Assessing In Situ Stiffness of Curing Portland Cement Concrete with Seismic Tests

GLENN J. RIX, JAMES A. BAY, AND KENNETH H. STOKOE II

In situ measurement of surface wave velocity using the spectral-analysis-of-surface-waves (SASW) method shows that this type of seismic measurement offers a reliable alternative to conventional penetration resistance and cylinder compression testing for determining the stiffness of portland cement concrete during curing. Both surface wave velocity and penetration resistance exhibit similar rates of increase during the initial stages of curing, suggesting that in situ measurements of wave velocity are potentially useful to assess the degree of curing that has occurred. At later stages of curing, values of Young's moduli calculated from in situ seismic tests agree well with values of Young's moduli from cylinder compression tests for similar curing histories. Advantages of nondestructive and nonintrusive seismic tests like the SASW test are that, unlike penetration resistance and cylinder compression tests, these tests (a) require no samples, (b) can be performed directly on the concrete slab to evaluate spatial variability, and (c) can be performed repeatedly at the same locations at different times during the curing process.

In situ seismic methods are among several methods available to evaluate the elastic moduli of portland cement concrete (PCC) pavements. The spectral-analysis-of-surface-waves (SASW) method, a seismic method using the analysis of dispersed surface waves in a layered system, is particularly well suited for this purpose because the test is nondestructive and nonintrusive (*1*). The SASW method is flexible in that it can be used to (a) provide a detailed modulus profile of the subgrade and base materials during all phases of construction (*2*); (b) provide a profile of the entire pavement system, including the pavement surface layer, during the subsequent life of the pavement (*1*); or (c) evaluate the modulus of only the pavement surface layer rapidly (*3*).

The SASW method has recently been applied to measuring the stiffness of curing concrete in situ. This approach was undertaken because few in situ tests are available for this purpose. The usual practice is to evaluate the degree of curing or "set" of freshly placed concrete using penetration tests on small representative samples (ASTM C 304). During later stages of curing, cylinder compression tests are used to determine the strength and stiffness properties of the concrete (ASTM C 39).

The use of the SASW method to determine the properties of curing PCC in situ is the focus of this paper. Results from tests performed on prototype and full-scale concrete slabs are presented that indicate in situ seismic measurements to be a reliable, alternative means of evaluating the stiffness of curing concrete. Although this paper describes results obtained on pavements, the approach applies equally well to structural concrete.

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OVERVIEW OF SASW METHOD

The SASW method is an engineering seismic method that uses the dispersive property of surface waves to determine the shear or Young's modulus of pavement components (surface layer, base, and subgrade) in situ. The nondestructive and nonintrusive aspects of the SASW method make it particularly useful for evaluating pavements. Brief descriptions of the dispersive behavior of surface waves in a layered system and the procedure used in SASW testing are presented in the following sections.

Surface Wave Dispersion

To understand how surface waves can be used to determine the modulus profile of a pavement, it is first necessary to understand surface wave dispersion in a layered profile. A dispersive wave is one in which the velocity of propagation varies with frequency (which is the same as saying that velocity varies with wavelength). Surface wave dispersion is caused by the distribution of particle motion with depth. As wavelength increases, particle motion extends to greater depths in the profile as illustrated in Figure 1. The velocities of surface waves are representative of the material stiffness over depths in which there is significant particle motion. For example, the particle motion of a wave that has a wavelength shorter than the thickness of the pavement surface layer is confined to this layer (Figure 1b). Therefore, the wave velocity is influenced by the stiffness of the surface layer and not by the lower layers. The velocity of a wave with a wavelength of several feet is influenced by the properties of the surface layer, base, and subgrade because a significant portion of the particle motion is in these layers (Figure 1c). Thus, by measuring the velocity of surface waves over a wide range of wavelengths, it is possible to assess the stiffness of the layers over a range of depths. However, if one desires only to determine the stiffness of the PCC layer, only wavelengths shorter than the thickness of this surface layer need to be generated and measured.

The objective in SASW testing is to make field measurements of surface wave dispersion (i.e., measurements of sur-

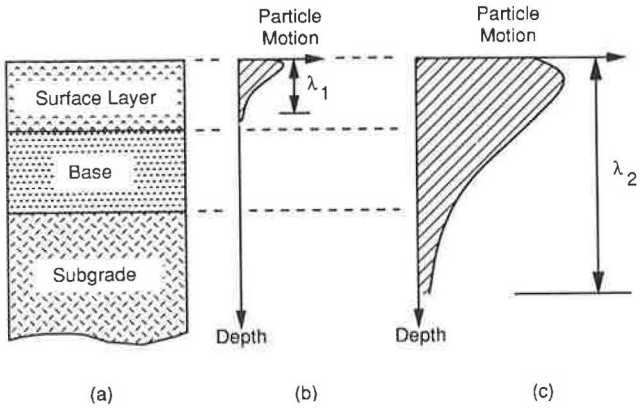

FIGURE 1 Approximate distribution of vertical particle motion with depth for two surface waves of different wavelengths: (a) material profile; (b) shorter wavelength, λ_1; and (c) longer wavelength, λ_2.

face wave velocity, V_R, at various wavelengths, L_R) and then to determine the shear wave velocities of the layers in the profile. These velocities can, in turn, be used to calculate values of shear and Young's moduli using simple relationships from the theory of elasticity as follows:

$$V_s = CV_R \quad (1)$$

$$G = \rho V_{s2} \quad (2)$$

$$E = 2G(1 + \nu) \quad (3)$$

where

C = function of Poisson's ratio (as given in Table 1),
G = shear modulus,
E = Young's modulus,
V_s = shear wave velocity,
ν = Poisson's ratio, and
ρ = mass density.

SASW Test Procedure

The procedure used to perform an SASW test can be divided into three steps: (a) field testing, (b) dispersion calculations, and (c) inversion. Brief descriptions of each of these steps are now presented.

TABLE 1 VARIATION IN THE RELATIVE VALUES OF SEISMIC WAVE VELOCITIES WITH POISSON'S RATIO

Poisson's Ratio ν	V_S/V_R	V_P/V_R	V_P/V_C
0	1.144	1.618	1.000
0.05	1.132	1.644	1.003
0.10	1.120	1.680	1.011
0.15	1.108	1.727	1.028
0.20	1.098	1.793	1.054
0.25	1.088	1.884	1.095
0.30	1.078	2.017	1.160
0.35	1.070	2.226	1.267
0.40	1.061	2.600	1.464
0.45	1.054	3.495	1.948
0.50	1.047	∞	∞

*V_R = surface (Rayleigh type) wave velocity, V_S = shear wave velocity, V_P = constrained compression wave velocity, and V_C = unconstrained compression wave velocity

Equipment and Field Setup

The general configuration of source, receivers, and recording equipment used in SASW testing in shown in Figure 2. The most common types of sources used on curing concrete slabs have been small hammers lightly striking the surface or piezoelectric transducers placed on the surface. Both of these sources create a transient wave containing a broad range of frequencies. Recently, the use of random input motion with piezoelectric transducers has also been used effectively (*4,5*).

Selection of receivers is based on the range of frequencies that will be used. For profiling curing concrete, piezoelectric accelerometers work well. Testing the hardened PCC layer requires the use of high frequencies (up to 50 kHz) to generate short wavelengths so that the stiffness of the surface layer can be accurately evaluated. Piezoelectric accelerometers, which are coupled rigidly to the pavement with mounting studs, are typically used in this range of frequencies. When the concrete is first placed, surface wave velocities are low (only a few hundred feet per second), and frequencies as low as 500 Hz are used. Fortunately, piezoelectric accelerometers also perform well in this frequency range.

A dual-channel fast Fourier transform (FFT) analyzer is used to record and analyze surface wave motion at the two receivers. This type of analyzer permits real-time field evaluations of the data. Finally, a microcomputer is used to transfer data from the analyzer and to perform dispersion calculations, which are described subsequently.

The spacing between receivers ($D = d_2 - d_1$ in Figure 2) varies according to the range of wavelengths used. In a "general purpose" test in which the goal is to determine the stiffness of all the components of the pavement system using a wide range of wavelengths, several receiver spacings from 0.25 to 16 ft (0.08 to 4.9 m) are used in a single test. For "special purpose" tests in which the goal is to evaluate the stiffness of a single layer (in this case the curing concrete), a limited range of wavelengths is used, and it is possible to employ only one source-receiver setup. For the tests performed in this study, the receiver-to-receiver spacing ranged from about 5 to 12 in. (0.13 to 0.3 m), depending on the thickness of the PCC layer.

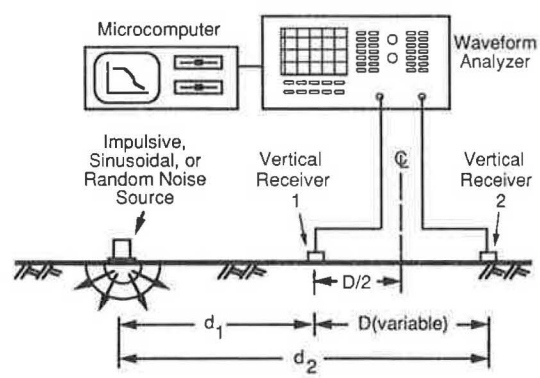

FIGURE 2 General configuration of equipment used in field testing.

Dispersion Calculations

For a given source-receiver spacing, the time histories recorded by the two receivers, $x(t)$ and $y(t)$, are transformed to the frequency domain resulting in the linear spectra of the two signals. The cross-power spectrum of the signals, the coherence function, and the auto-power spectrum of each signal are then calculated using the linear spectra. All calculations are performed in real time by the FFT analyzer.

The key data are the phase of the cross-power spectrum and the coherence function. The coherence function reflects the signal-to-noise ratio and should be nearly equal to one in the range of acceptable data. The phase of the cross-power spectrum, denoted $\theta_{yx}(f)$, is used to calculate the time delay between receivers as a function of frequency from which surface wave velocity and wavelength are then determined.

Two sets of measurements showing the phase of the cross-power spectrum and the coherence function are presented in Figure 3. The first set of measurements, performed soon after placement of the concrete, is shown in Figure 3a, and the second set of measurements, made after the concrete was quite stiff, are presented in Figure 3b. Both sets of measurements were made at the same location on the slab.

Dispersion curves are determined from these measurements as follows. The time delay between receivers is

$$t(f) = \theta_{yx}(f)/2\pi f \tag{4}$$

where the phase angle is in radians and the frequency, f, is in cycles/second. The surface wave phase velocity, V_R, is

$$V_R(f) = (d_2 - d_1)/t(f) \tag{5}$$

and the corresponding wavelength of the surface wave is

$$L_R = V_R/f \tag{6}$$

These calculations yield a dispersion curve (V_R versus L_R) for the receiver spacing.

Examples of dispersion curves measured on two curing concrete slabs are presented in Figure 4. The individual dispersion curves show results from measurements made at var-

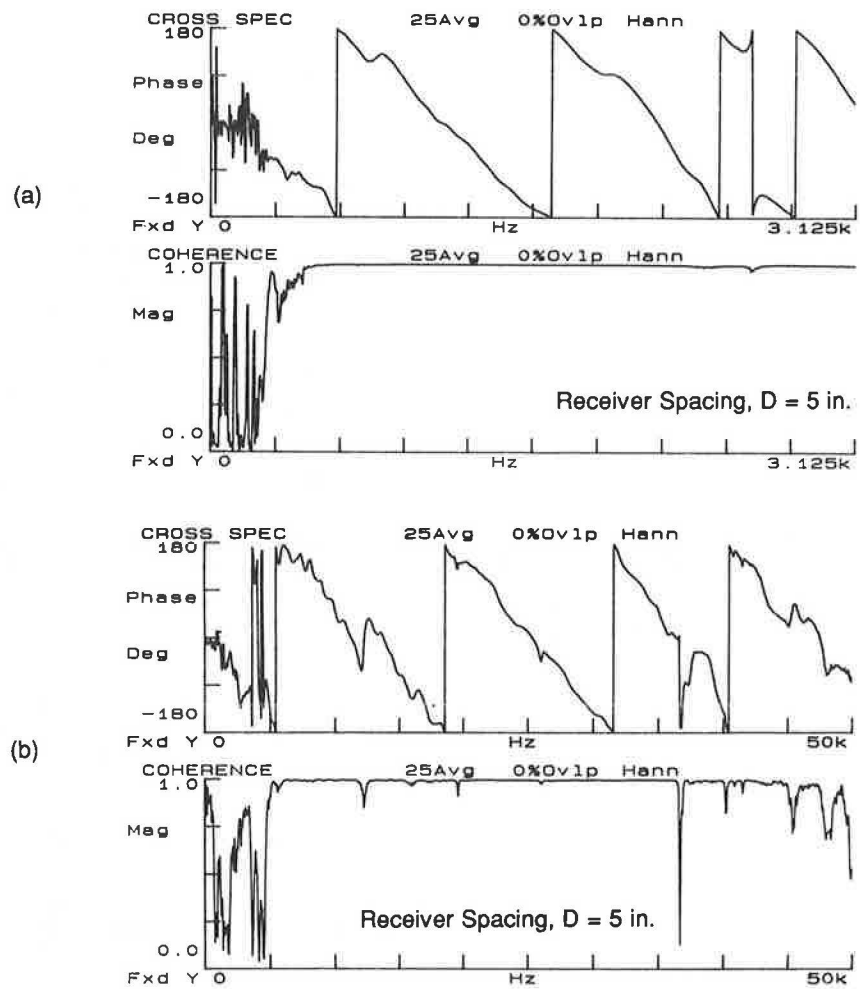

FIGURE 3 Spectral functions measured at Balcones Research Center: (a) measurements performed 255 min after addition of water to cement aggregate mixture and (b) measurements performed 750 min after addition of water to cement aggregate mixture.

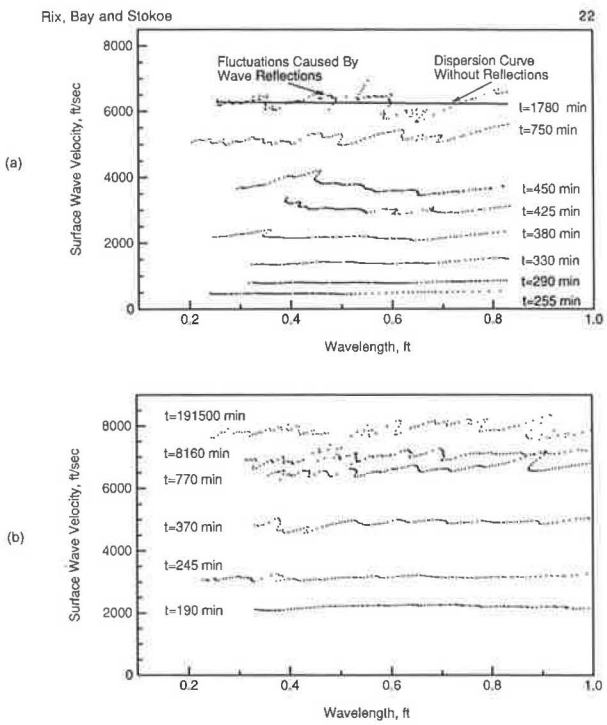

FIGURE 4 Dispersion curves measured on curing concrete slabs at various times after addition of water to the mix: (a) prototype slab at BRC and (b) continuously reinforced PCC pavement section in El Paso, Texas.

ious times. (The measurements shown in Figure 3 were used in constructing two of the dispersion curves shown in Figure 4a.) The most important aspect in Figure 4 is that the individual dispersion curves are nearly constant for values of wavelength less than the slab thickness, indicating that only the curing concrete was sampled and that the stiffness was uniform at any given time. Fluctuations observed in the dispersion curves at large elapsed times result from reflections of shear, compression, and surface waves from the lateral and vertical boundaries of the slab (*5–7*) as discussed in the following.

The dispersion curves in Figure 4 are appropriate for assessing the stiffness of the concrete surface layer using Equations 1–3. If it is necessary to determine the moduli of the base and subgrade in addition to the surface layer, individual dispersion curves from larger receiver spacings would be combined with the curves shown in Figure 4 to form a composite dispersion curve.

Inversion

Inversion is the process of calculating the shear wave velocity (or modulus) profile using the experimental dispersion data. In the inversion process, a theoretical dispersion curve is calculated for an assumed velocity profile and is then compared with the experimental dispersion curve. The assumed velocity profile contains a sufficiently large number of sublayers to define the variation of pavement properties with depth accurately. The theoretical curve is calculated using a modified Haskell-Thomson matrix algorithm (*8–10*). The shear wave velocities and thicknesses of the sublayers in the assumed profile are adjusted by trial and error until a satisfactory match is obtained; the final profile is assumed to represent the actual pavement profile.

If only the stiffness of the pavement surface layer is of concern, it is possible to use a greatly simplified form of inversion. The basis of the simplified method is that, for wavelengths that are less than the thickness of the slab (see Figure 1b), the slab will appear to be a uniform half space if the properties are nearly constant (*3,7,10*). This point is illustrated in Figure 4a in which the phase velocities are nearly constant for measurement times less than about 400 min for wavelengths shorter than the slab thickness. At larger measurement times, the fluctuations in the dispersion curve are caused by wave reflections (*3,5–7*) and a "best-fit" straight line placed through the data most nearly represents the dispersion curve without reflections. For a uniform half space, the shear wave velocity is approximately 1.1 times the surface wave phase velocity. Thus, for short wavelengths, it is possible to estimate the shear wave velocity of the concrete by multiplying the observed surface wave phase velocity by 1.1. For the dispersion curves shown in Figure 4a, this simple calculation yields shear wave velocities ranging from about 550 ft/sec (168 m/sec) at t = 255 min to about 7,000 ft/sec (2,135 m/sec) at t = 1,780 min. The resulting Young's moduli are then 28 ksi (193 MPa) and 3,830 ksi (26,400 MPa), respectively.

It must be emphasized that this simple method of determining shear wave velocity is only applicable to the surface layer. A crude inversion procedure such as this can lead to large errors if it is used to determine the shear wave velocities and elastic moduli of layers other than the surface layer. Also, if a reasonable estimate of Poisson's ratio can be made, the value of C in Equation 1 can be estimated more closely using Table 1 (from the value of 1.1 assumed), and a more accurate value of V_s can be estimated.

CASE HISTORIES

Several sites have been used to evaluate the use of the SASW method for the purpose of determining the stiffness of curing PCC. One of the sites is the Hornsby Bend (HB) test facility, located in Austin, Texas. At this site, a prototype concrete slab was cast on a silty clay subgrade. The slab was unreinforced and had dimensions of 8 by 12 ft (2.4 by 3.7 m) with a nominal thickness of 10 in. (0.25 m). Class S concrete with Type I cement and a maximum aggregate size of 0.75 in. (0.019 m) was used for the slab. The mix was specified to be 6 sacks/yd^3 and 5 gal/sack, with a design 28-day compressive strength of 3,600 psi (24.8 MPa). The slump of the concrete was 1.5 in. (0.04 m). Finishing consisted of vibrating, screeding, and floating. In addition to the slab, twenty-five 6- by 12-in. (0.15- by 0.3-m) cylinders and two penetration resistance samples were cast to perform additional comparative tests.

The second site was a prototype PCC slab cast at the Balcones Research Center (BRC) of the University of Texas. The slab was unreinforced and had dimensions of 6 by 12 ft (1.8 by 3.6 m) and a nominal thickness of 10 in. (0.25 m). The slab was cast on a silty clay subgrade. The mix was specified to have a maximum aggregate size of 1.5 in. (0.038 m),

5 sacks of Type I cement per cubic yard with 25 percent fly ash, a retarder, and an air-entraining admixture.

The third site was a section of Interstate 10 in El Paso, Texas. The tests were performed on a continuously reinforced PCC pavement that was being constructed to widen the expressway. The pavement system consisted of 12 in. (0.3 m) of PCC pavement over 13 in. (0.33 m) of hot-mix asphalt concrete (HMAC) over a silty sand fill. The PCC mix was specified to have a maximum aggregate size of 1.75 in. (0.044 m), 5 sacks/yd^3 with 25 percent fly ash and 5 percent entrained air. Unlike the first two sites, the pavement section in El Paso was continuously reinforced. The presence of the reinforcing steel does not influence the oberved surface wave phase velocity because the diameter of the steel is much smaller (by about 4 times) than the wavelengths used for the measurements.

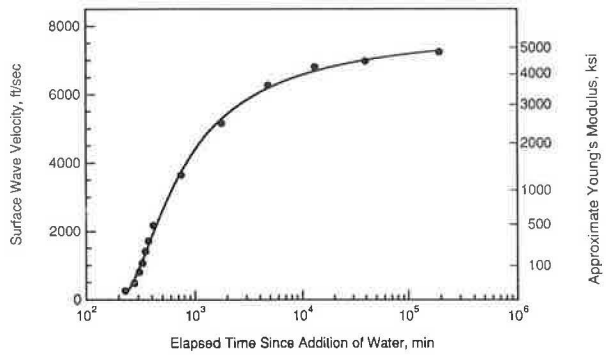

FIGURE 6 Variation in surface wave velocity of PCC layer during curing at Balcones Research Center.

Variation of Surface Wave Velocity with Time

The fundamental idea behind the use of seismic tests to determine properties of curing PCC is that changes observed in the surface wave velocity or shear wave velocity (and, hence, modulus) during curing are direct indicators of the curing process. To investigate this hypothesis, a series of surface wave tests was performed on the concrete slabs at each location beginning immediately after the slabs were poured and finished, and continuing throughout the time that curing was taking place. Surface wave measurements were conducted using the procedure described previously. Because only the wave velocity of the curing concrete (the surface layer) was of interest, it was possible to use the simplified form of inversion described earlier rather than the more rigorous inversion method.

Examples of the dispersion curves measured on the concrete slab are presented in Figure 4. The dispersion curves were measured at various times after water had been added to the cement-aggregate mixture at the batch plant. The increase in surface wave velocity with time for each of the three sites is shown in Figures 5–7. Clearly, the wave velocity increases very rapidly initially and then begins to level off. Intuitively, this behavior mimics the expected curing process.

An independent series of compression wave measurements was also performed at the BRC slab. As expected, the curing process is also clearly reflected by the increase in compression wave velocity. However, in the authors' experience, the SASW measurements are easier to perform. Values of Poisson's ratio during curing are shown in Figure 8 on the basis of surface and compression wave velocities. The uncured PCC initially is more "fluid-like" and the measured values of Poisson's ratio approach 0.5, which is the expected value for an incompressible fluid. Later, when the PCC has more fully cured, Poisson's ratio is approximately 0.22, which is typical of hardened concrete.

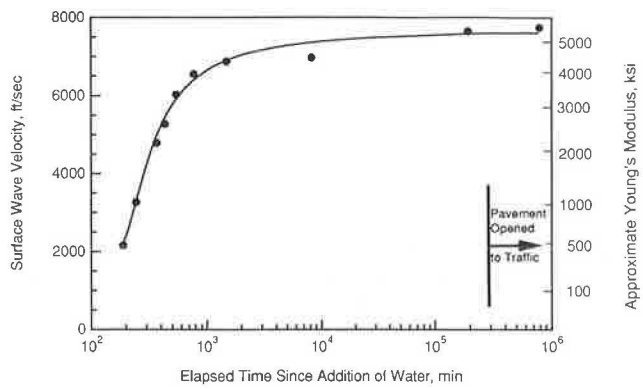

FIGURE 7 Variation in surface wave velocity of PCC layer during curing for pavement at El Paso, Texas.

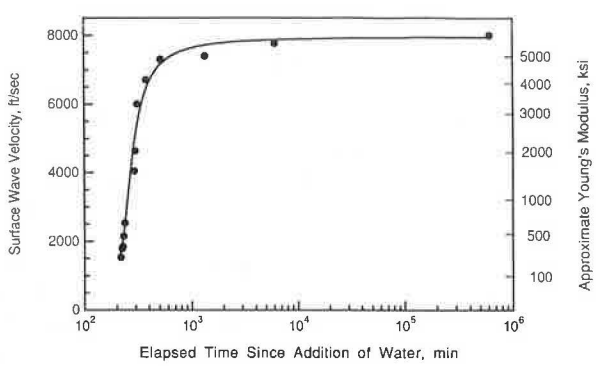

FIGURE 5 Variation in shear wave velocity of PCC layer during curing for Hornsby Bend slab.

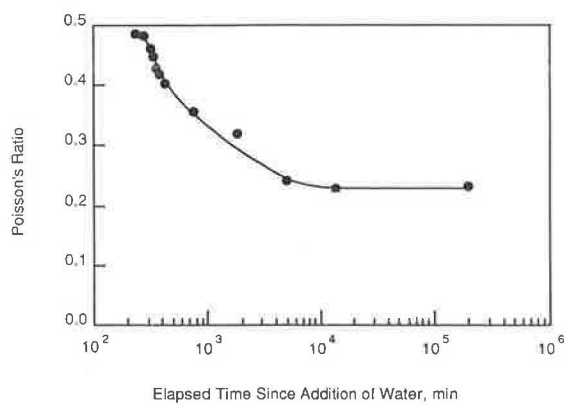

FIGURE 8 Variation in Poisson's ratio of the PCC layer during curing at Balcones Research Center.

Comparison of Seismic Wave Velocity with Penetration Resistance

The penetration resistance of fresh concrete is a common test used to determine to what extent that concrete has cured or, in other words, its set. These tests require a sample of concrete that has been passed through a No. 4 sieve to remove the large aggregate. A cylindrical penetrometer is forced into the sample and the load necessary to cause 1 in. (0.025 m) of penetration is recorded. The load is divided by the cross-sectional area of the penetrometer to calculate the penetration resistance. Initial set is defined as the time at which the penetration resistance is equal to 500 psi (3.45 MPa). Final set occurs when the penetration resistance has increased to 4,000 psi (27.6 MPa). A complete description of the test procedure is given elsewhere (ASTM C 403).

To evaluate the use of surface wave velocity measurements as an alternative to penetration resistance tests for determining set, results of the two tests are plotted together in Figures 9 and 10 for the two sites where both types of tests were performed. At the HB site, initial set occurred 180 min after the addition of water. The time of final set, 300 min, was extrapolated from the final two readings because the sample could not be penetrated following the 3,600-psi (24.8-MPa) reading at 280 min. At the BRC site, initial set occurred 355 min after the addition of water and final set occurred at 386 min. In both cases, penetration resistance and surface wave velocity exhibit similar, rapid rates of increase during the initial stages of curing, indicating that in situ measurements of wave velocity are potentially useful for determining the degree of curing that has occurred in new concrete. Furthermore, seismic tests performed using the SASW test procedure allow the degree of set to be evaluated without the need to cast special samples for this purpose. It is therefore possible to perform more tests on the slab itself, rather than a limited number of tests on samples that have been altered by sieving and may be curing at different rates because they have been separated from the slab.

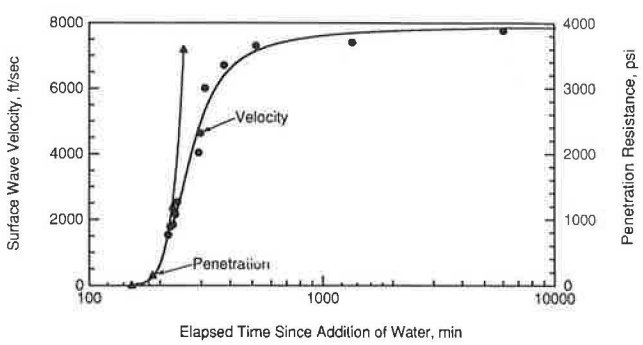

FIGURE 9 Comparison of surface wave velocity and penetration resistance measured during curing of the concrete slab at Hornsby Bend.

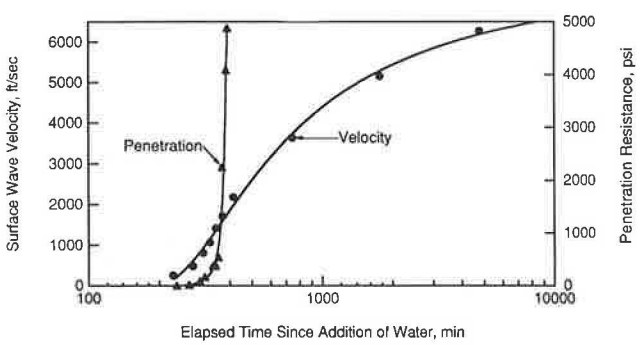

FIGURE 10 Comparison of surface wave velocity and penetration resistance measured during curing of the concrete slab at Balcones Research Center.

Comparison of Seismic Moduli with Secant Moduli from Cylinder Tests

Another use of seismic measurements is to determine the in situ Young's modulus of new concrete without relying on test cylinders. To examine the feasibility of this approach, standard cylinder compression tests (ASTM C 39) were performed on 6- by 12-in. (0.15- by 0.3-m) samples in order to compare Young's moduli from these tests with Young's moduli from seismic tests at the HB slab. Compression tests were performed 1, 3, 7, and 28 days after the slab was cast. The procedure used in this series of tests is as follows: (a) several compression tests were performed to determine the average compressive strength of the cylinders and (b) Young's modulus tests were then conducted on other cylinders using the compressive strength to choose the proper stress level at which to measure the secant Young's modulus. The average compressive strength of the concrete cylinders is given in Table 2. The values in Table 2 are substantially greater than the specified compressive strength, 3.6 ksi, for the slab at HB.

Values of Young's modulus were calculated at 40 percent of the average compressive strength. Examples of typical stress-strain curves used to determine Young's modulus are shown for tests performed at 1 day and 3 days (Figure 11). For each test the strain corresponding to a stress equal to 40 percent of the compressive strength was determined, and this point was then used to calculate the secant Young's modulus from the origin. Young's moduli determined using this method along with the associated strain levels are summarized in Table 3.

Values of Young's moduli were calculated from the results of surface wave velocity measurements using Equations 1–3. An assumed unit weight of 145 lb/ft^3 was used to calculate the shear modulus from the measured values of wave velocity. To convert shear modulus to Young's modulus using Equation 3, values of Poisson's ratio were measured in situ at various

TABLE 2 AVERAGE VALUES OF COMPRESSIVE STRENGTH AT 1, 3, 7, AND 28 DAYS FOR PCC SAMPLES FROM HORNSBY BEND

Elapsed Time (days)	Number of Tests	Range in Compressive Strengths (ksi)	Average Compressive Strength (ksi)
1	2	4.89-4.93	4.91
3	3	5.20-5.74	5.44
7	2	5.69-5.74	5.71
28	4	6.30-6.69	6.47

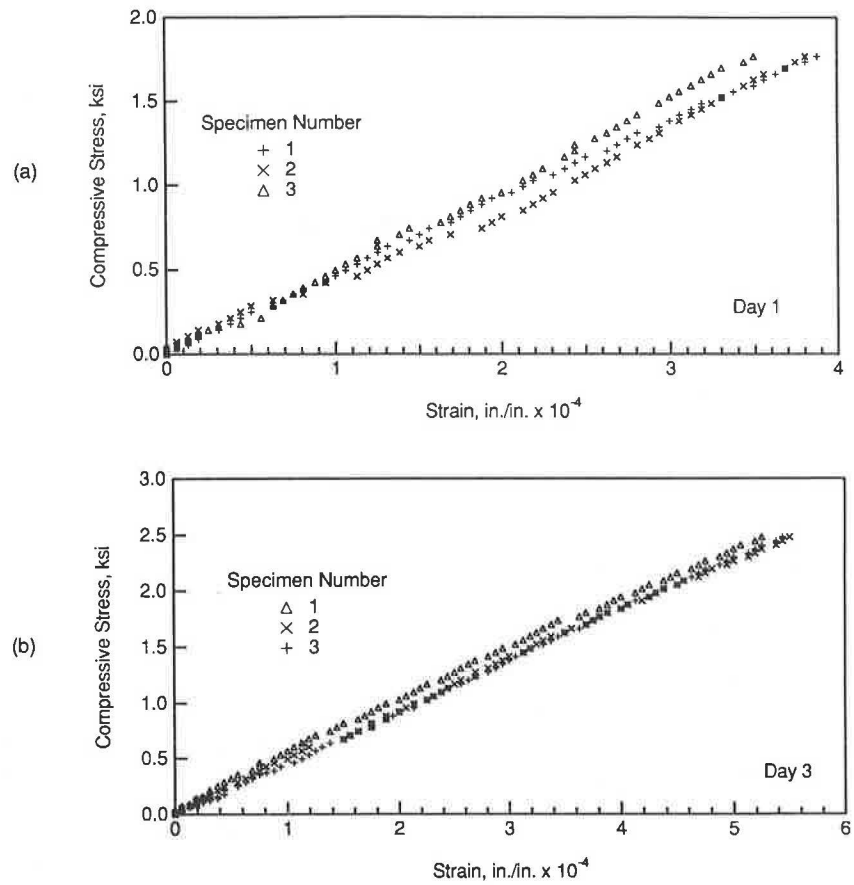

FIGURE 11 Stress-strain curves for Young's modulus tests performed at different times after casting of the slab at Hornsby Bend: (a) three tests performed 1 day after casting and (b) three tests performed 3 days after casting.

TABLE 3 VALUES OF YOUNG'S MODULUS DETERMINED USING CYLINDER TESTS FOR PCC SAMPLES FROM HORNSBY BEND

Elapsed Time (days)	Number of Tests	Average Young's Modulus (1000 ksi)	Average Value of Strain (in./in. x 10^{-3})
1	3	4.75	0.38
3	3	4.63	0.47
7	2	4.79	0.48
28	3	4.86	0.54

TABLE 4 COMPARISON OF YOUNG'S MODULI FOR SEISMIC TESTS AND THOSE DETERMINED USING CONVENTIONAL CYLINDER TESTS FROM HORNSBY BEND

Elapsed Time (days)	Modulus from Seismic Tests (1000 ksi)	Modulus from Cylinder Tests (1000 ksi)
1	5.04	4.75
3	5.30	4.63
7	5.60*	4.79
28	5.63*	4.86

* Interpolated from the data in Fig. 5

times during the curing of the concrete by also measuring compression wave velocities. Values of Poisson's ratio presented in Figure 8 for several elapsed times are typical of these values. At times greater than 1 day, the unit weight and Poisson's ratio usually vary within a relatively small range and any errors in assumed values do not have a significant impact on the resulting values of Young's modulus.

Moduli from cylinder compression tests and from in situ seismic measurements at 1 and 3 days are compared in Table 4. Because seismic measurements were not performed at exactly 7 and 28 days, values of moduli at these times were interpolated from Figure 5. Because the trend is well defined in Figure 5, it is believed that there is little error introduced by the interpolation. The two different methods used to determine the moduli compare favorably, as shown in Table 4. One possible reason why the seismic moduli average about 13 percent more than the cylinder moduli is that the concrete in the slab cured at a different rate than did the concrete in the cylinders. If this hypothesis is true, it highlights the advantage of using in situ seismic methods to evaluate curing concrete. Another possible reason that the seismic moduli are slightly greater is that seismic measurements determine the initial tangent modulus at very small values of strain, less than 0.01×10^{-3}, whereas cylinder compression tests determine

the secant modulus at strain levels ranging from 0.38×10^{-3} to 0.54×10^{-3}. Both of these reasons probably contributed to the differences.

As in the case of measurements of set, seismic measurements appear to offer the potential of reliable in situ determinations of the Young's modulus of new concrete without the use of samples. Additional studies that include comparisons for a large number of tests are needed to confirm the results of this feasibility study.

IMPLEMENTATION

The equipment and procedures currently used to make seismic measurements on curing concrete are oriented toward research studies. It is believed, however, that the equipment and simplified procedures used in such studies lend themselves to the development of an automated system for surface wave measurements. With an automated system, measurements of the in situ moduli and estimates of the set could be obtained easily and rapidly by highway agencies or contractors.

CONCLUSIONS

In situ seismic measurements using the SASW method offer a potentially useful alternative to conventional penetration resistance and cylinder compression tests for determining the characteristics of PCC during curing. The SASW method is a nondestructive and nonintrusive method based on the analysis of dispersed surface waves in a layered half space. In addition to the ability to determine the modulus profile of the entire pavement system with the SASW method, it can also be used to evaluate the pavement surface layer rapidly, which makes it particularly useful for measurements on curing concrete pavements.

Several series of tests performed on two research slabs indicated that the surface wave velocity of concrete and the penetration resistance both increase at similar rates during the initial stages of curing. On the basis of these results, it appears that in situ measurements of surface wave velocity can be useful in assessing the degree of curing in fresh concrete. Values of Young's moduli from in situ seismic tests also agree well with the values of Young's moduli measured using cylinder compression tests, indicating the potential usefulness of SASW tests in this area. However, one must be careful when making these comparisons because dissimilar curing processes and strain levels can cause differences between Young's moduli measured by in situ seismic and cylinder compression tests.

One distinct advantage of nondestructive, nonintrusive seismic measurements over conventional penetration resistance and cylinder compression testing is that the need to cast samples can be avoided and that a larger number of tests can be performed on the concrete slab itself.

ACKNOWLEDMENTS

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

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Publication of this paper sponsored by Committee on Mechanical Properties of Concrete.