Field and Laboratory Determination of Elastic Properties of Portland Cement Concrete Using Seismic Techniques

J. A. BAY AND K. H. STOKOE II

Seismic techniques, including the Spectral-Analysis-of-Surface-Waves test, direct and interval compression wave tests, and resonance tests, provide reliable techniques for determining the elastic properties of portland cement concrete (PCC). These techniques can be applied to pavement structures, such as slabs, and to laboratory specimens, such as cylinders. The nondestructive nature of these tests makes them ideal for monitoring PCC from the earliest stages of curing and continuing throughout the life of the structure. Elastic properties, typically expressed as Young's modulus and shear modulus, provide an easy way to compare the similarity of laboratory specimens with each other and with the structures they are intended to represent. The results of different seismic tests on curing slabs and field-curing cylinders demonstrate the applicability of the tests and show that, in these tests, the field-cured cylinders did not obtain the stiffnesses of the slabs. Small-strain static tests performed on cylinders are also shown to be consistent with moduli determined by dynamic (seismic) tests on the same cylinders when both types of tests are performed at similar strain levels. However, these small-strain moduli are shown to be about 10 percent greater than Young's moduli measured in conventional static tests at 40 percent of the unconfined strength, because of the decrease in modulus with increasing strain.

Seismic wave velocity measurements provide nondestructive techniques for determining the elastic properties of portland cement concrete (PCC). These techniques can be applied to PCC structures, such as slabs or beams, and to laboratory specimens, such as cylinders. The nondestructive nature of seismic tests makes them ideal for monitoring PCC, beginning immediately after placement of the concrete and continuing throughout the life of the structure.

A number of different techniques that employ different types of seismic waves can be used. These tests include Spectral-Analysis-of-Surface-Waves (SASW), direct and interval compression waves, and resonance. Because velocities of seismic waves differ, it is important to know which type of wave is being measured. Once velocities of two types of seismic waves have been measured, all elastic properties of a homogeneous, isotropic material can be determined.

A brief overview of the relationships between seismic wave velocities and elastic properties is presented here. Methods that can be employed to measure the various wave velocities in different situations are then discussed. The results of tests performed on curing PCC slabs and cylinders are used to illustrate the measurement methods. Seismic wave velocities are also used as a means of comparing the similarities of slabs and field-cured cylinders. Finally, values of Young's moduli obtained seismically, or dynamically, are compared with values obtained in low-strain static tests and conventional static tests on the same specimens.

Department of Civil Engineering, University of Texas at Austin, Austin, Tex. 78712-1076.

ELASTIC PROPERTIES AND SEISMIC WAVE VELOCITIES

Seismic wave velocities are a function of the elastic properties and mass density of the material through which the stress waves are propagating. This characteristic makes seismic testing a powerful tool in the measurement of elastic material properties. The velocities of different stress (seismic) waves are controlled by different elastic moduli. If the material can be characterized as elastic, homogeneous, and isotropic, only two elastic constants are required to describe the material, and these constants can be determined by measuring the velocity of two types of seismic waves. The PCC materials tested in this work can be so described. On the other hand, if more elastic constants were required to characterize the material (such as for an elastic, homogeneous, cross-anisotropic material that requires five elastic constants), then additional stress wave measurements would have to be performed.

To understand which elastic modulus controls which type of seismic wave, one must look at the deformation of an element during stress wave loading. The deformation resulting from a shear wave is represented in Figure 1a. The only deformation in this case is in shear, so that shear modulus (G) controls the wave velocity. The equation relating shear wave velocity (V_s) and shear modulus is as follows:

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

where ρ is the mass density (unit weight divided by gravity) of the material.

The deformation caused by an unconstrained compression wave (also called a rod wave) is represented in Figure 1b. In this case the wave deforms the material in the direction of wave propagation and also in the lateral directions. Unconstrained modulus, or Young's modulus (E), controls the wave velocity in this case. The equation relating unconstrained compression wave velocity (V_c) and Young's modulus is as follows:

$$E = \rho V_c^2 \tag{2}$$

The deformation caused by a constrained compression wave is represented in Figure 1c. In this case, the element is re-

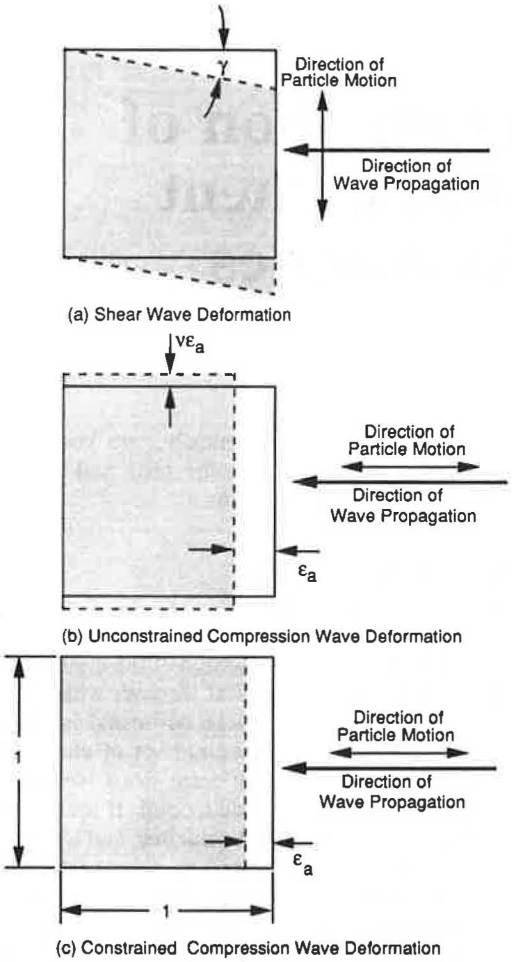

FIGURE 1 Deformation of a unit element of material loaded by a shear wave or compression waves.

strained from deforming in the lateral directions. This wave velocity is controlled by the constrained modulus (M). Because the constrained modulus has the largest value of the elastic moduli, this type of stress wave, known as a primary or P-wave, has the fastest wave velocity. The equation relating constrained modulus and P-wave velocity (V_p) is as follows:

$$M = \rho V_p^2 \tag{3}$$

For an elastic, homogeneous, isotropic material like the PCC material tested in this work, all of the above moduli (G, E, and M) can be related to each other using the following equations:

$$M = \frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)} E \tag{4}$$

$$E = 2 (1 + \nu) G \tag{5}$$

$$M = \frac{2 (1 - \nu)}{1 - 2\nu} G \tag{6}$$

where ν is Poisson's ratio.

One additional type of stress wave measured in this work is a Rayleigh-type surface wave. This type of wave travels along the air-solid interface and causes a complex deformation pattern that varies with depth beneath the interface. The deformation pattern contains both distortion and volume-change (shear and compression) components, which results in both horizontal and vertical motions that decay with depth. Because of this combination of distortion and volume change, the velocity of Rayleigh-type surface waves cannot be related to one modulus as simply as compression and shear waves. The velocity of the Rayleigh wave (V_R) is always slightly less than the shear wave velocity. However, it is strongly controlled by the shear modulus of the material. Rayleigh wave velocity can be approximately related to V_s using the following equation:

$$V_R \approx \frac{0.862 + 1.14\nu}{1 + \nu} V_s \tag{7}$$

A crude estimate of VR for values of Poisson's ratio between 0.1 and 0.3 is

$$V_R \approx 0.9 \, V_s \tag{8}$$

The type of wave that is excited and measured depends on the source, the receiver orientation, and the source/receiver location on the specimen being tested as described below.

SEISMIC MEASUREMENTS ON CURING PCC SLABS

Nondestructive seismic techniques can be employed to monitor the quality of PCC slabs beginning immediately after the concrete is placed, during curing, and throughout the life of the structure (*1*). Measured wave velocities are only functions of the elastic moduli and mass density of the slab. Hence, velocities can be used to calculate moduli directly. The seismic techniques used on the surface layer of concrete pavements include SASW, direct and interval compression waves, impulse-response, and impact-echo. However, the last two techniques require that the thickness of the slab be known to determine the velocity or stiffness of the concrete (*2,3*).

SASW Method

The SASW method is a nondestructive, nonintrusive seismic technique that uses the dispersive nature of surface waves to determine the stiffness profile of layered systems. Because all testing is done on a single exposed surface, the SASW technique is particularly effective for evaluating the pavement surface layer and for repeated monitoring of pavements. A more complete treatment of the SASW method applied to pavements can be found elsewhere (*4–7*).

The SASW method involves measuring the velocities of Rayleigh-type surface waves over a wide range of frequencies. Surface waves propagate along the air-solid interface with particle motion limited primarily to depths less than about one wavelength. Thus, lower-frequency waves with longer wavelengths sample material deeper. Higher-frequency waves with shorter wavelengths only sample shallow material. To measure the stiffness of a concrete surface layer, the velocity of wavelengths shorter than the concrete thickness are evaluated.

SASW Testing Procedure

The SASW source and receiver configuration is shown in Figure 2. A vertically oriented piezoelectric shaker on the concrete surface is used as the source, and two vertically oriented accelerometers positioned linearly from the source are used as receivers. The accelerometers are coupled to the slab immediately after the surface is finished using a fast-setting cement. The waveforms from the two accelerometers are transformed into their frequency spectra using the fast Fourier transform (FFT). The velocities of the various frequencies (which are related to the wavelengths) are determined by comparing the phase of the two spectra at each frequency. These operations are performed in real time using a FFT signal analyzer.

Typical SASW Results

A typical dispersion curve, a plot of surface wave velocity versus wavelength, for a 0.8-ft thick slab is shown in Figure 3. It can be seen that wave velocities for wavelengths less than 0.8 ft oscillate about a constant value. These oscillations are caused by surface waves that reflect off various boundaries of the slab and by the influence of additional compression

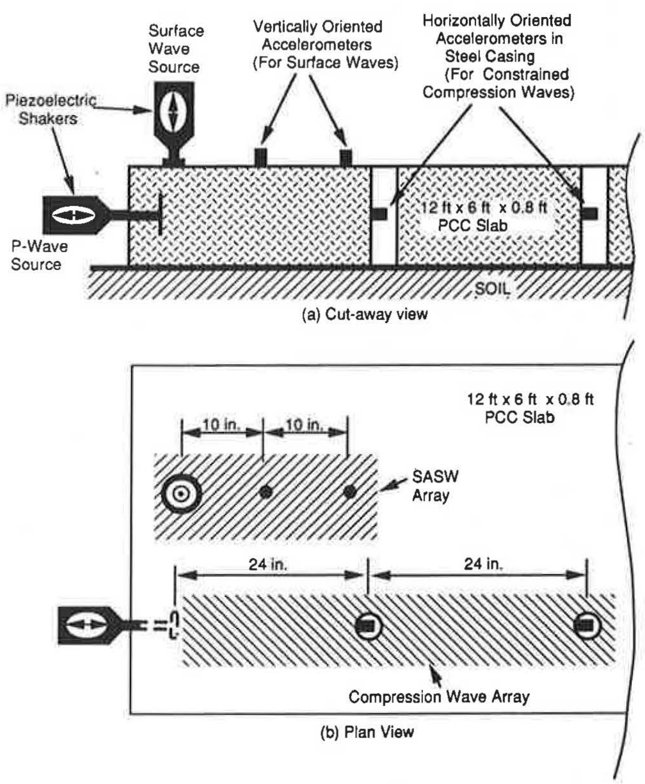

FIGURE 2 Test configuration for measuring compression and surface waves on PCC slabs.

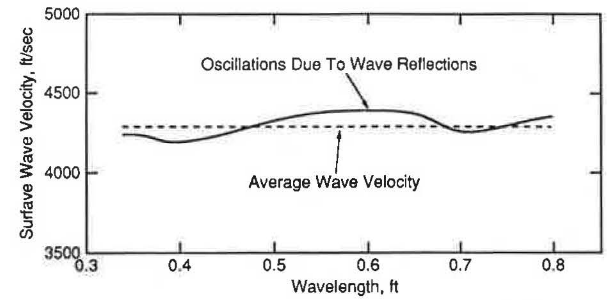

FIGURE 3 Dispersion curve for SASW testing of 0.8-ft-thick PCC slab 14.5 hr after water was added to concrete mix.

and shear waves. The average velocity of the wavelengths that are shorter than the slab thickness closely represents the surface wave velocity of a uniform layer (*5–7*).

Constrained Compression Wave Velocity Measurements

Compression wave velocities can also be measured in PCC slabs. This type of measurement requires one or more accelerometers oriented in line with the source. In theory, testing can be performed on one exposed surface. However, in the authors' experience, the tests are best performed between two parallel surfaces or between boreholes extending into the slab. If this procedure is not followed, a velocity somewhat below the constrained wave velocity will likely be measured. The constrained compression wave velocity can be measured in either a direct or an interval test. The direct test involves measuring the travel time between the source and receiver. The interval test involves measuring the travel time between two identical receivers. The interval test is preferable because some period of time (delay) will always result at the generation and reception points, which can be difficult to calibrate. In an interval test, this delay time can be assumed identical for the two receivers, and therefore can be neglected. However, the delay time must be accounted for in a direct test and becomes especially critical when the travel time is short. This is the case when the velocity of stiff materials like PCC are measured over short travel paths on the order of 1 or 2 ft. The constrained compression wave is the fastest seismic wave. Therefore, to measure V_p, with both direct and interval compression wave tests, the first wave arrival is measured.

Constrained Compression Wave Testing Procedure

The source and receiver configuration is shown in Figure 2. A horizontally oriented piezoelectric shaker was mounted on the slab edge. Two steel casings were cast in the slab. An accelerometer was positioned in each casing at the center of the slab and in line with the source. Interval measurements were then performed between the two accelerometers.

Typical Compression Wave Results

Typical wave traces from an interval test are shown in Figure 4. The constrained compression wave is the initial wave arrival

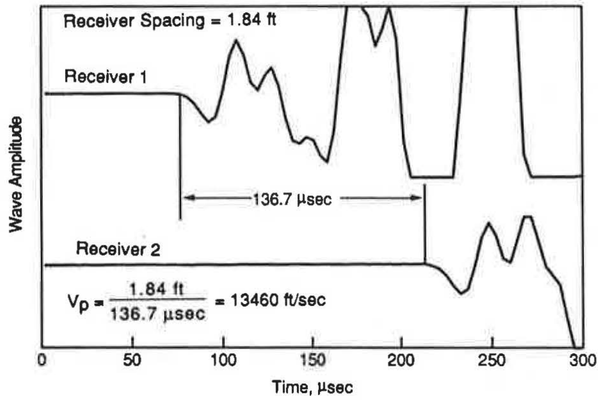

FIGURE 4 Wave traces from an interval compression wave test performed on PCC slab 24 hr after water was added to concrete mix.

on each trace. The velocity is determined simply by dividing the distance between the two receivers by the time difference between the first arrivals.

SEISMIC MEASUREMENTS ON PCC CYLINDERS

Seismic techniques can also be used to determine the properties of PCC cylinders. The SASW method has not yet been adapted for use on small specimens with reflecting boundaries close to the receivers. However, compression wave tests and resonance tests are readily employed (*8,9*).

Direct Constrained Compression Wave Measurements

Because of space and geometric limitations, it is not practical to use interval compression wave tests on small cylinders. Therefore, direct compression wave measurements are performed following ASTM C-597. This test configuration is shown in Figure 5a. Measurements are performed with the source and receiver centered on opposite ends of the cylinder. It is important that the source and receiver are centered as shown, because the *P*-wave in cylinders has a curved wave front with the leading point at the center.

Care must be exercised in direct *P*-wave measurements to determine the proper delay time in the source/receiver system. Calibrated specimens, with known elastic properties, were tested to determine the delay time. A delay time of 20.5 msec was found, which was about 20 percent of the total measured travel time in a cured, 1-ft-long cylinder. As a result, neglecting or using the wrong delay time can result in a significant error. Typical wave traces for a 1-ft cylinder are shown in Figure 6.

Resonance Tests

Another approach to determine the seismic wave velocity of small specimens is to use resonance tests (ASTM C-215). By exciting the end of a cylinder in compression or shear, waves will move up and down the cylinder, reflecting off the ends. As the waves reflect off the ends of the cylinder, some wave-

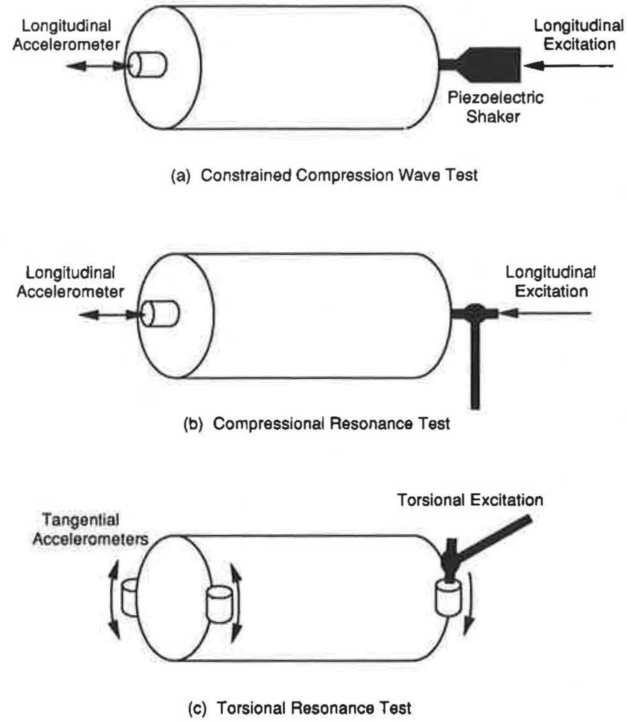

FIGURE 5 Configuration of direct compression and resonance tests on cylindrical specimens.

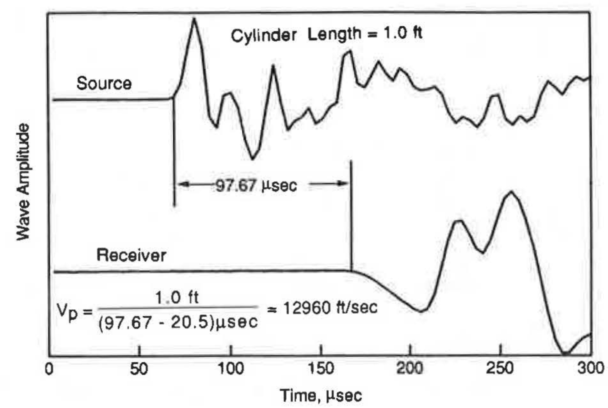

FIGURE 6 Wave traces from direct compression wave test performed on 1.0-ft-long PCC cylinder.

lengths will add destructively, and those wavelengths will die out quickly. Other wavelengths will add constructively, and they will persist so that the cylinder resonates at those wavelengths. For a cylinder with two free ends, the wavelengths at which the cylinder resonates can be calculated as follows:

$$\lambda_n = \frac{2L}{n}, \; n = 1, 2, 3, \ldots, \text{etc.} \tag{9}$$

where

λ_n = wavelength of nth mode,
L = length of cylinder, and
n = mode number.

The frequencies of the various resonant modes appear as peaks in the transfer function spectrum, which is calculated by dividing the FFT of the accelerometer output by the FFT of the input force. The wave velocity can be determined by

$$V = f_n \cdot \lambda_n \tag{10}$$

where

V = wave velocity,
f_n = frequency of nth mode, and
λ_n = corresponding wavelength of nth mode.

The peak strain in resonating cylinders can be determined using the following equation:

$$\varepsilon_p = \frac{\dot{u}}{V} \tag{11}$$

where $\dot{u}$ is peak particle velocity and V is wave velocity.

Resonant Compression Tests

By striking a cylinder parallel to its longitudinal axis, as shown in Figure 5b, and measuring numerous reflections of the wave moving up and down the cylinder, an unconstrained compression wave can be measured. This measurement represents that of a plane compression wave because the wave has traveled numerous times up and down the cylinder. Hence, the wave is not constrained against lateral deformation.

A typical transfer function spectrum from a resonant compression test of a 1.0-ft-long cylinder is shown in Figure 7a. Notice the close agreement between velocities determined by the first and second modes, which adds validity to the measurement. The authors, however, use the results from the first-mode measurement because this mode most closely corresponds to plane-wave theory.

Resonant Torsional Tests

By striking a cylinder tangentially at its circumference, a torsional shear wave can be generated. The resulting wave motion can be measured with one or more tangentially oriented accelerometers, as shown in Figure 5c. A typical transfer function spectrum from a resonant torsional test of a 1.0-ft-long cylinder is shown in Figure 7b.

Comparison of Wave Velocities on Cylinders

The same concrete cylinder was used for the direct compression test shown in Figure 6 and the resonance tests shown in Figure 7. The velocity of any two types of seismic waves is sufficient to determine all elastic properties of a homogeneous, isotropic material. For example, by combining Equations 1–6 one can calculate Poisson's ratio from any two wave velocities as follows:

$$\frac{V_p}{V_c} = \sqrt{\frac{(1 - \nu)}{(1 + \nu)\,(1 - 2\nu)}} \tag{12}$$

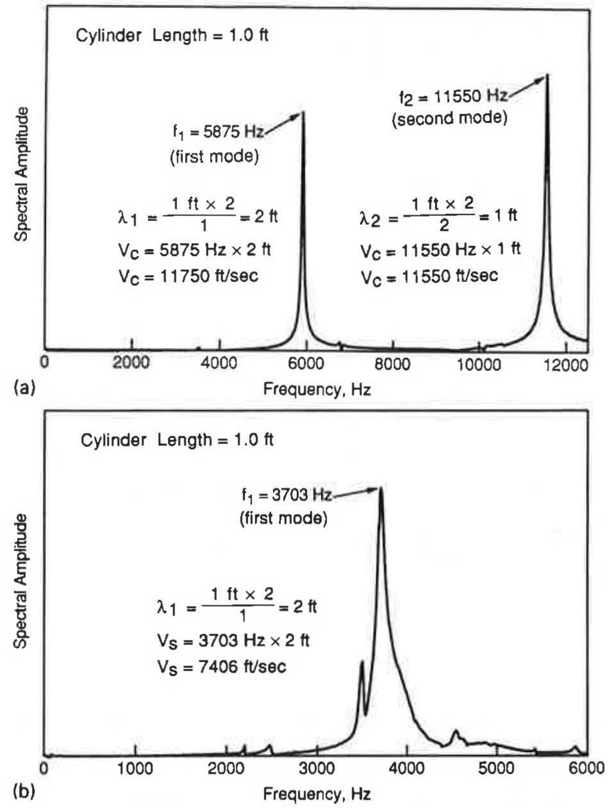

FIGURE 7 Response spectra from resonant testing of 1.0-ft-long PCC cylinder: *a*, compression test; *b*, torsional test.

$$\frac{V_c}{V_s} = \sqrt{2(1 + \nu)} \tag{13}$$

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1 - \nu)}{(1 - 2\nu)}} \tag{14}$$

By applying these equations to the velocities from Figures 6 and 7, Poisson's ratio of the cylinder can be determined as shown in Table 1. The fact that any two wave velocities give essentially the same value for Poisson's ratio indicates that the different tests are consistent and that PCC does act as a homogeneous isotropic material at the strain levels and wavelengths generated.

ELASTIC PROPERTIES OF CURING PCC SLABS

Two prototype PCC slabs were constructed at the Balcones Research Center of the University of Texas at Austin. The slabs were not reinforced and had dimensions of 6 ft × 12 ft and a thickness of 0.8 ft. The slabs were cast directly on a silty clay subgrade. The mixes had a maximum aggregate size of 1.5 in., 5 sacks of cement per cubic yard with fly ash for 25 percent of the cementitious material, and an air entraining admixture. SASW tests and interval *P*-wave tests were performed on the slabs, beginning immediately after the final surface finishing was completed. Direct constrained compression wave measurements were performed on 6- × 12-in. cyl-

TABLE 1 Poisson's Ratio of a PCC Cylinder Based on Different Combinations of Wave Velocities

Types of Seismic Wave Velocities Used in Calculation	Poisson's Ratio
V_P, V_C	0.257
V_C, V_S	0.259
V_P, V_S	0.258

inders that were prepared according to ASTM C-31 and field cured next to the slabs. Because there are no radial deformations associated with *P*-wave motion, testing results are unaffected by the confinement of a cylinder mold. Therefore, early *P*-wave tests on cylinders were performed on cylinders still in their molds with an accelerometer protruding through the bottom of the cylinder to be in direct contact with the concrete.

Variations in Seismic Wave Velocities with Time

Monitoring the seismic wave velocity of curing concrete shows how concrete increases in stiffness during curing. Because seismic techniques are effective over an extremely wide range of stiffnesses, testing can begin on freshly placed plastic concrete and can continue through curing and at subsequent times. Testing during early stages can be used to give an early indication of concrete quality. Continued seismic testing can also be used as a means of monitoring the quality of the concrete throughout its design life.

A typical plot of surface wave and constrained compression wave velocities with time is shown in Figure 8a. The error bars on the plot of the *P*-wave results indicate the maximum error due to the resolution of the recording equipment. The plot of surface wave results shows the average wave velocity of all of the surface waves measured with wavelengths less than the slab thickness, with error bars indicating plus or minus one standard deviation of those wave velocities. The curves fit through the data indicate the probable wave velocities during curing.

Variations in Elastic Moduli with Time

By applying Equations 1–7 to the seismic wave velocities, the elastic properties of curing PCC can be determined. A typical plot of E, G, and ν with time is shown in Figure 8b. It is interesting to note that the value of ν in freshly placed concrete approaches the theoretical limit of 0.5, which would indicate an incompressible fluid.

CURING PCC SLABS AND FIELD-CURED CYLINDERS

In addition to measurements on the slabs, constrained compression wave measurements were also conducted on field-cured cylinders during curing. A comparison of *P*-wave ve-

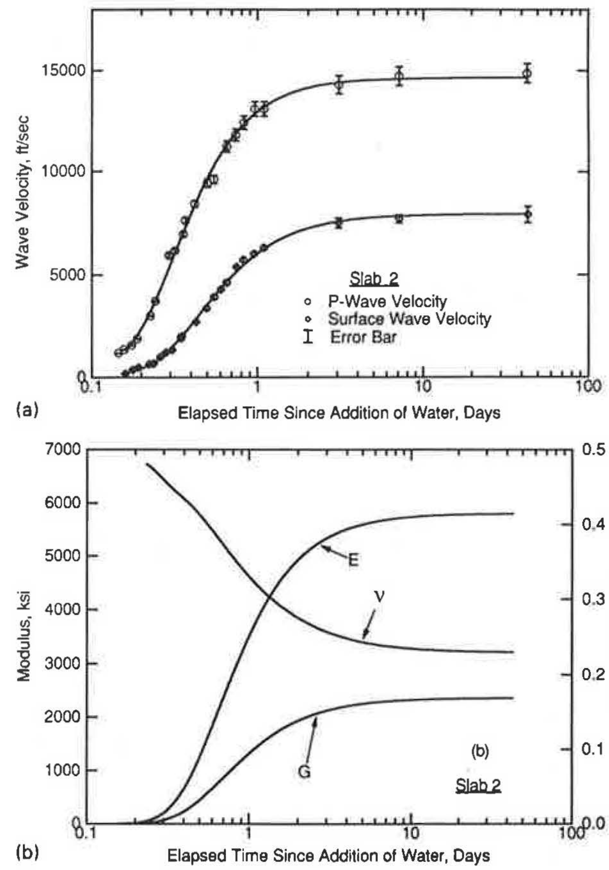

FIGURE 8 Wave velocities and resulting elastic properties from stress wave measurements on a curing PCC slab: *a*, constrained compression and surface wave velocities; *b*, typical plot of *E*, *G*, and *ν*.

locities in the slab and in the cylinders indicates how well the cylinders represent the properties of the slab. The *P*-wave velocity of two cylinders along with the *P*-wave velocities of the associated slabs are shown in Figure 9. Again the error bars on the slab measurements indicate the resolution of the recording equipment and the error bars on the cylinders measurements indicate the resolution of the recording equipment plus the uncertainty of the delay time used.

It is evident by the error bars that the quality of direct *P*-wave measurements on short cylinders decreases as the velocity increases. This occurs because the equipment delay time and the sampling interval of the equipment becomes a larger percentage of the measured travel time. However, interesting points can still be determined about how closely the field-cured cylinders represent the slab. The cylinder associated with Slab 1 was slightly stiffer than the slab in the initial stages of curing whereas the cylinder associated with Slab 2 was slightly softer. Later in the curing process, both slabs became considerably stiffer than the cylinders; this difference continued during the approximately 40 days of monitoring.

These results clearly indicate that the cylinder properties are somewhat different than the slabs. It is hypothesized that cylinder breaks at 7 and 28 days would underestimate the strengths of the slabs. Unfortunately, no cores of the slabs were taken so that no strength measurements of slab cores could be performed. The difference in properties of the slab

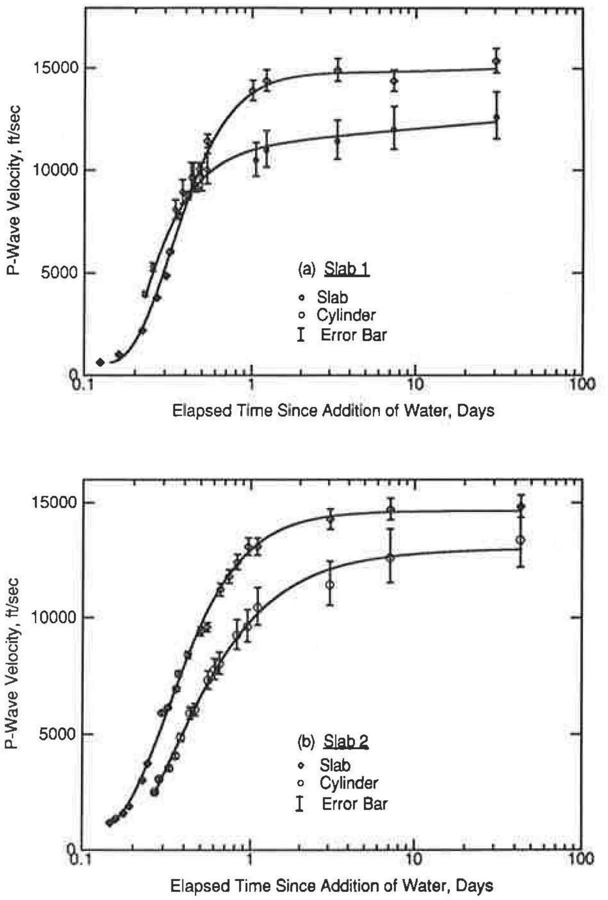

FIGURE 9 Comparison of constrained compression wave velocities measured on curing slabs and field-cured cylinders.

and the cylinders highlights the importance of using nondestructive testing techniques, such as the SASW and *P*-wave methods, on actual structures. The relative wave velocities of a structure and its cylinders might also be used to more accurately infer material properties in the structure from cylinder tests.

MODULI MEASURED STATICALLY AND DYNAMICALLY

To determine how statically and dynamically measured moduli compare, four cylinders were cast and cured for two weeks in 180°F water to ensure that all curing was complete. Low-strain unconfined compression tests were then performed on the cylinders using micro-proximeter extensometers to measure the deflection between third points of the cylinders. Additional tests were performed according to ASTM C469 up to 40 percent of the ultimate strength of the cylinders. Resonant compression wave tests were also performed to determine values of *E* dynamically. The peak strain level of the dynamic tests was determined using Equation 11. A plot of modulus versus strain level for both static and dynamic tests on one cylinder is shown in Figure 10. It is quite clear that moduli measured statically and dynamically compare closely when the tests are performed at the same strain levels.

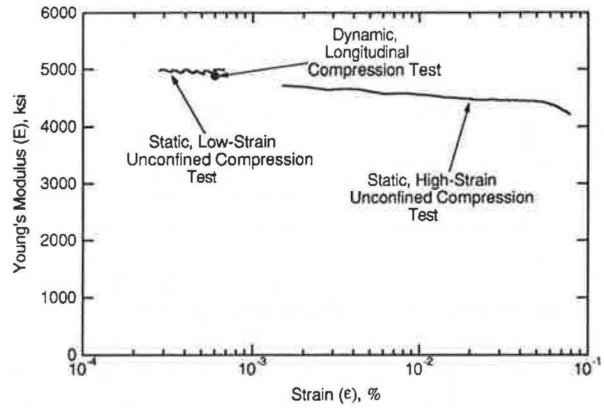

FIGURE 10 Variation of Young's modulus with strain for static and dynamic tests on PCC cylinder.

The results of static and dynamic tests on four cylinders are tabulated in Table 2. Again the modulus from the low-strain static tests agrees closely with the dynamic tests; however tests performed up to 40 percent of the ultimate strength yielded moduli about 11 percent lower. Other researchers have found the difference between moduli determined by conventional static tests and dynamic tests to be as great as 20 percent to 30 percent (*10*). Caution must be used in evaluating such results to be sure that the proper wave velocities are used in determining Young's modulus. If constrained wave velocity is used, a constrained modulus rather than Young's modulus will be determined. Constrained modulus is about 10 percent higher than Young's modulus for cured PCC (Equation 4).

CONCLUSIONS

Measurement of the velocities of seismic (stress) waves is an effective method of determining the elastic properties of PCC in structures and laboratory specimens. Because seismic techniques are nondestructive and effective over any range of stiffness, they provide a means of monitoring PCC from the earliest stages of curing and continuing throughout the life of the structure. This was demonstrated by monitoring the stiffness of PCC slabs beginning just hours after the concrete was placed until after curing was complete.

The SASW method and direct or interval compression wave methods are especially effective for slabs or large structures.

TABLE 2 Statically and Dynamically Measured Low-Strain Young's Modulus

Cylinder No.	"Static" E ($\varepsilon = 6 \times 10^{-4}\%$) ksi	"Dynamic" E ($\varepsilon \approx 6 \times 10^{-4}\%$) ksi	High Strain "Static" E* ($\varepsilon \approx 6 \times 10^{-2}\%$) ksi
1	4860	4830	4260
2	5040	4870	4410
3	4860	4880	4410
4	4900	4890	4280

* Conventional measurement at about 40% of unconfined strength

On the other hand, resonance methods are effective on small prismatic members and laboratory specimens. Direct compression wave tests may be less reliable on small specimens than resonance or interval measurements unless equipment calibration is carefully controlled. Direct or interval compression wave tests measure the velocity of the constrained compression wave, whereas resonance tests can measure the unconstrained compression wave and shear wave velocities.

All of the elastic properties of a homogeneous, isotropic material can be determined by measuring the velocity of two different seismic waves. Redundant seismic tests on PCC cylinders show a high degree of consistency between tests, and indicate that this concrete behaves as an isotropic, homogeneous material at the strain levels and wavelengths generated in this testing. Values of Young's modulus, which were determined from dynamic tests, agreed closely with values measured statically at the same stain levels as the dynamic tests. Static tests that were performed at 40 percent of the ultimate strength of the concrete yielded values of Young's moduli that were about 11 percent lower than the values determined dynamically and the values determined in low-strain static tests.

Seismic techniques provide a means of comparing the similarity of laboratory specimens with the field structures they are intended to represent. Comparisons between slabs and field-cured cylinders showed that the stiffness of the cylinders was considerably less than the slab stiffness. This demonstrates the importance of using nondestructive techniques to determine the properties of actual structures. The relative seismic wave velocities of structures and cylinders could also be used to more accurately relate cylinder properties to the properties of the structure.

ACKNOWLEDGMENTS

This work was supported by the Texas Advanced Technology Program and the Texas State Department of Highways and Public Transportation. The authors wish to express their appreciation for this support.

REFERENCES

1. G. J. Rix, J. A. Bay, and K. H. Stokoe II. Assessing In Situ Stiffness of Curing Portland Cement Concrete with Seismic Tests. In *Transportation Research Record 1284,* TRB, National Research Council, Washington, D.C., 1990, pp. 8–15.
2. M. Sansalone and N. J. Carino. Detecting Delaminations in Concrete Slabs With and Without Overlays Using the Impact-Echo Method. *ACI Materials Journal,* Vol. 86, No. 2, March–April 1989.
3. H. S. Limaye and G. J. Klein. Investigation of Concrete Arch Bridges Using The Impact-Echo Method. In *Proc., Nondestructive Evaluation of Civil Structures and Materials,* University of Colorado, 1990, pp. 221–231.
4. S. Nazarian. *In Situ Determination of Elastic Moduli of Soil Deposits and Pavement Systems by Spectral-Analysis-of-Surface-Wave Method.* Ph.D. dissertation. University of Texas at Austin, Dec. 1984.
5. J. A. Bay and K. H. Stokoe II. Field Determination of Stiffness and Integrity of PCC Slabs Using the SASW Method. In *Proc., Nondestructive Evaluation of Civil Structures and Materials,* University of Colorado, 1990, pp. 71–85.
6. J. M. Roesset, D.-W. Chang, K. H. Stokoe II, and M. Aouad. Modulus and Thickness of the Pavement Surface Layer from SASW Tests. In *Transportation Research Record 1260,* TRB, National Research Council, Washington, D.C., 1990, pp. 53–63.
7. J.-C. Sheu. *Applications and Limitations of the Spectral-Analysis-of-Surface-Waves Method.* Ph.D. dissertation. University of Texas at Austin, Dec. 1987.
8. V. M. Malhotra. *In Situ/Nondestructive Testing of Concrete.* Publication SP-82. American Concrete Institute, Detroit, Mich., 1984.
9. E. A. Whitehurst. *Evaluation of Concrete Properties from Sonic Tests.* ACI Monograph 2. American Concrete Institute, Detroit, Mich., 1966.
10. S. Mindess and J. F. Young. *Concrete.* Prentice-Hall, Inc., Englewood Cliffs, N.J., 1981.

Publication of this paper sponsored by Committee on Rigid Pavement Design.