield resistance is infinite.

Fig. 12 Mounting and air drying

11. Cover the bender element by slight chemical-resistant epoxy. A second layer may be applied if needed. Let it air dry for at least two days.

Fig. 13 Coating with epoxy

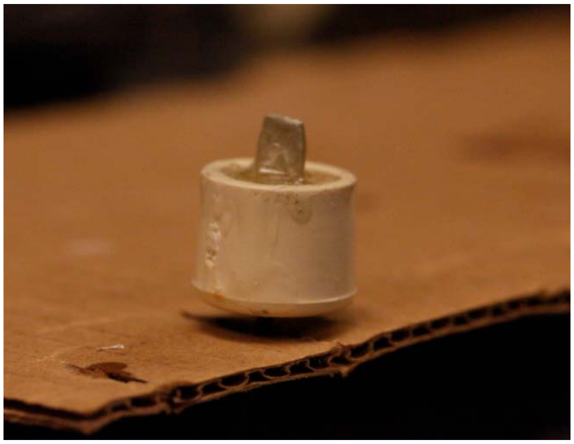
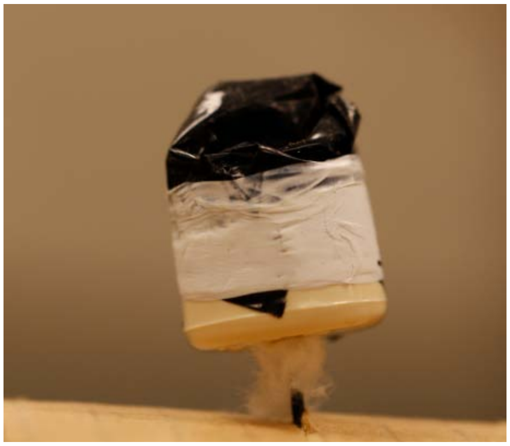


Fig. 14 Extra protections



12. Cover the exposed portion of bender element with nylon bag, which is extra protection from corrosion. Wrap the nylon cap with mackintosh, which can tighten with cylinder wall and prevent leakage.

Setup of apparatus

Bender elements have two types: series type and parallel type (figure15).Two piezoelectric material layers with a metal shim middle layer. In this test parallel type BEs were applied.

Fig. 15 Bender elements: (a) schematic representation of bender element, (b) series type, and (c) parallel type [2]

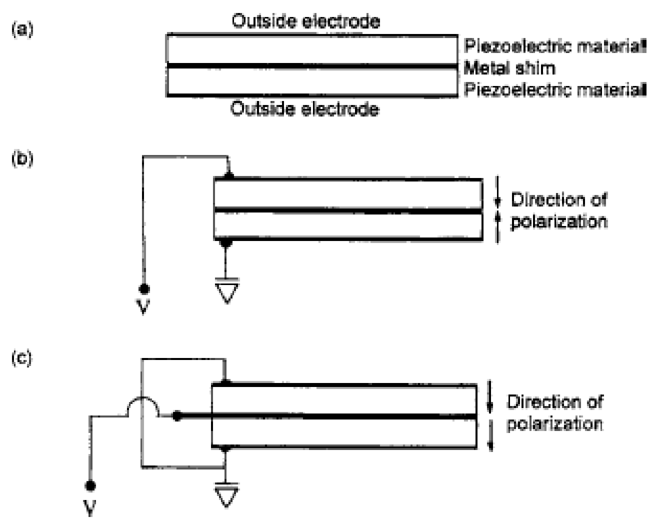
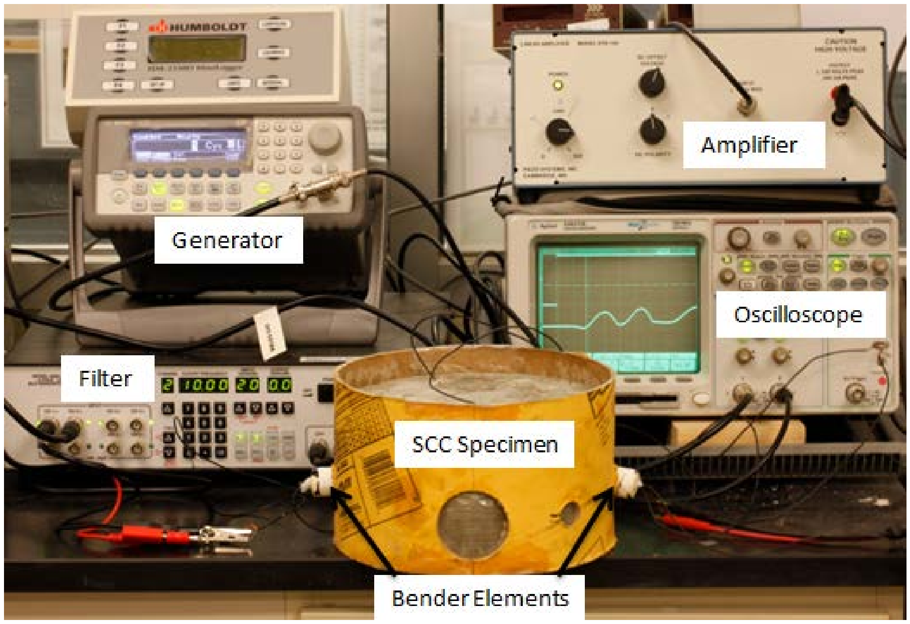


Figure 16 shows the apparatus needed to detect shear wave. A pair of bender element is composited by source and receiver. The benefit of applying square wave is that it includes a wide frequency range, and it will naturally respond at its resonant frequency. [2, 8] Square shear wave is preferable in this study due to the uncertainty of resonant frequency of the fresh SCC. When the shear waves generated by the source, the signals transmit through test specimen and arrive at receiver. Then, filter will give a frequency cut of the waves; waves appear on oscilloscope after going through the amplifier. Travel time can be known from the comparison of generate wave and receive wave.

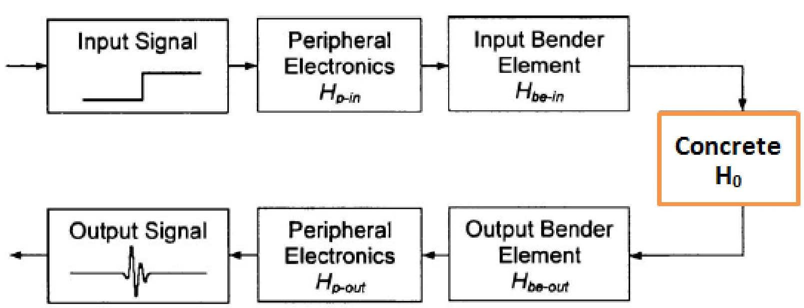
Fig. 16 Bender element apparatus



Floating bender elements have better coupling with the surrounding materials (e.g., fresh concrete), which could save the processes of using nylon cap and drilling holes for the anchor. Furthermore, the bender elements' size would be relatively small because of good vibration of the entire elements. However, floating bender elements could not be reused after the concrete hardening. So this study used nylon cap as a permanent anchor.

To prevent transmitting the vibrations through the concrete wall, cardboard cylinder was used in this study instead of PVC pipe, which could be too stiff and disturbs signals.

Fig. 17 Sequence of frequency response functions [2]



Twine the cap of bender elements with mackintosh to prevent the leakage of water. Insert BEs carefully with one rotated direction until they are tightly fixed with the pipe. Caution: a couple of BEs should have the same angle to the wall; perpendicular to the horizontal plane is preferable. Assume the poisson's ratio of concrete is 0.20-0.24, and then $R_{\text{P-wave radius}}/L_{\text{tip-to-tip}}$ should be larger than 0.694 based on the following equation.

$$R_{P-wave\ radius} \geq \frac{L_{tip-to-tip}}{2\sqrt{1-2v}}$$

Besides, $L_{\text{tip-to-tip}}$ should be larger than double wave length to avoid the near-field regime. Spread epoxy around the contact circle of BEs and cylinder wall, in case there will be leakage. BE test was performed on a cardboard cylinder with diameter of 8 inches and height of 5 inches. The travel distance (tip-to-tip distance) was measured as 180mm. Square shear wave with frequency of 60Hz was applied. The frequency cutoff was from 1Hz to 30kHz.

Description of concrete specimen:

Type of cement: ASTM type I

Type of fine aggregate: Missouri river sand

Type of coarse aggregate: Well-graded gravel with maximum size of 20mm and minimum size of 1.25mm

w/c: 0.38

Density: 2480 kg/m3

Room temperature: 20 ˚C

Table 1 Mixture design of self-consolidating concrete

Cement	Fly ash	Water	Fine aggregate	Coarse aggregate	HRWRA	VMA
14.57%	7.29%	8.30%	34.86%	34.86%	0.089%	0.03%

Procedures of concrete mix:

1. Evenly divide water into two buckets, one of them mix with HRWRA.
2. Mix the entire fine aggregate and coarse aggregate.
3. Add a bucket of water which is without HRWRA.
4. Add all the cement and fly ash.
5. Add the other bucket of water at a slow rate. Mix for 3 minutes.
6. Stop mixing for 2 minutes.
7. Add VMA and keep mixing for 6 minutes or until the concrete shows good viscosity and flowability.
8. Fill the cardboard container with SCC with volume around 5 dm^2. Make sure the surface of concrete is flat; otherwise, it may affect the transition of shear wave.

Test result and comparison

Raw data of BE test is Excel format, it needs to be converted to Text (Tab delimited) format when processing data with Mathcad program. The first arrival time could be read from Mathcad output graph. (Figure 18)

Fig. 18 Received signal at 17 hours curing

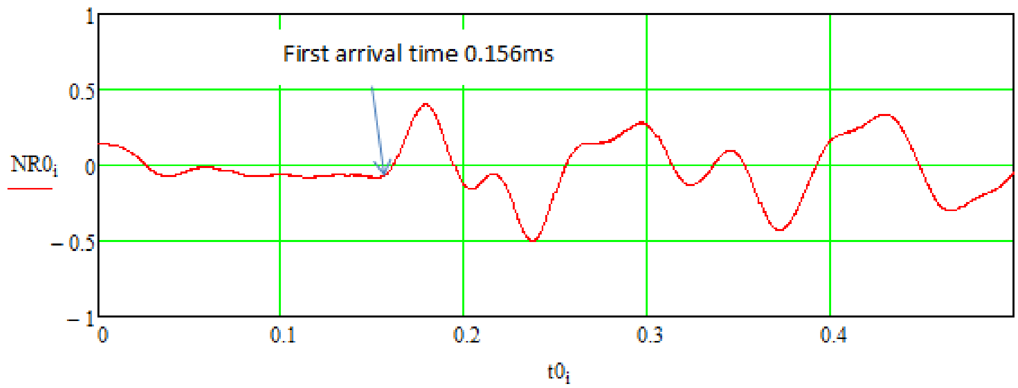


Fig. 19 Vs evolution over time of a fresh concrete

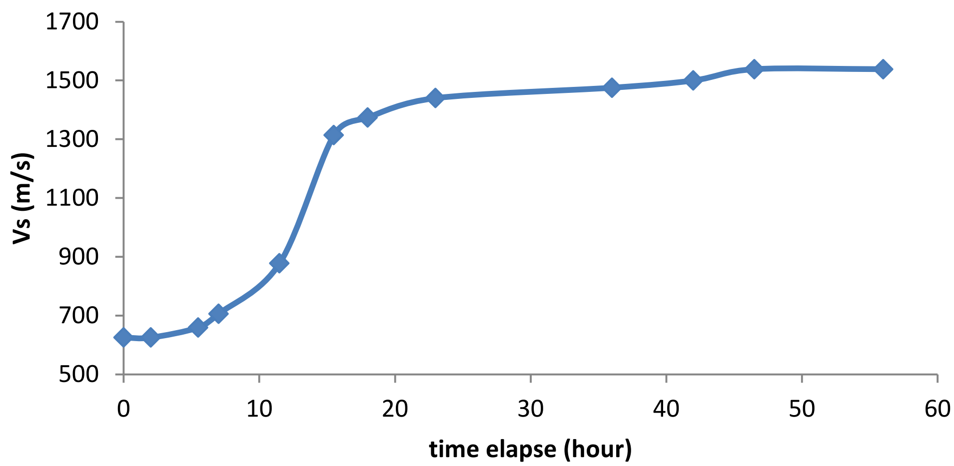


Fig. 20 G_{max} evolution over time of a fresh concrete

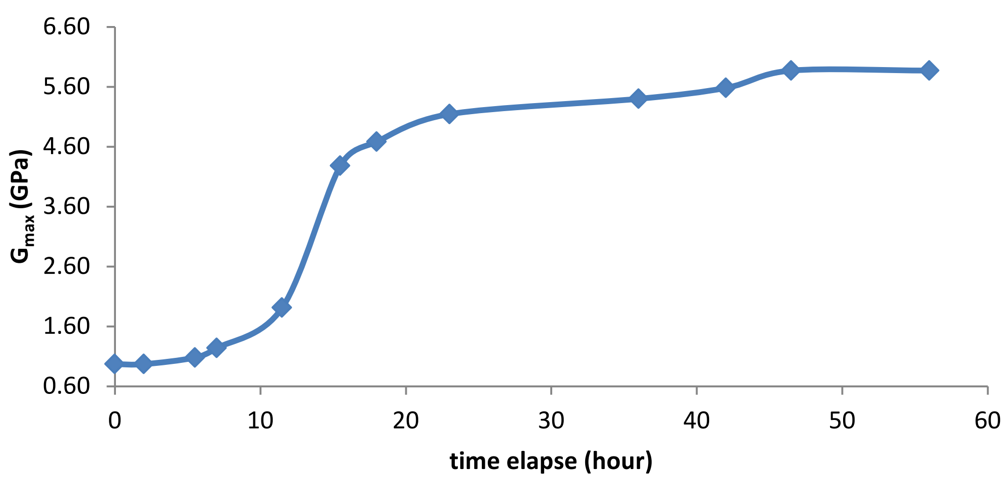
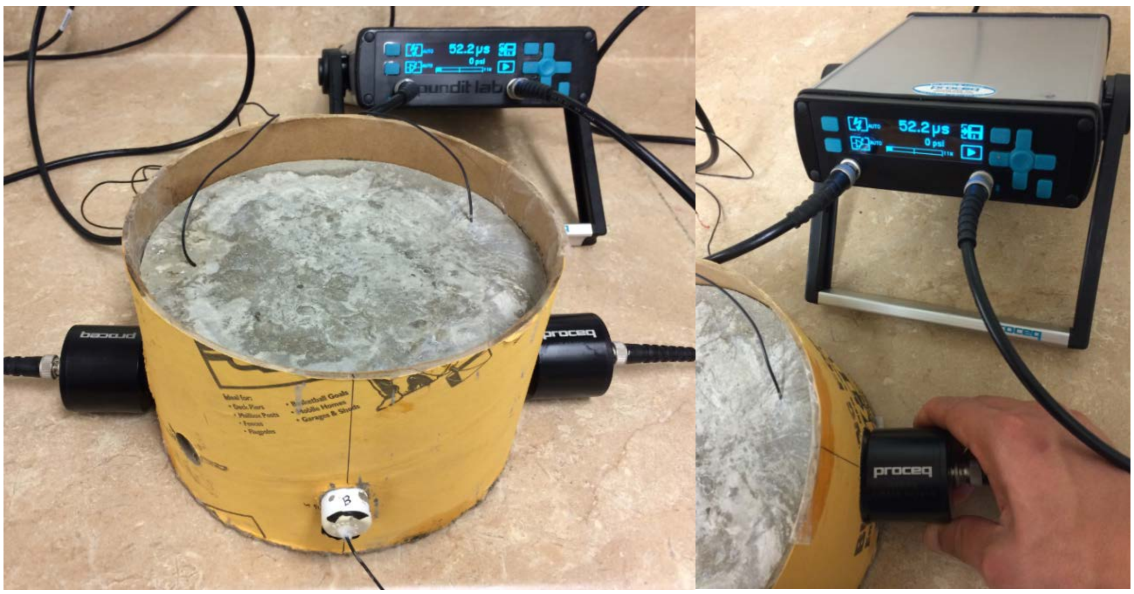


Table 2 Test parameters

Frequency cutoff	Excited signals	Travel distance	Concrete head	Mass	Volume	Specific gravity
1Hz – 30kHz	8 Volts 60Hz	180mm	55mm	7800g	3142cm^3	2.48g/cm^3

Fig. 21 Ultrasonic pulse velocity test



Test result shows the shear wave velocity increased dramatically along with time elapse. At the time of 56 hours, V_s was detected as high as 1538 m/s (Figure 19). It needs 52us to transmit the ultrasonic pulse wave through SCC specimen with diameter of 200mm, which indicates the pulse wave velocity V_p of 3846m/s. However, V_p was a little larger in vertical measurement (4167m/s) than horizontal measurement. Maximum shear modulus G_{max} developed from 0.97GPa to 5.87GPa in 48 hours after placing concrete. (Figure 20) The measured V_s result in this study is lower than the typical values of those reported in the literature (Table 3). This is primarily due to the short travel distance of 180mm. Poisson's ratio, bulk modulus (K) and Young's modulus (E) can be calculated by Equations 2-4.

$$G = \rho V_s^{\,2} \tag{1}$$

$$v = \frac{1-2(\frac{V_s}{V_p})^2}{2-2(\frac{V_s}{V_p})^2} \tag{2}$$

$$E = 2\rho {V_s}^2(1+v) \tag{3}$$

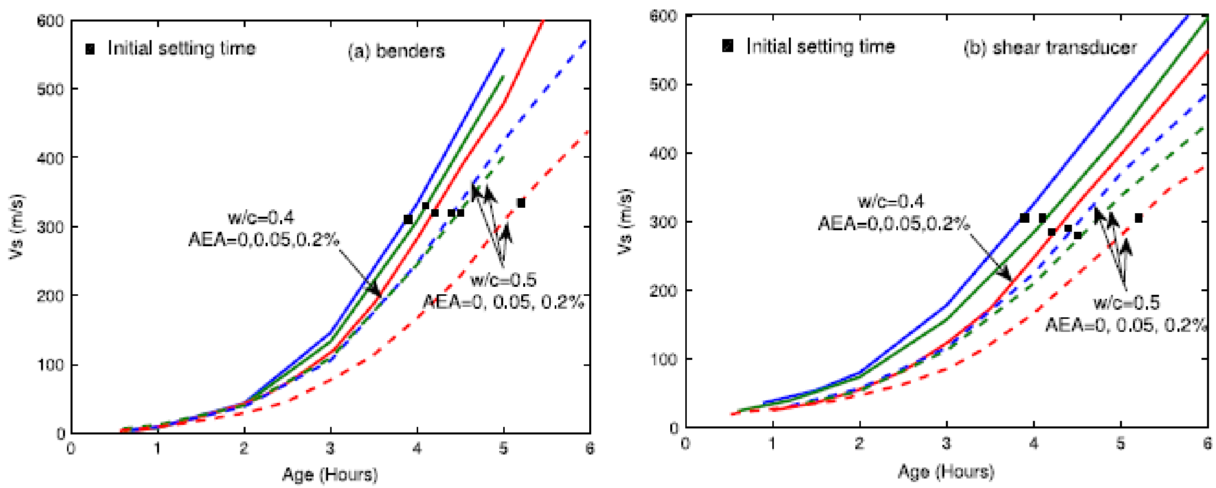
$$\mathrm{K} = \rho \mathrm{V_p^2} - \frac{4}{3}\mathrm{G} \tag{4}$$

Table 3 Comparison of test results [3-8]

		V_s (m/s)	V_p (m/s)	v	E (GPa)	ρ ($kg/m3$)	w/c
This study	at 48th hour	1538	3846	0.4	16.4	2480	0.38
Recep (2009)	at 28 days	2417±104	4181±38	0.24	28.4	2190	0.45
Malhotra and Carino (2004)	hardened concrete	60%V_p	~4000	-	-	-	
Zhu et al. (2011)		600 (cement paste at 6 hours)	4010 (hardened concrete)	-	-	-	0.4
Finno and Chao (2005)	hardened concrete	2200-2800 (assumed)	-	0.14-0.28	-	~2350	-
An et al. (2009)	Different curing age	450-2700	-	-	-	-	0.38

J. Zhu et al. (2011) performed a comparison test of concrete using bender elements and ultrasonic transducers. Ordinary Type I/II Portland cement was used in all tests. Six cement paste mixtures were prepared according to the proportions. 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). 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.

Fig. 22 Shear wave velocities and setting times for all cement pastes measured by (a) bender elements and (b) shear wave transducers [3]



The test result shows the shear wave velocity measured at the initial setting time in fresh cement pastes is around 320±10 m/s. 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. [3]

Recep (2009) pointed out there are mainly three types of arrangement of transducers. (Figure 23) It is clear that the best arrangement is the direct transmission type since the maximum energy of the pulse is transmitted and received with this arrangement. The indirect or surface transmission type is the least satisfactory method because the amplitude of the received signal may only be about 3% or less than that received by the direct transmission method. Figure 24 is his test result on hardened concrete lab-deck. It indicates the S-Wave velocity of 2285m/s and P-Wave velocity of 4122m/s by the using of Hilbert Transformation.

Fig. 23 Transmission type [4]

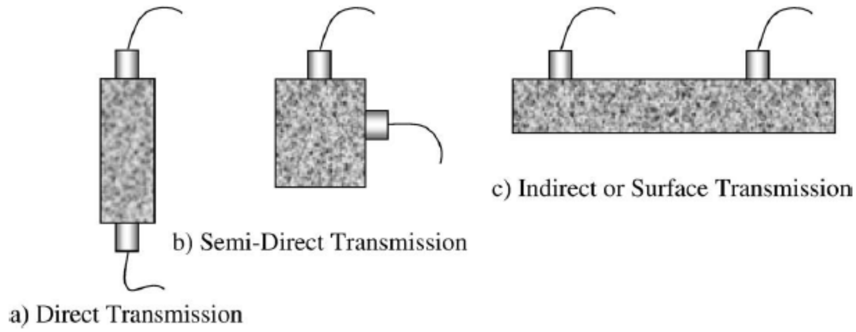
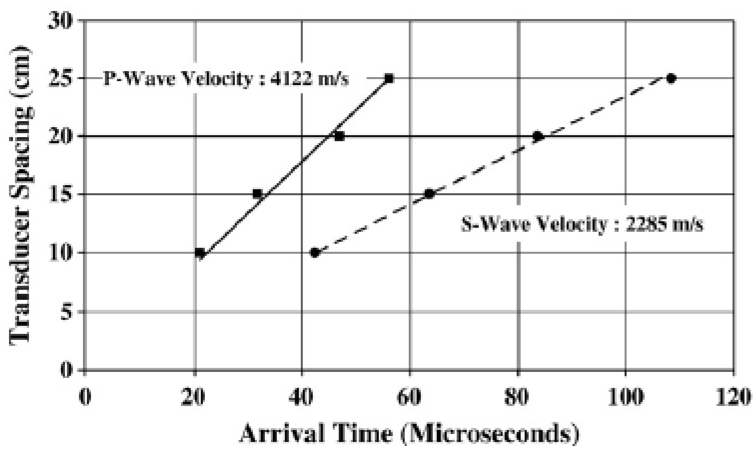


Fig. 24 P- and S-wave velocity measured via Hilbert Transformation [4]



An et al. (2009) used shear wave velocity to estimate the compressive strength of concrete. The compressive strength of concrete was estimated according to various curing ages as well. In the results, shear wave velocity was very closely related to the compressive strength. The results further showed that the estimation of compressive strength of concrete using shear wave velocity is very effective and reliable. [7] Specimens were made in the field and tested to measure elastic wave and compressive strength according to various curing ages. The J.J Pickel Research Campus in the U.S. and the Seoul Beltway in Korea were chosen for field tests by the American Center for Transportation Research (CTR). (Table 4)

Table 4 Mix design [7]

Field	Flexural strength	Max Agg.	Slump	Air Void	Water	Cement	W/C	S/a	Sand	Aggregate		AE
	kg/㎠	m/m	cm	%	kg/m3	Kg	%	%	kg/m3	32mm	19mm	kg
CTR	45	32	7.6	4.9	79	278	28.2	45	898	1098		0.742*
Seoul Beltway 1st	45	32	2.5	5.5	127	334	38	41	762	678	452	1.002
Seoul Beltway 2nd	45	32	2.5	5.5	127	334	38	41	762	678	452	1.002

* High efficiency AE water-reducer was used.

Fig. 25 Correlation between shear wave and compressive strength based on curing age [7]

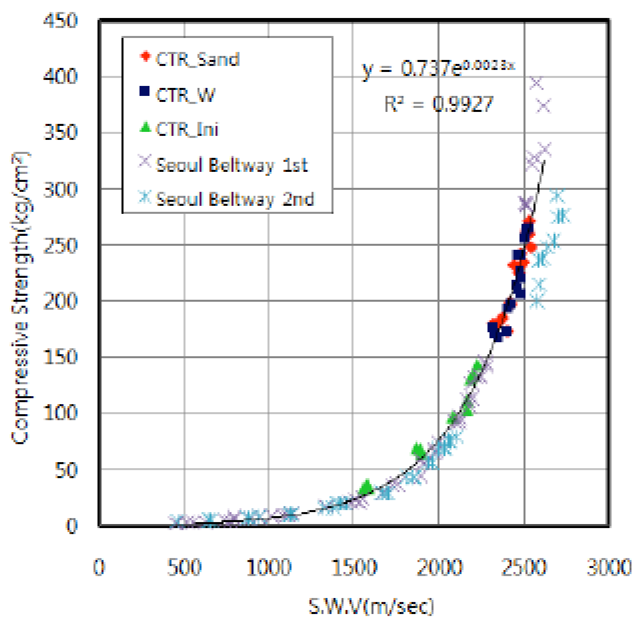


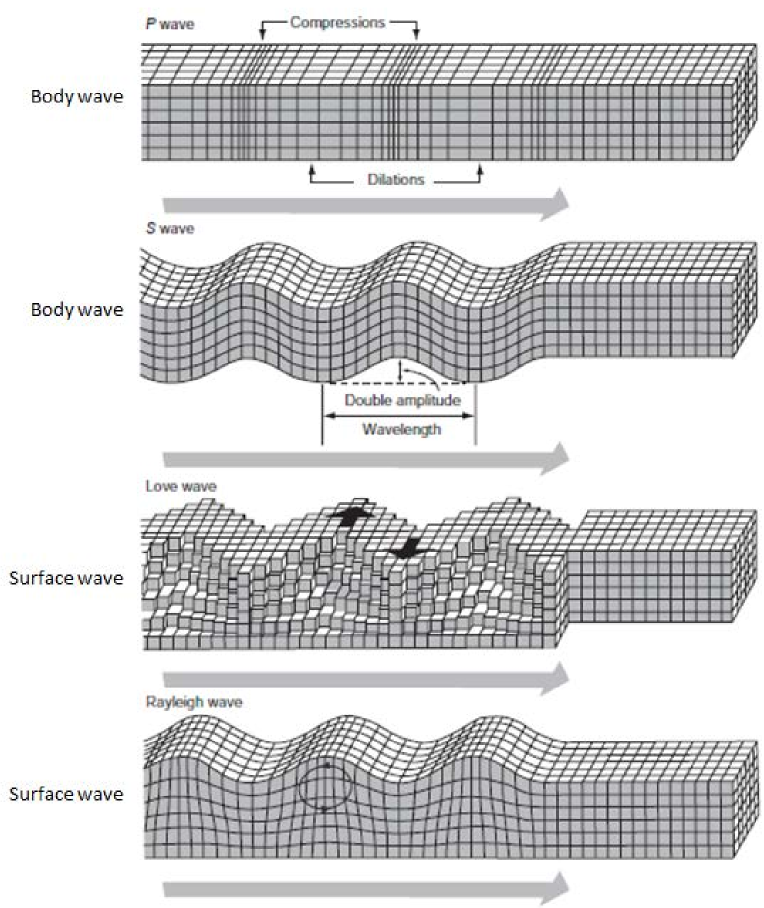
Figure 25 shows the correlation between shear wave and compressive strength was very high and it was given by an exponential function. Compressive strength appeared to be the same when the concrete maturity was similar, even if the curing conditions are different. Under similar mixture conditions but different environmental conditions, compressive strength appeared to be different. However, the correlation between the elastic wave and compressive strength was similar. If the compressive strength in the same curing age was high, the elastic wave velocity appeared to be high, and vice versa.

Due to the characteristics of compressive strength, early age concrete strength hardly had deviations. However, as concrete aged, the deviation became higher. Therefore, the estimation of compressive strength using shear wave would be more accurate in the early curing ages. [7]

P-wave and S-wave

When elastic wave signals propagate through a medium and meet an interface boundary, a part of them are refracted or reflected. The basic principle of measurement using an elastic wave is to receive these signals and analyze them to investigate a structure. Using nondestructive testing of concrete pavement to evaluate its engineering characteristics is based on this theory of elastic wave propagation. Elastic waves are categorized into body waves and surface waves. Body waves are further subdivided into a P-Wave (Primary Wave, Compression Wave) and an S-wave (Secondary Wave). Surface waves are subdivided into a Love wave and a Rayleigh wave [7]. (Figure 26)

Fig. 26 Body wave and surface wave [9]



Biot (1808) performed the first experiment to determine the velocity of the longitudinal wave in a solid. He used ingenuous and inexpensive test equipment: a 1000-m iron water pipeline in Paris. Biot rang a bell in one extremity of the pipe and a collaborator measured the time difference between the wave arrival in the pipe and in the air. Because the length of the pipe and the velocity of sound in air were known, it was possible to make a fair estimate of the sound velocity in the metal pipe. Geophysicists were among the pioneers in the experimental study of wave propagation, particularly in regards to measuring waves generated during earthquakes. In an earthquake, longitudinal waves travel faster than the transverse waves, therefore, a seismograph registers the longitudinal waves first. For this reason, longitudinal waves are also called primary or P waves and the transverse waves are called secondary or S waves. [9]

The determination of elastic modulus of concrete could be based on measuring the primary wave and secondary wave velocities.

$$V_s = \sqrt{\frac{G}{\rho}} \tag{5}$$

$$V_p = \sqrt{\frac{E(1-v)}{\rho(1-2v)(1+v)}} \tag{6}$$

$$V_s = \sqrt{\frac{E}{2\rho(1+v)}} \tag{7}$$

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-v)}{1-2v}} \tag{8}$$

where ρ = density of the material

v = Poisson’s ratio

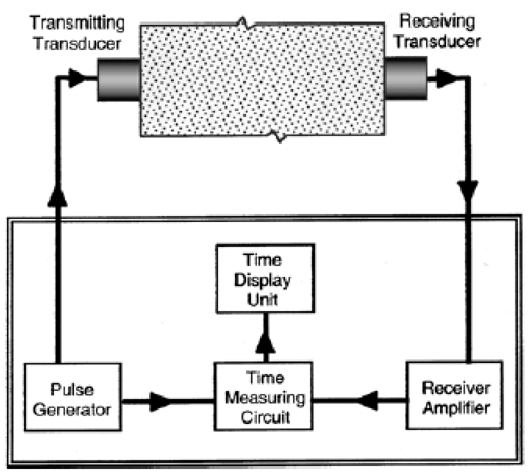
E, K and G =Young’s, bulk and shear moduli, respectively

V_p and V_s = primary and secondary wave velocities, respectively

If assumed Poisson's ratio of concrete is 0.2, the velocity ratio of primary wave and shear wave is 1.63.

The ultrasonic pulse velocity (UPV) method consists of measuring the travel time of a pulse of longitudinal ultrasonic waves passing through the concrete. Longitudinal waves with frequencies in the range of 20 to 150 kHz are normally used. The travel times between the initial onset and reception of the pulse are measured electronically. The path length between transducers divided by the time of travel gives the average velocity of wave propagation. [9]

Fig. 27 Schematic of pulse velocity apparatus [10]



It has been decades to apply the UPV technique to nondestructive evaluation of concrete quality. The pulse velocity is independent of the dimensions of the test object provided reflected waves from boundaries do not complicate the determination of the arrival time of the directly transmitted pulse. The least dimension of the test object must exceed the wavelength of the ultrasonic vibrations. The wavelength of the vibrations equals the pulse velocity divided by the frequency of vibrations. For example, for a frequency of 54kHz and a pulse velocity of 3500 m/s, the wavelength is 3500/54000=0.065m. Signals come from the pulse generator and go through the sample by a pair of transducer; time measuring circuit determine the travel time [10]. (Figure 27)

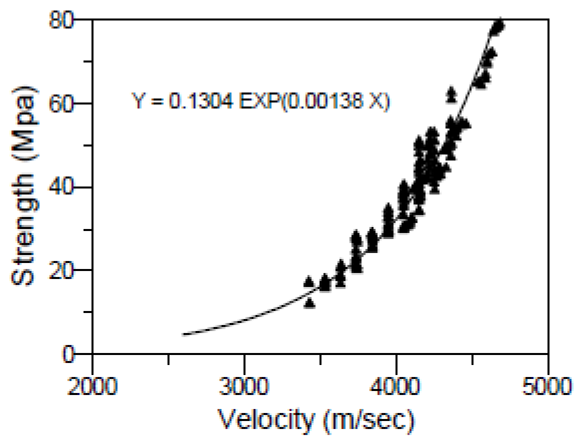
Lin et al. (2011) revealed the relationship between UPV and strength as Figure 28. In that study, two plate-like specimens were made of self-consolidating concrete and cured in different ways. Primary wave velocity increased along with the increase of strength and following the equation:

$$Y = 0.1304\, e^{0.00138x} \tag{8}$$

where x = ultrasonic pulse velocity in m/second

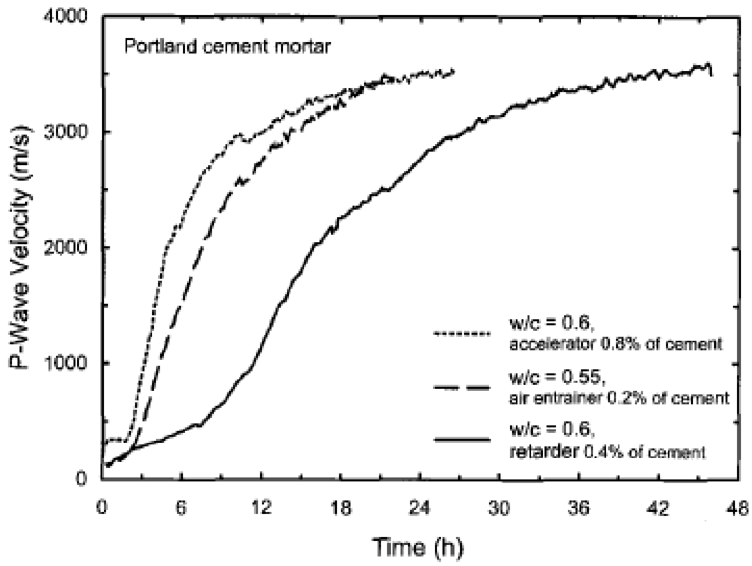
y = strength in Mpa

Fig. 28 Compressive strength versus ultrasonic pulse velocity [11]



Voigt et al. (2005) found that when penetration resistance increase, P-wave velocity has already reached values much larger than those during the initial stage, which indicates during the phase, the P-wave velocity is affected by the formation of hydration products, such as ettringite. Figure 29 indicates the evolution of primary wave velocity. [12]

Fig. 29 V_p evolution over time of mortars [12]



The five compared standards, American (ASTM), British (BS), German (DIN), Russian (GOST) and Slovak (STN) standards, on measuring P-wave velocity show none of the standards rate these applications according to their reliability. Actually, the optimal way is for checking the uniformity of concrete and for monitoring changes in a concrete with time. There is ±20% error on strength estimation; the other applications (defect detection, crack depth measurement, etc.) are even less reliable. [13]

Conclusion

In this study bender elements test was performed to measure shear wave velocity in fresh self-consolidating concrete. The fabrication of bender elements for concrete-testing purpose has been detailed described. Bender elements could be used as both source and receiver, and ultrasonic pulse wave velocity was measured at the end of the test. Experimental result indicates that shear wave velocity was around 1538m/s at the 48th hours after placing concrete, and it increased dramatically between the 6th to 16th hours. Young's modulus, bulk modulus, shear modulus and Poisson's ratio of concrete have been obtained by the measurement of V_s and V_p.

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