Research Article

The Measurement of P-, S-, and R-Wave Velocities to Evaluate the Condition of Reinforced and Prestressed Concrete Slabs

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1. Introduction

The accurate measurement of concrete properties, such as elasticity, strength, and Poisson's ratio, is important in terms of the quality assurance (Q/A) and quality control (Q/C) of concrete structures [1]. The Q/A and Q/C require numerous tests in the laboratory. In the field, obtaining core samples consumes a lot of time, budget, and labor and can deteriorate the structure itself. Therefore, nondestructive testing is needed to eliminate problems in both the laboratory and the field.

One of the most effective nondestructive evaluation methods for the assessment of concrete structures is ultrasonic measurement [2]. It has been popularly used in both reinforced and prestressed concrete structures to determine material properties, detect defects, and assess deterioration. Recent failures of prestressed concrete structures have highlighted the need to improve inspection and maintenance in the United States and Europe. However, the field application of ultrasonic methods to prestressed concrete structures should be cautious because the effects of prestressing on the ultrasonic methods have not been clearly validated. These effects are analogous to the acoustoelastic effects that the ultrasonic wave velocity of a solid medium changes with the stress state of the medium [3, 4]. Even though many researchers have developed the health monitoring techniques for steel structures based on the acoustoelasticity [5], only few studies have been related to reinforced or prestressed concrete structural members because of a few limitations; for example, the inelastic characteristics and the small relative velocity change over stress change in a concrete medium [6]. The theoretical study of elastic waves in an infinite prestressed solid that is homogeneous and isotropic is well-advanced [7, 8], but the deduced analytical equations offer no practically effective applications for nonhomogeneous and inelastic materials such as concrete under an inconsistent stress field. Thus, it is necessary to experimentally investigate and analyze the distribution of ultrasonic velocities in prestressed concrete structures in the field.

Generally, ultrasonic testing methods assess material conditions and deterioration by comparing velocity, attenuation, frequency, and energy against reference values such as ultrasonic pulse velocity (UPV) determined using laboratory specimens. The ratio of field UPV to the reference UPV...
indicates the level of material condition [9]. Traditionally, the pressure wave (P-wave) pulse velocity has been popularly applied to concrete structures for its easy generation and measurement. However, the statistical stability of experimental data for P-wave velocity is weaker than for shear (S-) or Rayleigh (R-) waves because the energy of a P-wave is much less than that of S- and R-waves [10]. Furthermore, the P-wave depends on the presence of pore water in the concrete. Therefore, S- and R-wave pulse velocities have recently been applied to various structures.

For this study, we measured and analyzed P-, S-, and R-wave velocities in both reinforced and prestressed concrete slabs to investigate the statistical distribution of each wave velocity with and without prestressing. The experimental results present practical guidelines for applying the ultrasonic methods to reinforced and prestressed concrete structures.

2. Ultrasonic Pulse Velocity and Its Measurement

In an elastic and stress-free solid medium, body waves travel within the body (P- and S-waves), and surface waves (R-waves) travel along the free surface of the material. The velocities of wave propagation depend on elastic constants and the mass density of the material. The relations among P-, S-, and R-wave velocities can be expressed by the following equations [15]:

\[
\begin{align*}
V_P &= \sqrt{\frac{E(1-v)}{\rho (1+v)(1-2v)}}, \\
V_S &= \sqrt{\frac{E(1-v)}{2\rho (1+v)}}, \\
V_R &= \frac{0.87 + 1.12v}{1 + v} \sqrt{\frac{E}{\rho (2(1+v)}})
\end{align*}
\]

where \(V_P, V_S, \) and \(V_R\) are the velocities of P-, S-, and R-waves, respectively, and \(E, \rho, \) and \(v\) are dynamic elasticity, density, and Poisson’s ratio, respectively.

\(V_P\) typically ranges from 3500 m/s to 4500 m/s and \(V_R\) from 1800 to 2500 m/s for sound concrete [16]. The motion resulting from R-waves is restricted to a region near the surface and decreases exponentially in amplitude away from the surface. The R-wave penetration depth is inversely related to the frequency of the wave. R-waves are easily generated in a solid by a transient point source and more readily sensed than P- and S-waves because of their large amplitude. The only limitation of R-waves is caused by the limited penetration depth; the disturbances are confined to the surface region of thickness, approximately twice the wavelength, \(\lambda_R\). Figure 1 shows the wave pressure field generated by a harmonic normal load applied at the interface. The propagating P-, S-, and R-waves in the concrete have 7, 26, and 67% of the source energy, respectively [11].

2.2 S-Wave (Shear Wave) Measurement. One of the most effective ways to measure S-wave velocity is with MIRA equipment that generates shear wave tomography [13]. The MIRA also operates on the basic ultrasonic pulse-echo principle. Unlike other pulse-echo methods, the MIRA device does not require a coupling agent with a spring-loaded design. Interactive postprocessing software uses the synthetic aperture focusing technique (SAFT) to generate 2D and 3D images of the test results [13] (Figure 3). The generated S-waves have particle motion that propagates perpendicular to the direction of the wave front with a velocity about 60 percent that of P-waves [11]. Samokrutov et al. [17] showed that using S-waves instead of P-waves reduces the amount of backscattering and signal attenuation in the direction parallel to the propagating wave.

Recent advances have improved the MIRA transducer, which can now create a 3D tomography of internal defects that might be present in a concrete element, with penetration depths up to about 2.0 m [13]. MIRA is based on the ultrasonic pitch-catch method and uses an antenna of dry point contact transducers that emit shear waves into the concrete with a nominal center frequency of 50 kHz. Using an array of point transducers rapidly produces 180 transit time measurements during each test. The antenna is composed of a 4 by 12 array of point transducers and a control unit that operates the transducers, as illustrated in Figure 4 [14]. The transducers act as transmitters and receivers in a sequential mode. The use of very high frequencies with the pulse-echo method could be beneficial in terms of improved defect resolution.

2.3 R-Wave (Rayleigh Wave) Measurement. The conventional measurement of R-wave velocity uses the time difference
between the first or second significant peaks in two R-waves from two receivers [18, 19]. However, system errors in catching the peak points can occur. The best way to make up for that shortcoming uses the dispersion curve of Lamb waves in the plate with MASW (multichannel analysis of surface waves) [20, 21].

MASW data collection is based on N-wave signals collected on the surface along a linear array of sensed points equally spaced (with spacing $dx$) from the wave source, such as the impact event illustrated in Figure 5. The impact event for wave generation must be provided by a high frequency impactor (small contact area). Multiple data are processed as individual signals obtained by each sensor. Data are transformed from the offset time-domain to the frequency-phase velocity domain using a 2D Fourier transform, producing a phase velocity that is usually called the dispersion curve.

MASW has been commonly applied to the surface wave testing of pavements, and the experimentally computed dispersion curve is interpreted to represent R-waves. Several modes of guided dispersive waves propagating in a pavement structure can be measured at the surface and used for material characterization, including the A0 and S0 Lamb modes used to determine Poisson’s ratio, R-wave velocity, and plate thickness [22]. An example of a dispersion curve in
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SAFT-C processing of the signals from each set of DPC modules

For 10 modules, \( N = 45 \) signals
For 12 modules, \( N = 66 \) signals

\[ N = \frac{n(n-1)}{2} \]

Figure 3: Schematic representation of the digitally focused array signal capturing scheme [13].

Table 1: Information on the prestress strand.

<table>
<thead>
<tr>
<th>Tendon type</th>
<th>Diameter (mm)</th>
<th>Area (mm(^2))</th>
<th>Elongation (%)</th>
<th>Tensile strength (MPa)</th>
<th>Jacking force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWPC7B</td>
<td>12.7</td>
<td>98.7</td>
<td>3.5</td>
<td>1860</td>
<td>128.5</td>
</tr>
</tbody>
</table>

Figure 4: Illustration of low-frequency ultrasonic tomography (MIRA) [14].

a concrete slab with 30 cm depth is presented in Figure 6. It is obtained by using MASW wave transformation in the following equation [20]:

\[
S(\omega, c_p) = \int e^{-i(\omega/c_p)x}U(x, \omega) \, dx,
\]  

where \( U(x, \omega) \) is the normalized complex spectrum obtained from the Fourier transformation of \( u(x, t) \), which is a multi-channel record at different offsets. \( \omega \) is the angular frequency, and \( c_p \) is the phase velocity.

3. Experiments

3.1. Test Specimens. To simulate the effects of prestressing on UPV into a concrete slab, we carried out a series of ultrasonic tests on the three types of concrete slab (S1, S2, and S3) shown in Figure 7. All of the specimens are 3000 mm \( \times \) 3000 mm with a nominal thickness of 250 mm, and they all contain transverse and longitudinal 13 mm diameter reinforcements with 560 mm spacing at 20 and 230 mm depths, respectively. We prestressed the S2 and S3 slabs in the two and one ways, respectively. Five 12.7 mm diameter strands with 350 mm spacing were applied in each direction. The details of the prestress strand are summarized in Table 1.

The specified w/c of the concrete mixture was 0.48 with 6% entrained air content. The mixture contained Type I cement and limestone aggregates with a maximum coarse aggregate size of 25 mm. At the time of concrete placement, slump was measured as 150 mm and density as 2250 kg/m\(^3\). The specimens were moist-cured for 7 days by covering them with saturated burlap with a bleed hose and plastic sheeting. Beyond the eighth day, the specimens were kept in laboratory air.

We determined the concrete's mechanical properties using tests performed on ten 150 mm \( \times \) 300 mm standard cylinders prepared from the same batch of concrete. For the same conditions as the S1, S2, and S3 slabs, we air-cured the standard specimens for 28-day strength, static modulus, and Poisson's ratio. We determined the compressive strength using ASTM C-39 [23] and conducted the modulus of elasticity (\( E_c \)) and Poisson's ratio tests (\( v \)) from ASTM C-469 [24]. The average results for the 28-day tests were 14.84 MPa for strength, 17.68 MPa for the modulus of elasticity, and 0.16 for Poisson's ratio. Also, the dynamic modulus (\( E_d \)) was 21.30 GPa, found by following the empirical relationship proposed by Lydon and Balendran [25]:

\[ E_c = 0.83E_d \text{ (GPa)} \]  

3.2. Test Methods

3.2.1. P-Wave Measurement. We measured the P-wave velocity of concrete, \( V_p \), according to BS 1881 [26] using a pair of P-wave transducers (MK-954 transmitters and receivers) connected to a pulse-receiver (Ultracon-170). The transmitter was driven by a 200 V square pulse, generating a transverse
ultrasonic pulse of 52 kHz. The receiver measured the transient stress waves through the surface of each slab (Figure 8).

We performed the P-wave measurements with a digital scope board synchronized with the pulser-receiver unit; therefore, data collection started at the time of pulse application. Measurement of flight time was affected by the electrical noise superimposed with the waveform. Therefore, to minimize random errors associated with identifying the arrival time, we performed wave averaging of 128 waveforms. The first step in identifying the flight time from the waveform was establishing the baseline. Afterward, the waveform was further smoothed using a 10-point moving average filter.

We made a total of 40 indirect measurements on each concrete slab using a coordinate system drawn on the slab surface (Figure 9). The coordinate system consisted of a primary grid at 353 \times 100 \text{ mm} spacing. The gridlines were labeled along the width of the specimens as axes A, B, C, D, E, F, G, and H and along the length of the specimens as axes I, II, III, IV, and V. We made indirect measurements longitudinally along the lettered axes. We placed the transmitter and receiver transducers at the grid nodes and measured the average P-wave velocity between them. For example, at A-I test position, upper and bottom circles represent the transducers (transmitter and receiver), and cross marks indicate the average P-wave velocity between two transducers.

We acquired the transmitter and conditioned receiver signals using a high-speed (1 MHz sampling rate) analog to digital data acquisition board. We developed a computer algorithm based on a fixed threshold level to determine the time of flight using the digitally acquired waveforms. Figure 10 presents a typical signal of the transmitter and receiver transducers.

3.2.2. MIRA Test for the S-Wave Measurement. For effective S-wave measurement, we used MIRA equipment that was verified in both Europe and the United States. The procedure is simple: a trigger button on the MIRA board starts reception of all possible combinations of pulse reflections from each test point location through the appropriate filtering and space-time processing based on the SAFT algorithm. Eventually, the digital display presents a B-scan image with the S-wave velocity.

We made a total of 20 direct S-wave measurements on each concrete slab using the same coordinate system as for the P-wave measurement. However, we conducted these tests only in the areas shaded in Figure 11. We labeled the gridlines along the width of the specimens as axes AB, CD, EF, and GH and those along the length of the specimens as axes I, II, III, IV, and V. We carried out direct measurements at a single position because the MIRA uses the pulse-echo method (Figure 12).

Figure 13 shows the result of the MIRA testing at the EF-V point on the S1 slab. The reconstructed B-scan image depicts an average transverse cross section (90° from the transducer array travel path). In the view, the center of the bright red color represents reflections from the back of the slab, which corresponds to a nominal thickness of 250 mm. Additional reverberations from the bottom of the slab, at approximately twice the thickness of each consecutive step, are observed at the 500 mm depth. Also, the average S-wave velocity computed by the SAFT algorithm is displayed in the left corner.

3.2.3. MASW Test for R-Wave Measurement. We applied an MASW testing configuration for the identification of R-wave velocity consistently to the three test specimens along the 12 paths shown in Figure 14.

We used a steel ball with an 18 mm diameter as the impact source for each MASW test. The forcing function
Figure 7: The plan and side views of specimens S1, S2, and S3. All dimensions in millimeters.
associated with the impact exhibits consistent and broad spectral content, ranging from DC to 15 kHz. We used 5 accelerometers (PCB 353B16), with a ±5% frequency range of 1 to 10 kHz and a resonance frequency around 70 kHz, in even 10 cm spacing along the test line to detect the surface vibrations generated by the ball impact event. For a rapid test, we mounted the 5 accelerometers to the frame, as shown in Figure 15. We stabilized the signals using a signal conditioner (PCB 482C16) and digitized them at a sampling frequency of 1 MHz using an NI-PXI 5105 oscilloscope.

The multichannel record consists of 5 time series (called traces) from the receivers in an ordered manner. MASW data processing consists of three steps: (1) detection of surface waves, (2) construction of the dispersion image and extraction of the signal dispersion curve, and (3) identification of the several Lamb wave modes and R-wave velocity. All these steps can be fully automated. The detection of surface waves examines the recorded seismic waves in the most probable range of frequencies and phase velocities. Construction of the phase velocity image is accomplished through a 2D (time and pace) wave field transformation method. This transformation eliminates all the ambient noise from human activities as well as source-generated noise such as scattered waves. The necessary dispersion curve, such as that of the A0, A1, S0, or S1 fundamental-mode, is then extracted from the accumulation pattern. The extracted dispersion curve is
Figure 12: S-wave measurement in the grid on concrete slab surface.

Figure 13: B-scan image from MIRA at the EF-V point in slab S1.

Figure 14: A plan view of the 12 test paths for the R-wave measurement. The ○ marks indicate the sensor positions in each path, and the arrows show the direction of each test.

Figure 15: MASW test for the R-wave measurement along predefined paths on the concrete slab surface.

finally used as a reference to identify the R-wave velocity. For each test, we obtained time signals of 10 ms duration. Because the amplitude of the input forcing function at each test point across the concrete surface is inherently inconsistent, we normalized the amplitude of each time signal with respect to the early-arriving negative peak of the R-wave pulse arrival within that signal, which provides more consistent MASW data.

Figure 16 shows the experimental results along path 6 in the S2 slab and exhibits dispersion images and curves up to 12 kHz. The Lamb wave curves in the single layer must be fit to one of the responses. The A0 and S0 modes beyond 10 kHz converge to about 2000 m/s phase velocity, corresponding to the R-wave. Also, the impact-echo mode (thickness mode), which is identical to the S1 mode, shows that 7.5 kHz corresponds to a nominal thickness of 250 mm.

4. Results and Discussion

4.1. The Experimental Data for P-, S-, and R-Wave Velocities.

To minimize the random errors associated with identifying the arrival time, we averaged the times for 128 waveforms for the P-wave measurement. For the S-wave measurement, we repeated the MIRA tests at each point until we identified a clear reflection from the back of the slab. We also carried out the MASW test on a single path until the computed dispersion image showed a distinct A0 mode. All the data for the P-, S-, and R-wave velocities are summarized in Tables 2–4.

The ranges for P-, S-, and R-wave velocities are 3002–3472 m/s, 1780–2160 m/s, and 1753–1988 m/s, respectively, for the reinforced concrete slab (S1). The data distribution for each type of wave is reasonably comparable to the theoretical velocity values of 3174, 1851, and 1827 m/s computed by (1) with Poisson’s ratio (0.16), dynamic elasticity (21.3 MPa), and density (2250 kg/m³). The difference between the maximum and minimum velocities in slab S1 tends to be smaller than those in S2 and S3, which have prestressing in two and one ways, respectively, because the stress field in the reinforced concrete slab is more consistent than those in the prestressed slabs.
### Table 2: P-wave velocities (m/s) at test grid points in slabs S1, S2, and S3.

<table>
<thead>
<tr>
<th>Test point</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
<td>III</td>
</tr>
<tr>
<td>A</td>
<td>3002</td>
<td>3301</td>
<td>3295</td>
</tr>
<tr>
<td>B</td>
<td>3136</td>
<td>3333</td>
<td>3283</td>
</tr>
<tr>
<td>C</td>
<td>3012</td>
<td>3197</td>
<td>3281</td>
</tr>
<tr>
<td>D</td>
<td>3029</td>
<td>3339</td>
<td>3318</td>
</tr>
<tr>
<td>E</td>
<td>3130</td>
<td>3268</td>
<td>3104</td>
</tr>
<tr>
<td>F</td>
<td>3018</td>
<td>3268</td>
<td>3300</td>
</tr>
<tr>
<td>G</td>
<td>3191</td>
<td>3207</td>
<td>3207</td>
</tr>
<tr>
<td>H</td>
<td>3334</td>
<td>3374</td>
<td>3271</td>
</tr>
</tbody>
</table>

Min: 3002
Max: 3472
Avg (m/s): 3285
Std (m/s): 97

Avg = average velocity and Std = standard deviation.

### Table 3: S-wave velocities (m/s) at test grid points in slabs S1, S2, and S3.

<table>
<thead>
<tr>
<th>Test point</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AB</td>
<td>CD</td>
<td>EF</td>
</tr>
<tr>
<td>I</td>
<td>1830</td>
<td>1870</td>
<td>2020</td>
</tr>
<tr>
<td>II</td>
<td>1950</td>
<td>1870</td>
<td>1840</td>
</tr>
<tr>
<td>III</td>
<td>1880</td>
<td>1840</td>
<td>1840</td>
</tr>
<tr>
<td>IV</td>
<td>1890</td>
<td>2160</td>
<td>1890</td>
</tr>
<tr>
<td>V</td>
<td>2020</td>
<td>1890</td>
<td>2010</td>
</tr>
</tbody>
</table>

Min: 1780
Max: 2160
Avg (m/s): 1911
Std (m/s): 95

Avg = average velocity and Std = standard deviation.

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**Figure 16:** MASW results along the 6th path in slab S2. The computed A0, A1, S0, and S1 Lamb modes corresponding to the slab depth overlap on the dispersion curve image.
Table 4: R-wave velocities (m/s) along 12 paths in slabs S1, S2, and S3.

<table>
<thead>
<tr>
<th>Slab</th>
<th>Path</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Min</th>
<th>Max</th>
<th>Avg</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td></td>
<td>1768</td>
<td>1855</td>
<td>1913</td>
<td>1751</td>
<td>1835</td>
<td>1988</td>
<td>1894</td>
<td>1882</td>
<td>1921</td>
<td>1917</td>
<td>1988</td>
<td>1880</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td>2025</td>
<td>1951</td>
<td>1874</td>
<td>1988</td>
<td>2006</td>
<td>1992</td>
<td>1894</td>
<td>2043</td>
<td>1855</td>
<td>1795</td>
<td>1932</td>
<td>1855</td>
<td>1795</td>
<td>2043</td>
<td>1934</td>
<td>79</td>
</tr>
</tbody>
</table>

Avg = average velocity and Std = standard deviation.

Table 5: The results of statistical analysis for slabs S1, S2, and S3.

<table>
<thead>
<tr>
<th>Type of measurement</th>
<th>Type of slab</th>
<th>Sample size</th>
<th>Avg(σ)* m/s</th>
<th>Std(μ)** m/s</th>
<th>COV****</th>
<th>Dmax</th>
<th>D5%</th>
<th>p value</th>
<th>Probability distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-wave</td>
<td>S1</td>
<td>40</td>
<td>3285</td>
<td>97</td>
<td>0.030</td>
<td>0.16</td>
<td>0.21</td>
<td>0.20</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>40</td>
<td>3367</td>
<td>146</td>
<td>0.043</td>
<td>0.20</td>
<td>0.21</td>
<td>0.05</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>40</td>
<td>3362</td>
<td>110</td>
<td>0.033</td>
<td>0.19</td>
<td>0.21</td>
<td>0.09</td>
<td>Normal</td>
</tr>
<tr>
<td>S-wave</td>
<td>S1</td>
<td>20</td>
<td>1911</td>
<td>95</td>
<td>0.049</td>
<td>0.23</td>
<td>0.29</td>
<td>0.18</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>20</td>
<td>1961</td>
<td>169</td>
<td>0.086</td>
<td>0.24</td>
<td>0.29</td>
<td>0.17</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>20</td>
<td>1952</td>
<td>62</td>
<td>0.032</td>
<td>0.20</td>
<td>0.29</td>
<td>0.33</td>
<td>Normal</td>
</tr>
<tr>
<td>R-wave</td>
<td>S1</td>
<td>12</td>
<td>1880</td>
<td>69</td>
<td>0.037</td>
<td>0.18</td>
<td>0.37</td>
<td>0.76</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>12</td>
<td>1934</td>
<td>79</td>
<td>0.041</td>
<td>0.20</td>
<td>0.37</td>
<td>0.65</td>
<td>Normal</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>12</td>
<td>1918</td>
<td>75</td>
<td>0.039</td>
<td>0.22</td>
<td>0.37</td>
<td>0.51</td>
<td>Normal</td>
</tr>
</tbody>
</table>

Avg(σ)* = average velocity; Std(μ)** = standard deviation; COV**** = coefficient of variable (=σ/μ×100 (%)).

4.2. Statistical Analysis. We conducted our statistical analysis on the UPV data mathematically to evaluate variation in the experimental data from the reinforced and prestressed concrete slabs. We used the sample size, mean, and standard deviation of the UPV from slabs S1, S2, and S3 for the basic input, as summarized in Table 5.

Generally, for an ultrasonic wave at 50 kHz with a wavelength of approximately 90 mm, the time of flight between the transmitter and receiver transducers can be influenced by the nonuniformity of coarse aggregate distribution, which creates a basic data error in the concrete material [26]. The statistical data show that the standard deviations and COVs of R- and S-waves are usually less than those of P-wave because of the two reasons. Firstly, P-wave has the highest velocity among all the ultrasonic waves. Secondly, the R- and S-waves depend less on boundary conditions and water pore pressure than P-waves. Therefore, it is possible to measure more distinct flight time, resulting in the more accurate wave velocity. Moreover, the MASW and MIRA tests for R- and S-wave measurements use improved algorithms to minimize noise signals from the multiple-sensor measurements. Thus, P-wave measurement of a single wave path associated with a single sensor has more systematic and electrical errors than R- and S-wave measurements.

All the COVs of the UPV data in the field concrete specimens are good (4.0 to 5.0) or very good (3.0 to 4.0), according to ACI 214R [27], except for the S-wave measurement on slab S2. The large COV (0.086) in the S-wave measurement might be caused by unstable convergence in the SAFT algorithm on the rough surface of the concrete slab or by the inconsistent stress field in the prestressed concrete slab, even though we repeated the MIRA tests several times.

In all the UPV tests, the COV tends to grow larger as the prestressing becomes stronger because the stress field in prestressed slabs is inconsistent, and the analytical characterization of ultrasonic waves in the inconsistent stress field of a nonhomogeneous material is almost impossible. Thus, our purpose in this study was to experimentally identify the statistical variations in UPV data from prestressed slabs and suggest practical recommendations.

We also applied the Kolmogorov-Smirnov goodness-of-fit test [28] to all the cases to check the statistical distribution of the UPV measurements. In this test (as shown in Figures 17–19), we assumed an empirical stepwise cumulative frequency distribution function and plotted the cumulative normal distribution function for each of the variables presented in Table 5. The observed D-statistic, $D_{\text{max}}$, was less than the critical value corresponding to the commonly used 5% level of significance (Table 5). Therefore, the null hypothesis that the data have a normal distribution cannot be rejected at the 5% level of significance. The $p$ value represents the probability that the observed sample statistic is equal to or more extreme than a statistical hypothesis, which means that the null hypothesis can be more accepted as the $p$ value becomes larger than the level of significance. For all the data, the null hypothesis was satisfied. Also, the experimental data for the R-wave are more statistically significant than those for the S- and P-waves.
To sum it all up, our inference is that all the types of UPV data can be represented as normally distributed variables with their respective means and standard deviations.

4.3. Comparison with the Dynamic Modulus from Static Test. We checked the accuracy of our experimental data by comparing the dynamic moduli from the measured UPV to one determined from the static modulus. Table 6 shows the comparison of the dynamic moduli for S1, S2, and S3. The error range for slab S1 (without prestressing) is 5–7%, and the R-, S-, and P-waves, in that order, have smaller errors compared with the dynamic modulus from the static test. However, the error increases 12% for S2 and S3 regardless of the wave type, even though error between S2 and S3 is below 2%. Thus, prestressing affects all the types of wave velocities and increases the dynamic modulus by more than 10% based on the wave velocity.

5. Conclusion

We conducted a series of experimental UPV tests to explore the variation of P-, S-, and R-wave velocities in a reinforced concrete slab and two prestressed concrete slabs. For the S- and R-wave measurements, we applied the MIRA and MASW tests, respectively, and verified that they are robust, promising test methods for wave velocity measurement. All of our experimental data are statistically stable and significant. Based on the data presented in this study, we draw the following conclusions.

(i) First, all the experimental UPV data are in the reasonable range theoretically computed from the physical properties found in the static test. The experimental data for the R-, S-, and P-waves, in that order, are statistically stable because of differences in energy magnitude, effects of confinement, and
Table 6: Comparison of dynamic moduli from ultrasonic and static tests.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Slab</th>
<th>Ultrasonic test</th>
<th>Static test</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg m/s</td>
<td>Edu* (GPa)</td>
<td>ν</td>
<td>fck** (Mpa)</td>
</tr>
<tr>
<td>P-wave</td>
<td>S1</td>
<td>3285</td>
<td>22.80</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>3367</td>
<td>23.96</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>3362</td>
<td>23.88</td>
<td>0.16</td>
</tr>
<tr>
<td>S-wave</td>
<td>S1</td>
<td>1910</td>
<td>22.67</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>1960</td>
<td>23.87</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>1950</td>
<td>23.63</td>
<td>0.16</td>
</tr>
<tr>
<td>R-wave</td>
<td>S1</td>
<td>1880</td>
<td>22.55</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>1934</td>
<td>23.87</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>1918</td>
<td>23.46</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Edu*: dynamic modulus by ultrasonic test, fck**: 28-day compressive strength.

![Cumulative distribution of S-wave velocities](image1)

**Figure 18**: Cumulative normal distribution function of S-wave velocities.
improvements in the measurement equipment and analysis associated with the various sensors.

(ii) The statistical analysis by COV and goodness-of-fit test showed good or very good data distribution rates, according to ACI 214R, and all the data represent the normal distribution at the 5% level of significance. Thus, all of the data can be trusted, statistically.

(iii) The ultrasonic velocities in the prestressed concrete, regardless of wave type, are 2-3% faster than those in the reinforced concrete slab. Also, the dynamic moduli from the UPV data in the PSC slab are 5–7% higher than those in the RC slab.

(iv) We obtained statistically reliable data using promising methods and showed the variation of elastic waves in PSC and RC slabs. Our experimental results offer practical guidelines for the application of ultrasonic methods to PSC structures.

**Competing Interests**

The authors declare that they have no competing interests.

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**References**


