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Engineering properties of lightweight aggregate concrete assessed by stress wave propagation methods

Ta-Peng Chang *, Huang-Chin Lin, Wen-Tse Chang, Ju-Fang Hsiao

Department of Construction Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan, ROC

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Abstract

This study investigates the variation of engineering properties and wave velocities of two kinds of lightweight aggregate concretes by non-destructive stress wave propagating testing methods. Both cylindrical specimens and plate specimens at ages of 7, 14, 28 and 56 days were studied. Experimental results show that, at ages from 7 to 56 days, the average strengths and moduli of elasticity of concrete cylinders increase by 25–37%, while the average ultrasonic pulse velocities increase only by 5–7%. The dynamic moduli of elasticity of concrete cylinders are higher than the static moduli of elasticity by about 41% in average, and both have a very close correlation with their corresponding ultrasonic pulse velocities. P-wave velocities across the section of concrete plates from the top to the bottom faces vary about 14–15% by linear extrapolation. Except for the concrete plate at age of 7 days, P-wave velocities measured at the top face of concrete plate by one-sided velocity method are smaller than those by impact-echo method by 2–5%.

Keywords: Stress wave; Impact-echo method; Non-destructive testing; Lightweight aggregate; One-sided wave velocity

1. Introduction

When the surface of a semi-infinite solid is suddenly subjected to a transient stress pulse, the stress pulse propagates through the solid as stress waves. There are three major modes of stress wave propagation: the longitudinal stress wave (also called the L-wave or the P-wave) and the shear stress wave (also called the S-wave) that travel into the solid, and the surface wave (also called the Rayleigh wave or R-wave) that travels along the surface of the solid. The propagating velocities of these three stress waves are functions of the physical and mechanical properties of solid. Among various available non-destructive testing methods, the stress wave propagation method is the one that uses the measurement of these three wave velocities of solid for the evaluation of its properties.

Although the stress wave propagating velocity of a homogeneous solid can be closely related to its inherent engineering properties, special attention ought to be considered in advance to properly quantify the dynamic parameters of heterogeneous concrete [1–4]. Quite a few number of small internal discontinuities usually exist in concrete, e.g., the interfaces between the aggregates and cement paste, micro-cracks and air voids in the matrix, that typically have dimensions of a few centimeters or less and will interact with the stress waves. The interaction between the stress wave and these micro-discontinuities in concrete will occur where the depth or/and dimension of the discontinuity is larger than the wavelength. For example, a P-wave velocity of 3500 m/s typically for lightweight concrete will have a wavelength of 50 mm or longer with a propagating frequency of 70 kHz or less. When such P-wave propagates through solid concrete, it does not interact with these inhomogeneities in concrete with dimension less than 50 mm, thus the concrete can be reasonably regarded as if it were a homogeneous material [4].

Depending on various characteristics, commonly used stress-wave methods for concrete structures may include the resonance frequency method, ultrasonic pulse-velocity

* Corresponding author. Fax: +8862 2737 6606.
E-mail address: tpchang@mail.ntust.edu.tw (T.-P. Chang).

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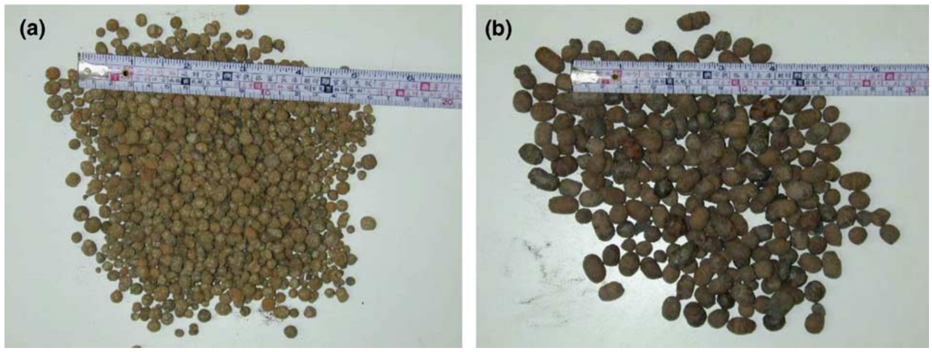

Fig. 1. Two types of sintered lightweight aggregates used in the study: (a) Type I sintered lightweight aggregate ($\gamma_{OD} = 0.625$, $D_{max} = 9.5$ mm), (b) Type II sintered lightweight aggregate ($\gamma_{OD} = 0.751$, $D_{max} = 12.7$ mm).

method (ultrasonic through transmission method), ultrasonic pulse-echo method, impact-echo method and spectral analysis of surface waves method (SASW), etc. [1–4]. These methods have been frequently applied to the investigation of the dynamic moduli, strengths, thickness and integrity, such as the surface opening cracks, interior flaws, delamination, voids, of concrete structures [1–4]. Basically, two different types of wave velocity measurements of concrete member can be characterized by these above-mentioned stress-wave methods. One is the through-thickness stress wave velocity that needs to access either both sides of the member such as the ultrasonic pulse velocity method, or just one side of the member such as the impact-echo method for measuring the thickness of plate. The other is the one-sided stress wave velocity that only applies to one face of the member such as the SASW method and the impact-echo method for measuring the P-wave velocity. A brief description of the basic principle to measure the wave velocity in concrete plate by these three methods will be briefly provided in Section 2.

On the other hand, uniform density is usually difficult to obtain in lightweight concrete member through its depth. Because of the porosity and buoyancy, the lightweight aggregates in freshly mixed concrete tend to migrate to the concrete surface resulting in a different kind of segregation from that in the normal weight concrete [5]. As a result, a latent layered hydrated concrete with dissimilar material properties characterized by containing more lightweight aggregates at the top than at the bottom of concrete members is always formed. Chi et al. reported that the property and the amount of lightweight aggregate in concrete are the significant factors affecting the compressive strength and elastic modulus of lightweight concrete [6]. The inherent layer feature of lightweight concrete also affects values of its wave velocity measurement by non-destructive testing methods using stress wave, and, as a result, the estimation of its elastic moduli and strength will be altered accordingly. In principle, the strategy to reduce the tendency of segregation of fresh concrete is to increase the yield stress, viscosity and density of the cement paste matrix [7]. One of the commonly used approaches is adding the mineral admixtures like silica fume, fly ash, blast-furnace slag, etc. to the fresh concrete during the mixing stage [7–10]. However, even such preventive maneuver has been taken in advance during the concrete mixing, the extent of segregation issue of lightweight concrete to a certain degree is still commonly encountered. Using non-destructive and partially destructive testing techniques, Bungey and Madandoust indicated that the strengths of lightweight concrete beams varied across the depth with a reasonably uniform distribution from the lower strength at the top to the higher strength at the bottom of member due to differences in compaction, curing and aggregate type [11]. Khayat et al. used the electrical conductivity to assess the segregation and homogeneity of mortar mixture with satisfactory results [12]. Nevertheless, little information is available on the quantitative assessment of the through-depth non-uniformity of lightweight concrete members using stress-wave techniques. Studies on this subject are limited in the technical literatures. To investigate the variation of engineering properties across the thickness of concrete member, two kinds of sintered lightweight coarse aggregates, as shown in Fig. 1(a) and (b), were used in this study to case $\varnothing 100 \times 200$ mm cylindrical specimen and $600 \times 600 \times 200$ mm plate specimen as shown in Fig. 2(a). Three kinds of P-wave velocities, V_{US}, V_{IE} and V_{OS}, measured by ultrasonic pulse velocity method, impact-echo method and one-sided wave velocity method as shown in Fig. 2(b)–(d), respectively, were used. This study provides detailed experimental results on the variation of material properties and wave velocities resulting from these effects.

2. Principles of measuring stress wave velocities

2.1. Ultrasonic pulse velocity method

In this method, as described in ASTM C597-02 [13], an ultrasonic pulse is created by a pulse generator and transmitted to the surface of concrete plate through the transmitter receiver. The time taken by the generated pulse to travel through the concrete, t, is accurately measured by the receiver transducer attached on other side of the concrete plate. A set-up of this test is schematically shown in Fig. 2(b). As both the transmitting and receiving transducers have a short cylindrical configuration of 50 mm in diameter and 42 mm long for most commercial testing units [14], the flat surfaces of both transducers must be in full contact with the rough concrete surface to avoid the air pocket between two surfaces that may introduce an error in the measured transit time of the pulse. A proper thin couplant like petroleum jelly is always required to place on the interfaces to assure a good contact. For the concrete with very rough surface, a means of obtaining a smooth surface, like by grounding or by coating a thin layer of adhesive plaster, may have to be done before performing the test. The longitudinal stress pulse transmitted to the concrete induces many reflections from the free surfaces and various aggregate-mortar boundaries in concrete, such that the waveform received by the receiving transducer consists of both the P-wave and S-wave. However, the first arrival wavefront comes from the fastest P-wave.

The measurement of the first arrival of the fastest ultrasonic P-waves is very important in determining the pulse velocity. The accuracy of first time of wave arrival depends on the transmitting frequency of transducer, the dispersive effect of wave propagation, the noise level of electrical signals from the ultrasonic receiver and the slope of ultrasonic signal emerging from the noise. Sharp first wave arrivals are obtained when higher ultrasonic frequencies are used. However, higher frequency waves also limit the depth of penetration to a smaller value. An optimal transmitting frequency is always a compromising value between these two boundaries. In a dispersive material, waves of different frequencies travel at different speeds such that the first arrival of ultrasonic pulse will have the lowest frequency and the smallest emerging slope resulting in a most inaccurate determination of arrival time. The improvement of signal-to-noise ratio can be achieved by physical devices during the stage of data acquisition or/and by the mathematical methods of signal filtering and signal averaging during the data processing to alleviate the electrical interference and background noise, and to increase the sharpness of emerging slope of arrival signal. These issues need to be properly deal with when the measuring system of pulse velocity uses an oscilloscopic display that captures and stores the ultrasonic curves for further processing to measure the first arrival of wave signal. Some other kinds of commonly used ultrasonic testers, on the contrary, simply use a digital readout on the device to show directly the arrival time of transmitting wave, handling internally the signal processing for the users. For this case, the determination of travel time is simplified by the use of a digital readout.

Thus, knowing the travel time, t and the distance of travel path, W, the P-wave velocity of the test concrete plate or cylinder by the ultrasonic pulse velocity method, V_{US}, can be calculated as

$$V_{\mathrm{US}} = \frac{W}{t}. \tag{1}$$

It is noted that various conditions of concrete specimen can influence the measured ultrasonic pulse wave velocity, for example, the wave velocity for a wet specimen may be higher up to 5% than that of a dried specimen [15].

2.2. Impact-echo method

In this method, as described in ASTM C1383-04 [16], the transient stress impulse is introduced into the concrete specimen by a mechanical impact at a point on the surface using small spheres of hardened steel attached on spring steel rods. A receiving transducer is placed close to the impact point apart with a distance of a_1 to record the displacements generated by the arrival of these reflected waves, as schematically illustrated in Fig. 2(c). The resulting spherical wavefronts of P-wave and S-wave propagate into the concrete and are reflected by the free surfaces of concrete on other sides or by the internal interfaces in concrete like cracks or voids. These reflected waves are then bouncing back and forth between the free surfaces of concrete to form a periodic waveform. For a plate-like structure, the surface displacements caused by P-wave arrivals are much larger than those caused by S-wave arrivals at points close to the impact point [2–4]. Thus the recorded waveform is primarily dominated by the displacements caused by the P-wave. A frequency analysis using the fast Fourier transform (FFT) is then performed to convert the recorded periodic displacement waveform signal in time-domain into frequency-domain to create an amplitude spectrum [17]. From the resulting amplitude spectrum, the dominant frequencies in the recorded waveform can be obtained as the frequencies associated with the large-amplitude peaks. Among these dominant frequencies, the frequency with a single large-amplitude peak is the so-called thickness frequency that corresponds to multiple reflections of P-wave between the top and bottom free surfaces of concrete plate. Suppose that the concrete plate has a thickness of T as shown in Fig. 2(a), and the bottom surface of concrete plate is adjacent to an interface having a lower acoustic impedance than the concrete, then, the period of thickness frequency in the recorded waveform is equal to the travel path, $2T$, divided by the P-wave velocity of plate, V_{IE}. Thus the P-wave velocity in the concrete plate can be calculated as [16]

$$V_{\mathrm{IE}} = \frac{2fT}{0.96} = 2.083fT, \tag{2}$$

where f is the thickness frequency of P-wave reflections and is the reverse of the period. The factor of 0.96 included in Eq. (2) is due to the consideration of inherent inertia effect of receiving transducer caused by the displacement of back-and-forth reflections of P-wave at the concrete surface [4,18]. Although, in practice, this empirical fixed correction shape factor of 0.96 is adequate to obtain the correct thickness frequency of plate structures, exact theoretical values of this shape factor have been found to be in the range from 0.945 to 0.957 for platelike concrete structures with values of Poisson's ratios varying from 0.16 to 0.25 [19].

The contact time t_c of the elastic impact of steel ball with the concrete surface affects the validity of wave velocity measurement by the impact-echo method. A shorter contact time generates a stress pulse with a broader range of frequencies. The transient stress pulse must contain a range of frequencies that covers the frequency corresponding to the flaw depth or the thickness of concrete plate under consideration. It has been shown that the relationship of contact time, t_c, and the diameter of small steel sphere, D, can be approximately expressed by the following linear equation [4]:

$$t_c = 0.0043D, \tag{3}$$

where t_c and D are in seconds and meters, respectively. In addition, considering a stress wave induced by an impact force in terms of a half-sine function on a solid, it has been also shown that the resulting amplitudes being sufficient for the impact-echo testing are roughly located below a maximum frequency of $1.25/t_c, f_{max}$, in the amplitude–frequency spectrum [4]. Combining this with Eq. (3) results in $f_{max} = 290.7/D$, where f_{max} is in Hz. Thus, as mentioned in the previous section, for a wave velocity of 3500 m/s of concrete requiring a minimum wavelength of 50 mm, the value of f_{max} is 70 kHz. A value of 4.2 mm for D can be calculated accordingly. On the other hand, the wavelength of stress wave is also needed to be less than twice the thickness of the concrete plate that is equal to 200 mm used in this study. Following similar calculation procedure, the value of D can be found as 33.3 mm. Therefore, diameters of steel ball ranging from 4.2 to 33.3 mm can be used theoretically. In this study, an impactor with a small steel ball of either 5- or 7-mm in diameter welded to a spring steel rod was used. The sampling rate used to record waveforms in the wave speed measurement was 0.5 MHz (2 μs sampling interval). The total number of samples was 2048, resulting in a resolution of 0.244 kHz in the spectrum. Other procedures basically following those provided in Procedure B—Impact-Echo Test in ASTM C 1383 [16].

2.3. One-sided wave velocity method (Fig. 2(c)) [20]

As described in ASTM C1383-04 [16] and schematically illustrated in Fig. 2(d), this method uses two receiving transducers separated with known distances apart and aligned in a straight line with the impact point. They were mounted on the same concrete surface to receive the waveform of the displacements generated by the arrival of waves. Unlike the impact-echo method, the main purpose of these two transducers is to receive the time history of displacement caused by the arrival of stress waves along the concrete surface rather than that reflecting from the free surfaces of concrete [4,20]. From the recorded displacement signals in time domain, the times of first arrival of P-wave to these two receivers can be identified as the one with a rise in displacement signal. Therefore, the one-sided P-wave velocity of the test concrete plate, V_{OS}, as shown in Fig. 2(d) can be calculated as

$$V_{OS} = \frac{c_2}{t_2 - t_1}, \tag{4}$$

where c_2 is the distance between two receivers; t_1 and t_2 are the first arrival times of P-waves received by the first and second receivers, respectively.

A steel ball of either 5-mm or 7-mm diameter mounted on a spring rod was used as the impact source in this study. For the one-sided P-wave speed measurement, the distance between the impact source and the first receiver in Fig. 2(d) was set to be the value of $c_1 = 150$ mm in order to separate the arrival signals of P-wave, S-wave and R-wave and the optimal distance between two transducers was kept at the value of $c_2 = 300$ mm [4,16]. In this study, the sampling interval of 1 μs (sampling rate of 1 MHz) and 2048 sample points were recorded for this measurement method.

3. Experimental program

3.1. Materials, specimens and experimental methods

Two kinds of lightweight coarse aggregates denoted by Types 1 and 2 with different sizes and densities as shown in Fig. 1 were used in the concrete mixture. Type 1 lightweight coarse aggregate is smaller, lighter and more porous than Type 2. These lightweight aggregates were made of expansive shale/clay by the sintering process. The engineering properties of fine aggregate and lightweight coarse aggregate are given in Table 1, in which the specific gravity and the water absorption of lightweight coarse aggregate were tested according to ASTM C127. Due to the high absorption rate for these lightweight coarse aggregate, they had been submerged in the water bath for 24 h before used in concrete mixture. The cement is the normal Type I Portland cement conforming to the ASTM C150 Standard. The fine aggregate is the locally available river sand. Two kinds of concrete mixture designated by LC1 using type 1 lightweight aggregate and LC2 using type 2 lightweight aggregate were prepared with same cement/binder (W/B) ratio of 0.31. Table 2 shows the mixing proportions for two lightweight concretes.

Cylindrical concrete specimens of ∅100 × 200 mm were cast in steel molds following ASTM C192. Two plate concrete specimens of 600 × 600 × 200 mm, respectively, as shown in Fig. 2(a), were also cast in two separate wood molds with a horizontal bottom wood board surrounding by four pieces of vertical side wood plates. No further mechanical compaction by the standard vibrating table was exerted. Both the cylindrical and plate concrete specimens were made from the same batch. The top surfaces of both concrete cylinders and concrete plates were wrapped with polyethylene sheet right after the cast. After 24 h, the cylindrical concrete specimens were removed from the

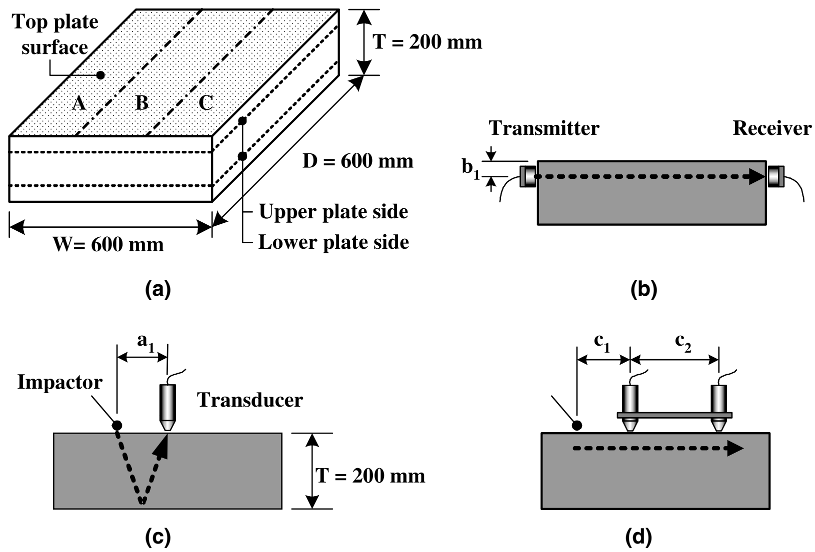

Fig. 2. Dimension and testing area of lightweight concrete plate, three kinds of stress wave velocity measurements and designations of wave velocities, V_{US}, V_{IE}, V_{OS}: (a) testing strips A–C, and locations on $600 \times 600 \times 200$ mm concrete plate, (b) ultrasonic pulse-velocity method (V_{US}), (c) impact-echo method (V_{IE}) and (d) one-sided wave velocity method (V_{OS}).

Table 1
Engineering properties of fine and coarse aggregates

Items	γ_{OD}	D_{max} (mm)	FM	Water absorption rate (%)		
Fine aggregate	2.59	–	3.00	3.40		
Type 1 lightweight coarse aggregate (LWA)	0.625	9.5	5.72	(60 min) 29.98	(24 h) 35.10	(14 days) 50.15
Type 2 lightweight coarse aggregate (LWA)	0.751	12.7	6.93	(60 min) 4.24	(24 h) 8.25	(14 days) 12.02

Notes: γ_{OD} is the specific gravity density on oven-dried condition, D_{max} is the maximum aggregate size and FM is the fineness modulus.

Table 2
Designation and constituents of concrete mixture proportions

Constituents	Mixture designation	
	LC1	LC2
W/C (water/cement)	0.456	0.456
W/B (water/(cement + slag + fly ash))	0.31	0.31
Cement (kg/m^3)	351	351
Type F fly ash (kg/m^3)	140	140
Slag powder (kg/m^3)	25	25
Normal weight coarse aggregate (kg/m^3)	–	–
Lightweight coarse aggregate (kg/m^3)	286	275
Fine aggregate (kg/m^3)	786	786
Water (kg/m^3)	160	160
Type G superplasticizer (liquid) (kg/m^3)	4.2	4.2
Total weight (kg/m^3)	1752.2	1741.2

molds and saturated by submersion in a water bath (25 ± 2 °C). On the other hand, the top surface of concrete plate was covered by the saturated burlap bag while four surrounding vertical side wood plates were still kept standing during the testing period in order to maintain a similar moisture content as close as possible to that in the cylindrical specimens. The cylindrical specimen was then removed from the water bath and allowed to dry naturally in laboratory air one day before the test.

Cylindrical concrete specimens were used for the uniaxial compressive test to obtain the compressive strengths, f_c, static moduli of elasticity, E_s, and static Poisson's ratios, ν_s, at ages of 7, 14, 28 and 56 days, respectively, according to ASTM C469. Before the destructive uniaxial compressive test, these cylindrical concrete specimens were also examined for the dynamic moduli of elasticity, E_d, and dynamic Poisson's ratios, ν_d, according to ASTM C215, and the ultrasonic pulse velocity according to ASTM C597. The concrete plate specimens were used for the one-sided wave velocity and impact-echo velocity measurements according to ASTM C1383.

3.2. Commercial experimental facilities of wave velocity measurement

1. Erudite Resonant Frequency Meter [21]:
   This complete test unit includes test bench, vibrator assembly with frequency range from 1 Hz to 100 kHz, torsional testing kit, LCD display, etc. It is used to measure the dynamic moduli of elasticity and dynamic Poisson's ratios of cylindrical concrete specimens.
2. Pundit Pulse Velocity Test System [14]:
   This complete test unit has two 54 kHz transducers, one calibration bar, two 3.6 m cables, a bottle of ultrasound

couplant, a 4-digit, 12 mm reflective LCD display to show the transit time with a resolution of 0.1 μs, etc. It is used to measure pulse velocities of cylindrical concrete specimens and plate specimens. This instrument does not have an oscilloscopic display to capture and store the ultrasonic curves for further processing. Rather, it simply uses a 4-digit LCD display to show a readout of arrival time during the test. As a result, before the transit time of the concrete specimens was measured, the test unit needs to be carefully calibrated to have a standard digital read-out of the time of 26 μs for the pulse to travel through a provided calibrating cylindrical metal rod. Then, the transmitting transducer is placed on one side of the concrete specimen to be measured and the other receiving transducer placed directly opposite on the other side. After the measuring switch is triggered, in a few seconds, a digital readout will be displayed in the LCD, which is measured travel time of pulse velocity used in this study.

3. LLC Impact-Echo Test System [22]:
   This whole testing unit is a complete system including all the necessary hardware components (A/D data acquisition system at sampling rate up to 1 megasample/s with 12-bit resolution, transducer units, spherical impactors, cables, etc.) and the Windows-based operating software called Imago. The software is used to capture the waveforms, make the FFT transformation and calculate the wave velocities. It is used to measure wave velocities of plate specimen by both the impact-echo method and one-sided velocity method.

4. Results and discussion

4.1. Densities, compressive strengths and elastic moduli of concrete cylinders

The mass densities of each type of hardened concrete specimens were determined by the average of values measured by five cylindrical concrete specimens, and found to be 1746.01 kg/m^3 ($s = 3.49$ kg/m^3) (LC1) and 1732.32 kg/m^3 ($s = 5.53$ kg/m^3) (LC2), respectively, where s is the sample standard deviation. Three concrete cylinders made of same batch at the same age were tested for the compressive strengths and moduli of elasticity at four ages and all the experimental results were recorded. One typical set of stress–strain curves under uniaxial compressive test at age of 28 days for two kinds of cylindrical concrete specimens is shown in Fig. 3. From this figure, the uniaxial compressive strengths, f_c', static moduli of elasticity, E_s, and static Poisson's ratios, ν_s, were obtained as 17.54 MPa, 12.84 GPa and 0.176 for LC1 concrete cylinder; and 23.11 MPa, 14.99 GPa and 0.181 for LC2 concrete cylinder, respectively. Before these cylindrical specimens were subjected to the uniaxial compressive test, their dynamic moduli of elasticity, E_d, also were measured by Erudite Resonant Frequency Meter, and P-wave velocities, V_{US}, by Pundit Pulse Velocity Test System. Average values of four measured material properties, f_c, E_s, E_d and V_{US} at four ages, together with the corresponding error bars, are shown in Fig. 4. Test data show that all the sample coefficients of variation are within 3.5% for both LC1 and LC1 cylinders except for the outlying value of 5.1% for compressive strength of LC2 cylinder at age of 56 days. Basically

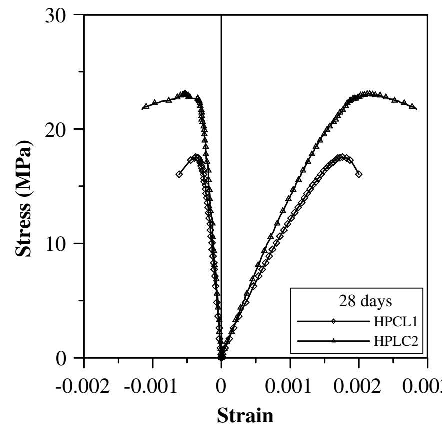

Fig. 3. Typical stress–strain curve for LC1 and LC2 concrete specimens at age of 28 days under uniaxial compressive test.

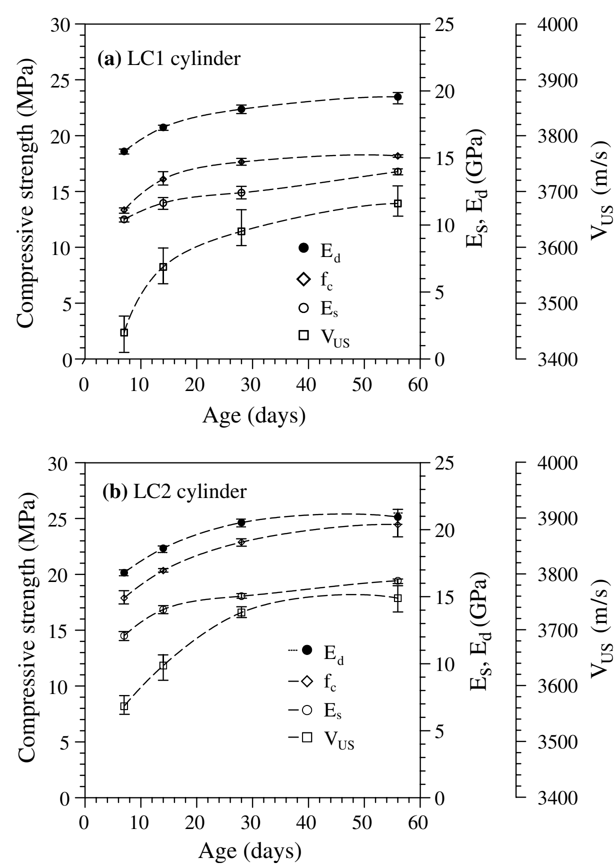

Fig. 4. Material properties of cylindrical specimens at various ages: (a) LC1 cylinder and (b) LC2 cylinder.

the within-test variations of test results for the concrete uniformity are acceptable.

The variation of test data between LC1 and LC2 concrete cylinders results from the difference in the porous structure and density of these two types of artificial lightweight aggregates. From Table 1, as an example, the water absorption rate of 35.1% at 24 h for Type 1 lightweight aggregate is much higher than that of 8.25% for Type 2 lightweight aggregate. Thus, due to a relatively loose and highly porous interior structure in Type 1 aggregate, all the engineering properties of LC1 concrete cylindrical specimens are lower than those of LC2 concrete specimens.

Fig. 4 also shows that, after the age of 28 days, the gains of engineering properties of concrete become relatively insignificant as compared to those in the earlier ages, specifically, the compressive strengths. As a result of the lower crushing strength for these two kinds of lightweight coarse aggregates, the compressive strengths seem to reach a low ceiling value of about 18 MPa for LC1 cylinders and about 25 MPa for LC2 cylinders, respectively. Similar results have been found for other types of lightweight concrete [6,23]. It is noted that the average difference between the static modulus of elasticity, E_s, and the dynamic modulus of elasticity, E_d, is about 47% for LC1 specimen and 34% for LC2 specimen, respectively. These two values are higher than those of about 23–32% for the concrete made of normal coarse aggregate [5]. The gap of difference between two elastic moduli is larger for the low-strength concrete like LC1 concrete cylinders.

4.2. Ultrasonic pulse velocities of concrete cylinders

Theoretically, the pulse velocity of a solid is proportional to the square root of its dynamic modulus of elasticity [2]. Meanwhile, ACI Building Code 213R-87 or CEB-FIP Model Code proposes that static modulus of elasticity of concrete is proportional to the square root or cube root of its compressive strength, respectively. Based on these two aspects, then, the pulse velocity will be proportional to the fourth or sixth root of the compressive strength. This means that as the compressive strength increases with ages, the increase in pulse velocity is proportionally smaller. In this study, the rate of increase in the compressive strength of concrete specimen is about 28.0–32.2% from ages 7 to 28 days, while the rate of increase in the pulse velocity is only about 4.7% to 5.3%, as shown in Fig. 4. From ages of 28 to 56 days, the increase in pulse velocity is even less sensitive to its gain in compressive strength.

In practice, some earlier researcher had proposed an exponential relation between the ultrasonic pulse velocity and compressive strength of concrete [24]. In this study, the relations between ultrasonic pulse velocity, V_{US}, and two elastic moduli, E_s and E_d, and compressive strength, f_c are approximately expressed by the following three exponential equations, respectively

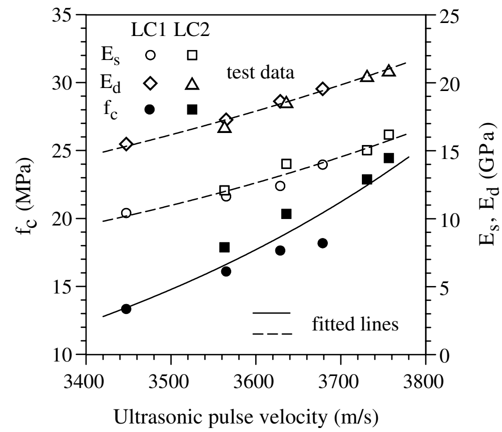

Fig. 5. Average compressive strengths and elastic moduli verse ultrasonic pulse velocity for cylindrical specimens.

$$E_d = 0.452e^{1.022\times10^{-3}V_{US}} \text{ (GPa)}, \tag{5}$$

$$E_s = 0.0797e^{1.407\times10^{-3}V_{US}} \text{ (GPa)}, \tag{6}$$

$$f_c = 0.0262e^{1.810\times10^{-3}V_{US}} \text{ (MPa)}, \tag{7}$$

where V_{US} is in the units of m/s. The corresponding correlation coefficients are 0.993, 0.969 and 0.939, respectively. The resulting curves from these three equations also are shown in Fig. 5, that indicate reasonable good fitting results.

4.3. Ultrasonic pulse velocities of concrete plates

As shown in Fig. 2(b), the ultrasonic pulse wave velocities of concrete plate specimen were measured at two elevations on its side face with values of b_1 by 50 mm (denoted by upper plate side) and 150 mm (denoted by the lower plate side), respectively. At each elevation, at least five measurements were taken. Their average values and the corresponding error bars together with the ultrasonic pulse velocity obtained from the concrete cylinder at various ages are plotted in Fig. 6(a) and (b). The sample coefficients of variance for all test data are less than 1.5% that indicates relatively consistent test results. These two figures show that there is an obvious distinction of two ultrasonic velocities of concrete plate measured at two different elevations, which, in turn, indicates that the material properties are different at different elevations of concrete plate specimen due to a possible segregation during the casting of fresh concrete. Since the specific gravity densities of 0.625 (LC1) and 0.751 (LC2) for both lightweight aggregates are less than the values of water and fresh cement past, it seems inevitable to cause the segregation of fresh concrete for most concrete mixtures with high-flowing characteristic, including the mix proportion used in current study. On the other hand, both LC1 and LC2 concrete cylinders and plates show a consistent increase of ultrasonic pulse velocities with the increase of ages.

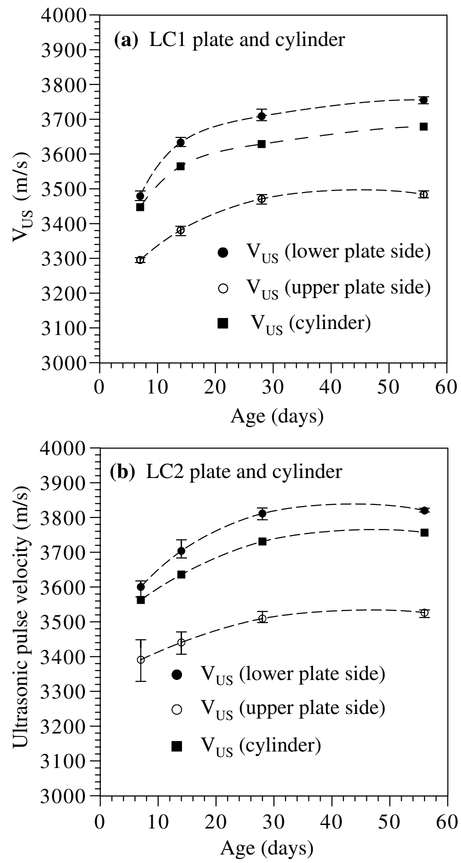

Fig. 6. Ultrasonic velocities for concrete specimens: (a) LC1 plate and cylinder and (b) LC2 plate and cylinder.

As mentioned previously, different degrees of moisture content in concrete will result in difference in the pulse velocities for concrete cylinder and concrete cylinder. Due to a cautious measure on the preparation of both concrete specimens in advance, the discrepancy in wave velocities between concrete cylinders and plates due to different moisture contents is believed to be small. In this study, the material density close to the bottom face of concrete plate specimen is higher than that close to its top face due to a segregation effect. Therefore, that the values of ultrasonic pulse velocity measured from the cylindrical concrete specimens are close to those measured form the concrete plate at the lower plate side seems to be a reasonable result. Accordingly, the strength, modulus of elasticity as well as the wave velocity are always higher at the bottom portion of concrete plate, and then gradually diminished at the portions toward the top surface of plate specimen. The average difference on the ultrasonic pulse velocity measured between these two different elevations is in the range from 6.9% to 7.7% for two concrete plates. If we simply assume a liner profile of wave velocity variation along the vertical cross-sectional plane of concrete plate specimen, the estimated deviation on ultrasonic pulse velocity between the very top and bottom surfaces of plate specimens could be double to a significant range from about 13.8% to 15.4%. But, for this case, the ultrasonic pulse velocity obtained from the concrete cylinders is still only about 1.5–2.0% higher than that of the average of two values measured at upper and lower plate sides. This verifies that, due to the difference in sampling and preparation of procedure, the properties of standard laboratory cylinders normally cannot realistically represent those of the in-place lightweight concrete plates as indicated in this study. Appropriate calibration between the results of in-place tests and the standard test of cylinder needs to established in advance in order obtain proper material properties used in the design codes.

4.4. Wave velocities of concrete plate by impact-echo method

The top surface of each concrete plate specimen was divided into three parallel strips, denoted by A–C, with equal width as schematically shown in Fig. 2(a). Five points of wave velocity measurement were carried out at each concrete strip. Average values of five velocity measurements at four ages together with their corresponding error bars are shown in Fig. 9. The test results and their statistical values showed a maximum coefficient of variance of 0.025 for the test data, which also indicated an acceptable consistency on test results. During the impact-echo test, it was noted that some test data obtained different amplitude waveforms but turned out to have a same thickness frequency after they were transformed into frequency domain by the FFT. For example, two typical impact-echo responses of displacement verse time signals and their FFT corresponding spectra for LC2 concrete plate at age of 56 days are shown in Fig. 7. Although these two test results have distinct waveforms, they nevertheless have same thickness frequencies, f, of 9.03 kHz. By using Eq. (2), the P-wave velocity, V_{IE}, can be obtained as 3763.8 m/s. On the other hand, in the impact-echo method, the equation for systematic error, e_f, is given by $\pm\Delta f/(2f)$ [16], where Δf is the resolution of frequency in the amplitude spectrum and is equal to 0.244 kHz in this study. Thus the systematic error for this test is about 1.35%. Noted that, for a given frequency resolution Δf, the systematic error increases with the decrease of thickness frequency. The tolerance of this P-wave velocity measurement due to this systematic error turns out to be ±50.9 m/s. The final measured P-wave velocities obtained from these two sets of impact-echo tests are expressed as 3673.8 ± 50.9 m/s at age of 56 days. Other values of measured P-wave velocities at four different ages were obtained following similar calculation procedure. It is also noted that the tolerance of P-wave velocity due to systematic error, $\pm\Delta V_{IE}$, is independent of the thickness frequency, f, and equal to $\pm T\Delta f/0.96$. This value is a constant in this case and equal to ±50.9 m/s in this study.

4.5. Wave velocity of plate specimens by one-sided velocity method

As schematically shown in Fig. 2(a), three locations were selected for the measurement of one-sided P-wave

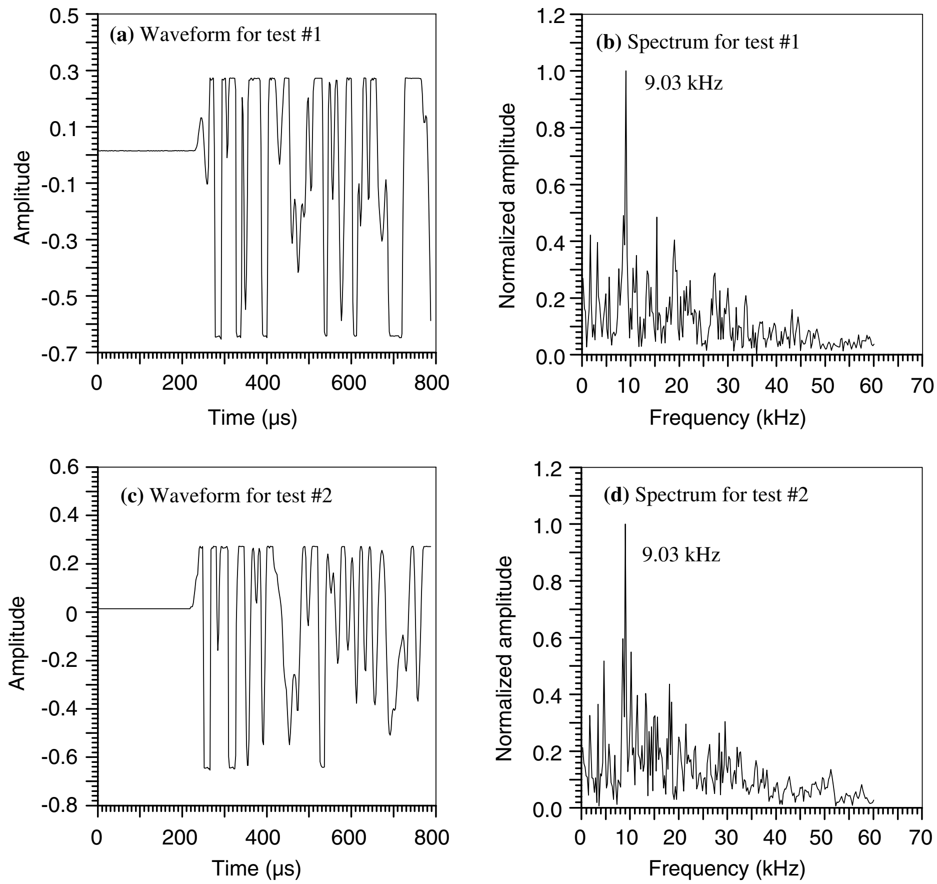

Fig. 7. Two typical impact-echo results for LC2 plate at age of 56 days: (a) waveform of test #1, (b) spectrum of test #1, (c) waveform of test 2 and (d) spectrum of test 2.

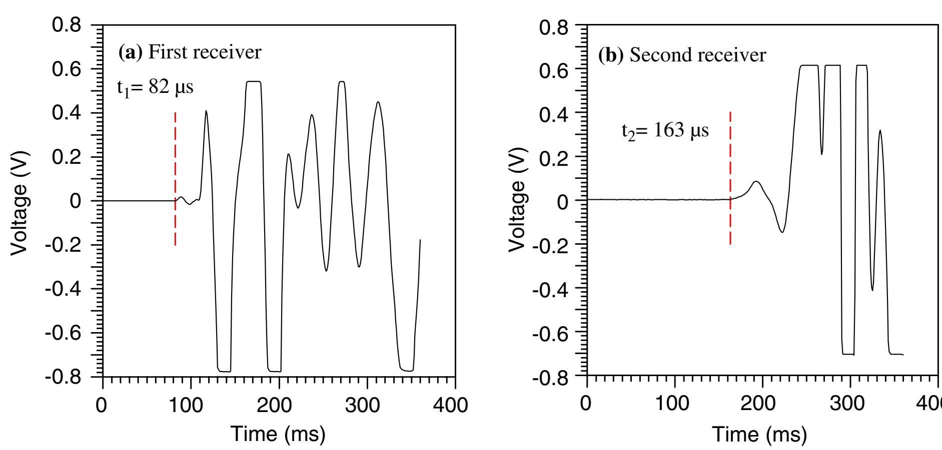

Fig. 8. Typical one-sided P-wave arrival feature of LC2 concrete plate specimen measured at upper plate side at age of 14 days.

velocities, i.e., top plate surface, upper plate side and lower plate side. Five points of wave velocity measurements were carried out at each measured location. A typical one-sided P-wave velocity measured at the upper plate side of LC2 concrete plate at age of 14 days is shown in Fig. 8. For this case the measured P-wave velocity is 3703.7 m/s by using Eq. (4). The maximum systematic error, e_p, in the calculated P-wave velocity for this case is given as $\pm\delta t/\Delta t$, where δt is sampling interval and Δt is measured P-wave travel time [16]. The sampling rate used in this study is 1 μs that results in a maximum systematic error of ±1.24% and a maximum tolerance of P-wave velocity of ±45.7 m/s. The final measured P-wave velocity for this test becomes 3703.7 ± 45.7 m/s. Other measured values of P-wave velocities were obtained following similar calculation procedure. Average data of five measured values of four types of

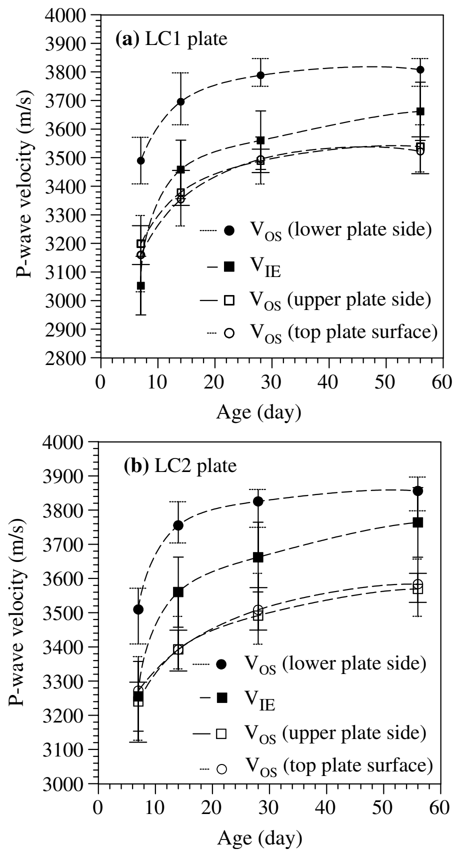

Fig. 9. Variation of P-wave velocities of concrete plates at different locations with ages: (a) LC1 plate and (b) LC2 plate.

P-wave velocities for LC1 and LC2 plate specimens at four ages, together with their corresponding error bard, are also shown in Fig. 9. The test results measured from top surfaces of two plate specimens from three equal-width strips A–C, and from the upper and lower plate sides had showed that the sample coefficients of variance were in the range between 0.010 and 0.027, which indicated a relatively consistent test data from these experiments.

4.6. Correlation among various P-wave velocities

From Fig. 9(a) and (b), we note that all the P-wave velocities show a rapid increase before the age of 14 days but become sluggish afterwards, specifically after the age of 28 days. Based on the inherent principle of wave measurement techniques, the stress wave introduced by impact-echo method propagates through and bounces back and forth between the top and bottom surfaces of concrete plate. As a result, the measured P-wave velocity by this method is roughly an averaging representative value of the overall inhomogeneous material properties of the concrete plate. On the contrary, the P-wave velocity evaluated by the one-sided velocity method only reflects more or less these material properties of concrete plate near its surface where the wave velocity was measured. Therefore, due to the latent segregation effects, the one-sided wave velocity measured at the faces close to the bottom face of lightweight concrete plate with a denser mass will be higher than that on its top face and upper plate sides. Consequently, the P-wave velocity determined by impact-echo method ought to be located between these two extreme values.

The experimental results shown in Fig. 9 verify this inference except for those values at the early age of 7 days when the material properties in the inside of lightweight concrete plates were probably still in an unsteady state. The unsteady material properties of plate specimen at early ages could be contributed to several factors such as a certain amount of free water still unevenly existed in the concrete, a delayed hydration of cement because of the addition of mineral admixture, an unbalanced amount of water absorbed in these porous lightweight aggregates, among others. The influence on the subtle variation of P-wave velocities resulting from these unsteady material properties inside the mass of concrete plate may only be fairly discerned by the impact-echo method characterized by a through-thickness waveform rather than the one-sided velocity method that detects near-surface material properties of plate specimen. If we temporarily neglect these outlying wave velocities at age of 7 days, the average one-sided P-wave velocities measured at the top surface of plate

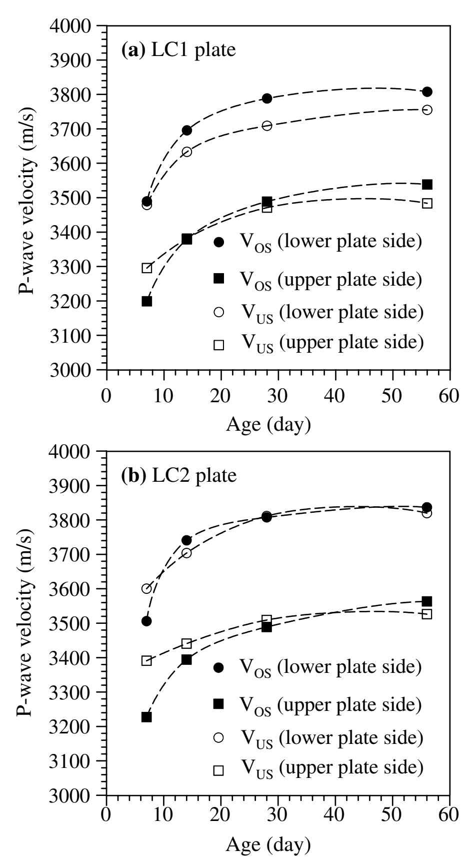

Fig. 10. Comparison of average measured P-wave velocities at various ages between one-sided velocity method and ultrasonic pulse velocity method: (a) LC1 plate and (2) Lc2 plate.

specimens at other ages are smaller by about 2–4% for LC1 plate and about 4–5% for LC2 plate than those measured by the impact-echo method, respectively.

From the experimental results shown in Fig. 9, the variation of engineering properties through the depth of plate specimens is significant. The average one-sided P-wave velocities measured at the upper plate side (located at a quarter of thickness from the top surface) are smaller by about 8–9% for LC1 plate and about 9–10% for LC2 plate than those measured at the lower plate sides (located at three quarters of thickness form the top surface). If a likely linear distributive profile of material composition through the thickness of concrete plate is simply assumed, the difference of P-wave velocities between the very top and bottom surfaces of plate might be as high as up to 16–20%. However, this deduction in the variation of P-wave velocity seems unable to be validated by the current one-sided velocity method, since, as shown in Fig. 9, the one-sided P-wave velocities measured at the top surface of plate specimen are very close to those measured at the upper plate side.

Fig. 10 shows the comparison of measured P-wave velocities at various ages between one-sided velocity method and ultrasonic pulse velocity method. As expected, excepted for these values at age of 7 day, the differences between measured P-wave velocities at other ages by these two methods are less than 2% for LC1 plate specimen and less than 1% for LC2 plate specimen, respectively.

5. Conclusions

The inherent porous and buoyant characteristics of lightweight aggregate used in the concrete mixture by this study result in a varied profile of dissimilar layered material properties through the thickness of concrete plate specimen, with the strongest concrete at the bottom. By using different non-destructive methods based on the stress wave, the objective of this study is to present the variation of engineering properties and P-wave velocities using two kinds of lightweight aggregate concrete at four different ages. For comparison, static uniaxial destructive tests were also performed on the companion concrete cylinders. From the experimental results and discussion presented in this study, the following conclusions can be drawn:

1. At ages from 7 to 56 days, the compressive strengths, static and dynamic moduli for two kinds of cylindrical concrete specimens increase by 25–37%, while the corresponding ultrasonic pulse velocities increase by only 5–7%. The ultrasonic pulse velocities of cylindrical concrete specimen are insensitive to the increases of strength at the age after 28 days.
2. As proposed by some previous researchers, the correlation between moduli of elasticity, compressive strengths and the ultrasonic pulse velocities for both lightweight concrete cylinders can be properly established by the exponential equations with satisfactory results.
3. The ultrasonic pulse velocities measured at the concrete cylinder are different from the average of those measured at the upper and lower plate sides of plate specimens due to the inhomogeneous profile of layered material property distribution through the thickness of plate specimen. The difference is about 2% in average.
4. As a result of a latent relatively looser hydrated structure of concrete near the top surface of lightweight concrete plate where both the one-sided velocity method and impact-echo method are performed, it has been observed that the P-wave velocities measured by the former are about 2–5% lower than those by the latter. In the impact-echo method, the measured one-sided P-wave velocity is normally used to detect the cracks and voids inside the concrete structure or the thickness of concrete member. Therefore, for the lightweight concrete structures, proper allowance should be exercised in advance on the discrepancy between P-wave velocities resulting from these two different measurement methods to improve the accuracy of test results.
5. Except for the age of 7 days, there is good agreement between the P-wave velocities of concrete plate at other ages measured horizontally at the plate sides by the ultrasonic pulse velocity method and those measured by the one-sided velocity method. The difference is within 2%. Although the lightweight concrete tends to have different layered material properties through the thickness, both methods can realistically observe similar P-wave velocities provided that their imposed impact sources are aligned with the receiving devices in a same horizontal layer of plate specimen that presumably has a uniform material property.

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