Determination of Layer Moduli in Pavement Systems by Nondestructive Testing

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Two methods of nondestructive testing of pavements (deflection basin measurement and surface wave propagation measurement) are compared. The assumptions associated with each are examined. Ideally, both methods should provide the same values of modulus for each layer in the pavement system if appropriate mathematical models are used and accurate field data are obtained. Falling Weight Deflectometer and Spectral Analysis of Surface Wave (SASW) tests were performed at five sites on a variety of different pavement systems. Results are compared and discussed. Because of the high contrast in modulus (or wave propagation velocity) between the pavement and the base, accurate values of modulus for granular base materials were difficult to obtain for both methods. Moduli for base materials obtained by the SASW method appeared to be more reasonable.

Nondestructive tests on pavements are having a significant impact on structural design and evaluation of pavement systems and on pavement management. To determine the modulus profile of the pavement system is the principal objective of those tests. Two types of nondestructive tests are studied in this paper: deflection basin measurement and surface wave propagation measurement.

The deflection basin measurements may be made by static loading (Benkelmann Beam), by steady state vibratory loading, or by impact loading. For this study, a Falling Weight Deflectometer (FWD) was used. The FWD is a device that applies an impact loading to the surface of the pavement. Sensors at the location of loading and at fixed radii are used to measure the resulting deflection (i.e., the deflection basin). Much background information on this method has been given in the literature (*1–3*). Special computer programs are used to calculate a modulus profile for the pavement system from the peak values of measured input force and resulting deflection basin.

The surface wave propagation measurements also rely on an impact to the surface. Waves are propagated, and the phase velocity of the surface wave is measured for a range of frequencies that span the audio range. The method was developed for geophysics in the 1950s by Haskell (*4*) and Thompson (*5*), Knopoff (*6*), and Jones and Thrower (*7*). Nazarian and Stokoe (*8*) pioneered the use of those techniques for pavement systems in the early 1980s, and it was they who named the technique Spectral Analysis of Surface Waves (SASW). Additional development of the method has occurred since then, and summaries are available (*9–11*).

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Rather than having an input force and deflection basin, SASW produces values of surface wave phase velocities versus wavelength (i.e., a dispersion curve). A computer program is used to establish a velocity profile with depth from the dispersion curve. From this velocity profile, moduli and thicknesses of layers are determined.

This paper describes a real pavement system and then outlines the basic assumptions associated with the models typically used by both the deflection basin method and the surface wave propagation velocity method. Some modifications to the SASW method for acquiring data in the field are given. Procedures used for converting acquired data to the final result also are discussed for both methods.

Field data were obtained at five Kentucky sites. Each site had a different pavement system, ranging from simple Portland cement concrete (PCC) over crushed stone to an asphaltic concrete overlay of a broken and seated Portland cement concrete pavement. Data are reduced and compared. Differences between the two methods (FWD and SASW) are discussed with consideration given to the nature of the test and assumptions made in the mathematical models.

PAVEMENT MODELS

Real Pavement System

A real pavement system is indicated schematically in the left side of Figure 1. The pavement itself is likely to have imperfections, such as cracks, ruts, and worn areas. The base, whether it be stabilized or unstabilized, may differ from one location to another in, for instance, thickness, density, and moisture content. The subgrade, especially in cut and nonengineered fill areas, may be extremely variable in composition, and its properties will vary with, for instance, location, depth, and moisture content. Finally, bedrock may be at shallow depths. When there is bedrock, the depth may vary significantly from one location to another, and its presence will significantly affect the performance of the pavement system.

Idealized Model for the Deflection Basin Method

Most deflection basin data currently are obtained by use of an FWD, which applies an impact to the pavement surface. The peak load is measured, and, by use of velocity-measuring

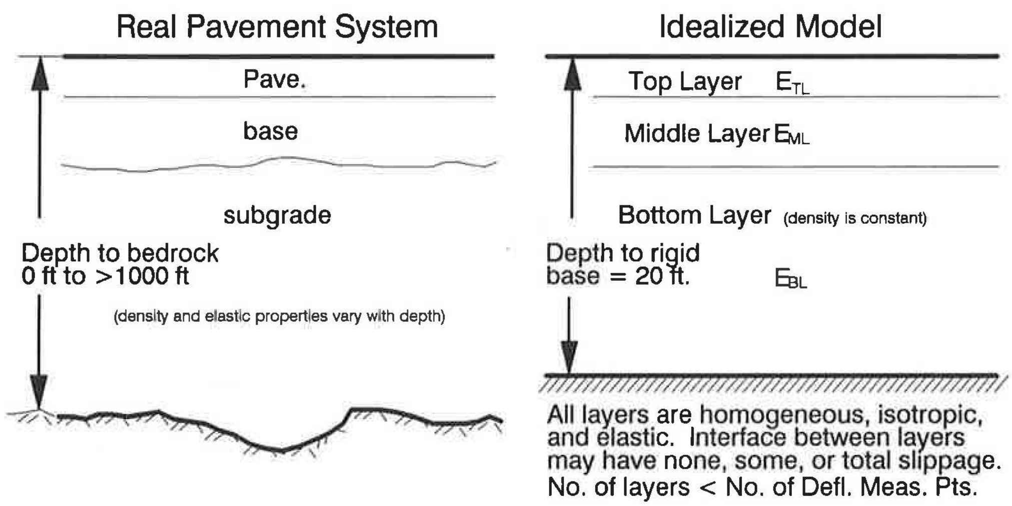

FIGURE 1 Real pavement system and idealized model for deflection basin measurement method.

transducers, the peak deflections are determined at various radii from the center of load application. A deflection basin composed of peak deflections never really occurs during the test because there is a phase lag between transducers. Anderson and Drnevich (*12*) have shown that phase lag effects are significant, even for "rigid" pavements, where the phase lag should be smaller than for flexible pavements. Nearly all models used for deflection basin analysis are placed on a static deflection basin and completely ignore wave propagation effects. Besides phase lag, wave propagation could significantly influence the measured peak deflections when bedrock or very stiff layers exist at shallow depths. Other assumptions associated with typical models used for deflection basin analyses are indicated on the right side of Figure 1. Usually, only three to five layers and their thicknesses are assumed. Because the depth to bedrock is not known, it is frequently assumed the depth is about 20 ft. Each layer is assumed to be continuous and of uniform thickness in all horizontal directions and homogeneous, elastic, and isotropic. Values of density and Poisson's ratio also must be assumed. Even in the layer representing the subgrade, the engineering properties of the layer are assumed to be constant. In the real pavement system, the engineering properties are likely to be highly variable in this layer.

Back Calculation of Moduli from Deflection Basin Measurements

The procedure followed by most computer programs is to start with some "seed" values of moduli for each of the assumed system of layers. The peak applied dynamic load is represented by a static load on the surface, and a static deflection basin is calculated for the model. A comparison is made of the calculated deflection basin with the measured deflection basin. Differences are used to guide adjustment of moduli in the various layers, and another set of deflections is calculated for the model. The comparison-adjustment-recalculation procedure is carried out until the calculated static deflections are within an acceptable tolerance of the measured peak dynamic deflections. The result is a set of moduli for the layers of the model that gives a calculated static deflection basin close to the measured dynamic deflection basin. Many users of this method mistakenly identify those moduli as inherent properties of the real pavement system. They are not. They are the properties of the model used to simulate the real pavement system.

Idealized Model for Surface Wave Propagation Velocity Method

Similar to the model for the deflection basin method, the model for this method assumes each layer to be continuous and of uniform thickness in all horizontal directions and homogeneous, elastic, and isotropic as indicated on the right side of Figure 2. Values of density and Poisson's ratio also must be assumed for a given layer. However, there may be many layers, and the thicknesses of each do not need to be known. The model is a dynamic one in that inertia of the materials and wave propagation (phase lags, reflections, and refractions) are accounted for.

Back Calculation for the Surface Wave Propagation Velocity Method

Like the deflection basin method, an impact is applied to the surface. However, its magnitude is much smaller. Vibration transducers are placed at fixed radii from the point of impact, and the phase lag of the surface wave is measured as a function of frequency by use of a spectrum analyzer, as indicated in Figure 3. With the horizontal distance between transducers and the phase lag, it is possible to calculate the phase velocity for each frequency by use of Equation 1.

$$C = \frac{2\pi f x}{\theta} \tag{1}$$

where

C = phase velocity,
f = frequency,
x = horizontal distance between transducers, and
θ = phase lag.

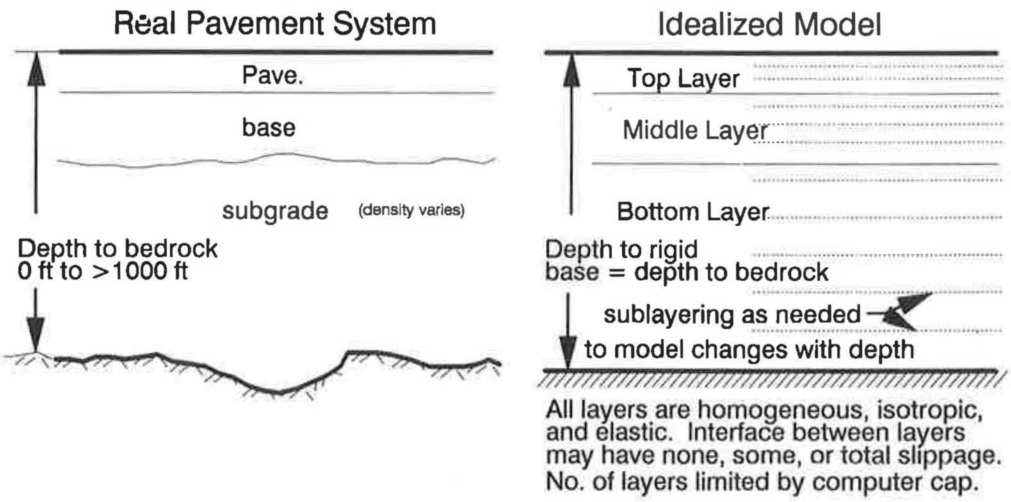

FIGURE 2 Real pavement system and idealized model for spectral analysis of surface waves method.

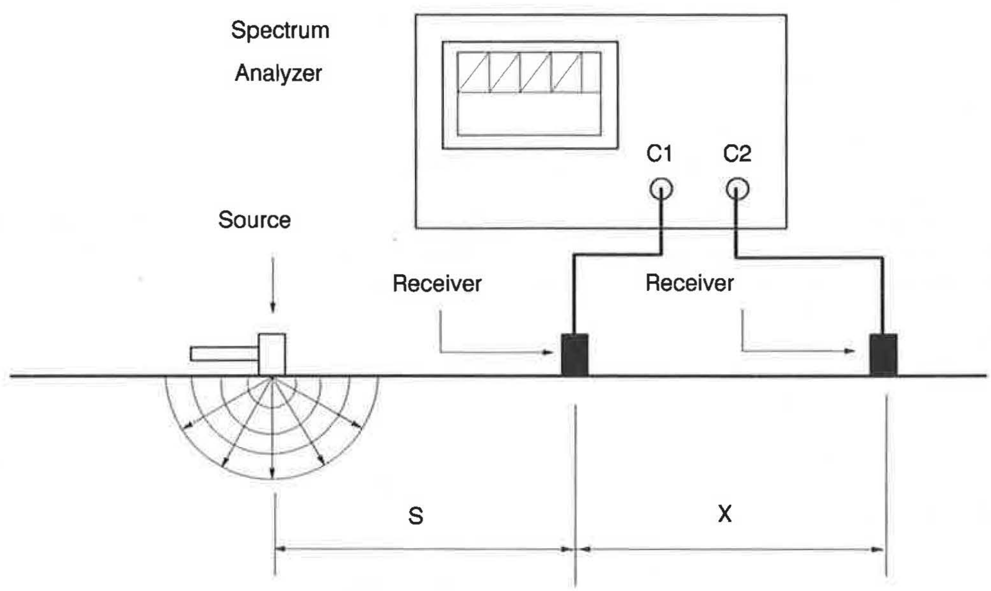

FIGURE 3 Typical configuration of SASW tests.

For each frequency, wavelength also is calculated from Equation two.

$$\lambda = C/f \qquad (2)$$

where λ equals wavelength.

A plot of phase velocity versus wavelength is called a dispersion curve, and it can be thought of as being analogous to the deflection basin. The back-calculation process for this method requires, for the dynamic model, a selection of layering and moduli such that the calculated dispersion curve is within tolerable limits of the measured dispersion curve. The process can be simple for dispersion curves that have well-defined and simple shapes (*13,14*) but usually requires an extensive computer program (*8,11*). Similar to the deflection basin method, the result of this method is a set of moduli for the layers of the model that gives a calculated dispersion curve close to the curve calculated from measured phase lags.

TESTING PROGRAM

Description of Test Sites

Five sites have been tested in this study, and they include one rigid and four flexible pavements. Pavement type and thickness for each test area are indicated in Table 1.

The rigid pavement of Site 1 exhibited some cracks. However, all tests were performed in the area of intact PCC.

TABLE 1 PAVEMENT TYPE, THICKNESS, AND MODULUS

Test Site	Location	Pavement Thickness and Material	Modulus of Elasticity (psi)	
			SASW	FWD
1	KTRB* Garage	6" PCC	5,070,000	4,000,000
		4" Crushed Stone	35,200	10,000
		36" Compacted Subgrade	55,000	16,000
		Limestone Subgrade	740,000	35,000
2	KTRB Compound	2.5" AC	690,000	650,000
		6" Crushed Stone	30,300	10,000
		36" Compacted Subgrade	51,900	75,000
		Limestone Subgrade	901,000	175,000
3	Louisa Bypass, Kentucky	13" AC	655,000	250,000
		4" Crushed Stone	24,200	18,000
		4" DGA	16,600	25,000
		12" Crushed Shale	42,600	57,000
		Shale Subgrade	103,500	130,000
4	I-64, Near Grayson Exit 172	12" AC	764,000	750,000
		18" DGA	14,550	35,000
		Shale Subgrade	66,250	65,000
5	Mountain Parkway, Kentucky	8" AC	890,000	650,000
		8" PCC (Broken)	1,980,000	200,000
		5" DGA	25,900	6,000
		Stiff Clay	45,700	45,000

* Kentucky Transportation Research Building

Asphalt in Site 2 was very thin when compared with that in other sites. The rest of the sites were in good performance conditions. In fact, Site 3 was a newly constructed bypass, and Site 5 consisted of new asphalt overlaying broken and seated concrete.

Description of Test Equipment and Configurations

Falling Weight Deflectometer Tests

The device used for deflection basin measurements was a JILS 20 Falling Weight Deflectometer, manufactured by Foundation Mechanics, Inc., El Segundo, Calif. The device has a capability of applying a peak dynamic load to pavements of up to 24,000 lb with a nominal duration of 25 msec and simultaneously measures the force applied to the pavement and the velocities at seven locations from the applied load (as indicated in Figure 4). The results of the peak force applied to the pavement and the peak displacements at each of the seven sensor locations were measured and stored by using a microcomputer-based data acquisition system. The seven sensors were located at distances of 2.95, 12, 24, 36, 48, 60, and 72 in. from the center of load application.

SASW Tests

The major components of the SASW testing system are a source, receivers, and a recording device. Several impact sources were used, such as hammers (4-oz, 8-oz ball peen, 16-oz claw, and 8-lb sledge hammers). Two types of vertical transducers (accelerometers and geophones) were used as receivers. The recording device was a Fourier spectrum analyzer, a digital oscilloscope that has a microcomputer built into it so it can perform operations directly in either time or frequency domains.

Mostly, two types of source-to-receiver geometries are used in the SASW method: Common Receiver Midpoint (CRMP) and Common Source (CS). To reduce the testing time, a third type of geometry, the Common Near Receiver (CNR), can be used, and it was used for this study.

Common Receiver Midpoint Geometry Proposed by Nazarian (*9*), an imaginary center line is selected between the receivers (Figure 5a). Two receivers are moved away from the imaginary center line at equal distances, and the source is also moved such that the distance between the source and near receiver (S) is equal to the distance between the two receivers (X) (i.e., $S/X = 1$).

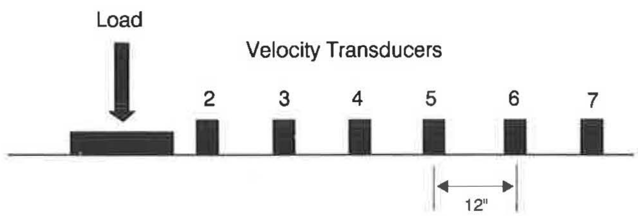

FIGURE 4 Typical FWD configuration.

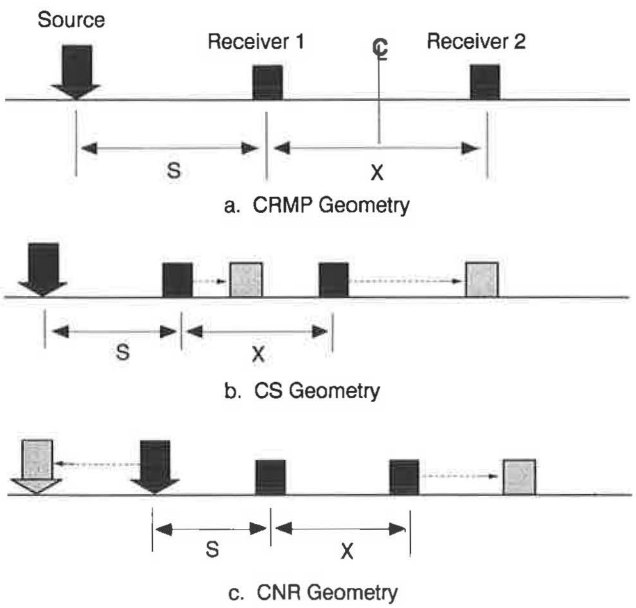

FIGURE 5 Source to receiver geometry for SASW.

Common Source Geometry The source is fixed at one location, and two receivers are moved during testing such that $S/X = 1$ (Figure 5b). It was observed from a series of SASW tests conducted at asphalt concrete (AC) pavement sites (*10*) that the scatter within all collected data was similar for each geometry. CS geometry is preferable to the CRMP geometry with regard to the testing time.

Common Near Receiver Geometry In both CS and CRMP geometries, considerable time is spent fixing receivers on the pavement surface. To save testing time, the receivers were fixed to the surface, and the source and the other receiver were moved (Figure 5c). A test was conducted at a concrete pavement site to study the effect of the three geometries on experimental dispersion curves. All the geometries gave almost identical average dispersion curves. Because CNR geometry reduces testing time considerably, this geometry was used in this study. The spacings between the receivers for all tests reported were 0.5, 1, 2, 4, and 8 ft while maintaining $S/X = 1$.

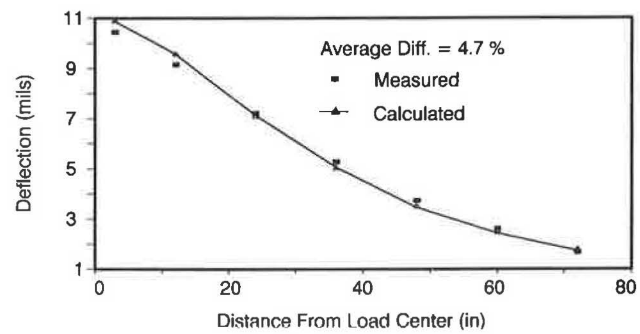

FIGURE 6 Deflection basins, Site 1.

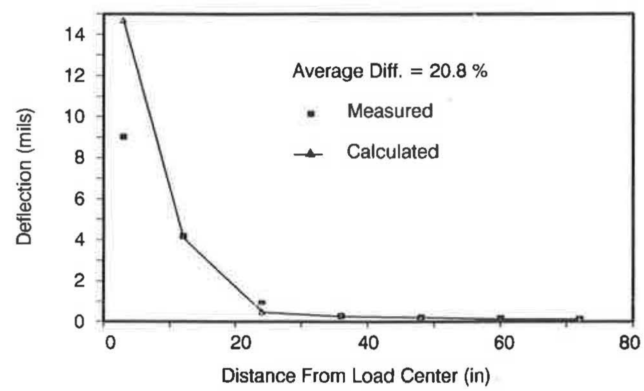

FIGURE 7 Deflection basins, Site 2.

TEST RESULTS

Falling Weight Deflectometer Tests

Back calculation of layer moduli was performed and was based on an iterative procedure that used a layered-theory program, ELSYM5 (*15*). Deflections were calculated from the initial input values of moduli obtained from SASW tests. At first, iterations were made to evaluate the subgrade modulus by matching the deflections corresponding to sensor locations 6 and 7. The modulus was accepted if the difference between measured and calculated deflections was around 5 percent. The next step was to adjust the modulus of the surface layer. The moduli of intermediate layers were determined by subsequent iterations. The calculated deflection basins for each site are presented with those measured in Figures 6–10. Average percent difference also is shown in those figures. The values are within 5 percent in almost all cases except Site 2. The reason for the 20.8 percent difference for Site 2 can be attributed to the behavior of the very thin asphalt layer, which was only 2.5 in. thick, and because of some fine cracks. Moduli calculated from FWD deflection basins are given in Table 1.

In performing the FWD data reduction, a new back-calculation program, WESDEF (*16*), was tried, even though the conditions at the sites were not well suited for those kinds of programs. In general, WESDEF gave values of moduli for pavement and subgrade similar to those obtained by ELSYM5,

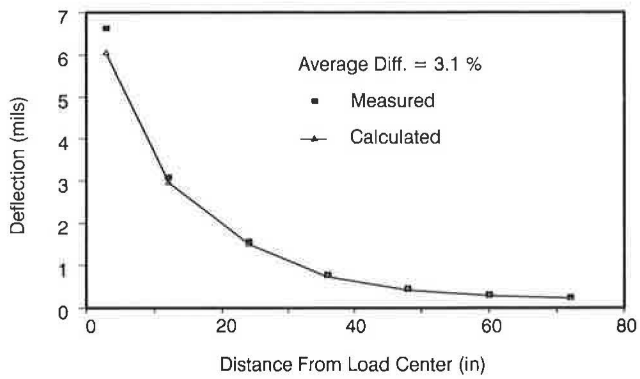

FIGURE 8 Deflection basins, Site 3.

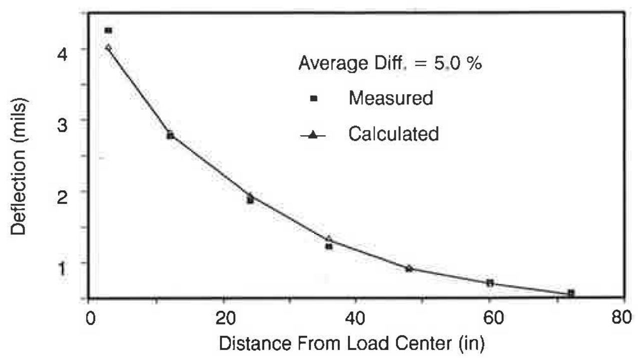

FIGURE 9 Deflection basins, Site 4.

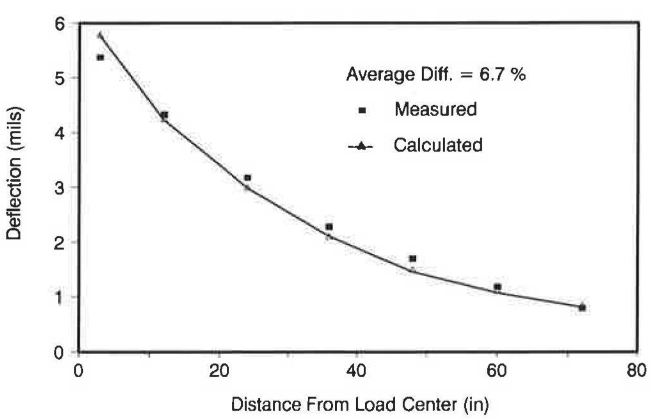

FIGURE 10 Deflection basins, Site 5.

which used manual iterations. However, WESDEF generally gave the built-in lower bound value for the base layers at all sites except for Site 4. The difficulty arose from having a low modulus layer (base) or layers (base and sub-base) between high modulus layers (pavement and stiff subgrade). The deflection basin and the procedures used by the program generally provide inaccurate values for the low modulus material, especially in the base because of the large modulus contrast.

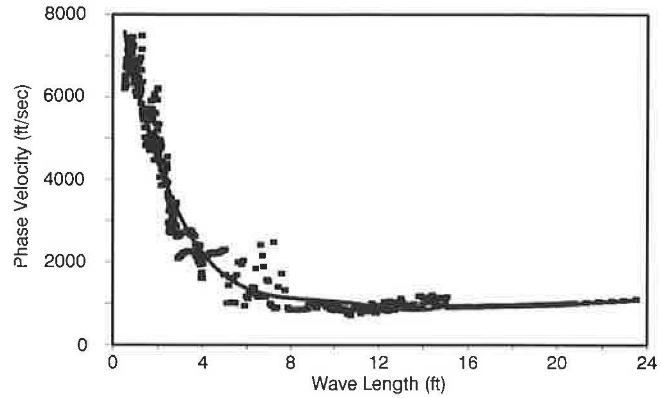

FIGURE 11 Experimental dispersion curve, Site 1.

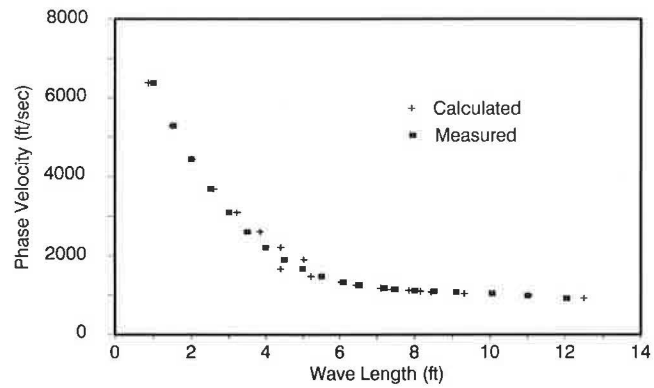

FIGURE 12 Dispersion curves, Site 1.

Automatic back-calculation programs should be used with caution for sites not well suited.

SASW Tests

SASW tests were performed at the same sites. After field testing, data were transferred from the Dynamic Signal Analyzer to a personal computer. The average experimental dispersion curve was obtained for each site by using the program SASWOPR (*17*). A typical experimentally determined dispersion curve is presented in Figure 11. There are 300 to 500 data points on this curve. For small and for large wavelengths the curve is relatively well defined, but, for intermediate wavelengths, the data show more scatter. This scatter is due to the mixing of various modes caused by the high-velocity contrast between the pavement and the base.

For back calculation, the program KENSALPS was then used to determine shear wave velocity profile. To execute the program, suitable data points were selected from the average dispersion curve (such as those in Figure 11) to provide a simplified measured dispersion curve. Those were used in the back-calculation process and are presented, along with the calculated dispersion curves, in Figures 12–16.

Thicknesses of individual layers for each pavement site were known from coring. Constant values of Poisson's ratio (0.33)

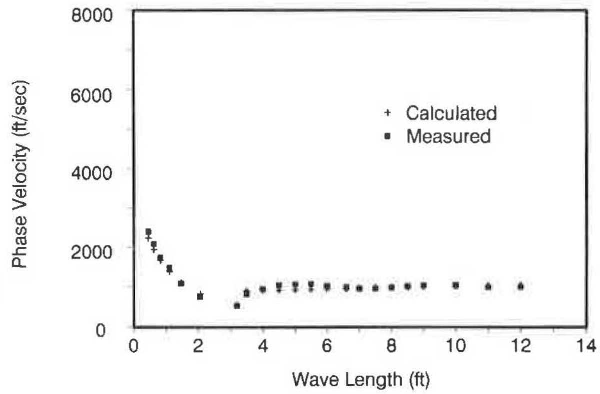

FIGURE 13 Dispersion curves, Site 2.

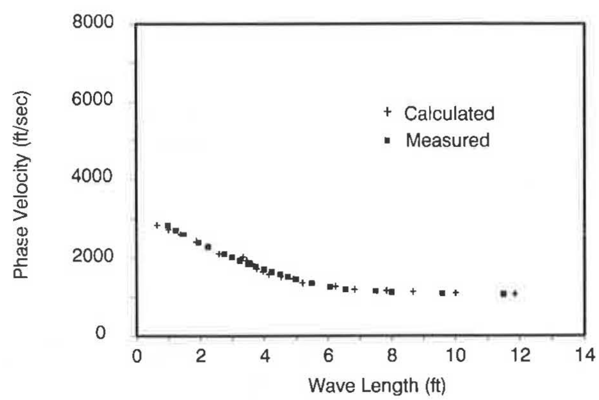

FIGURE 14 Dispersion curves, Site 3.

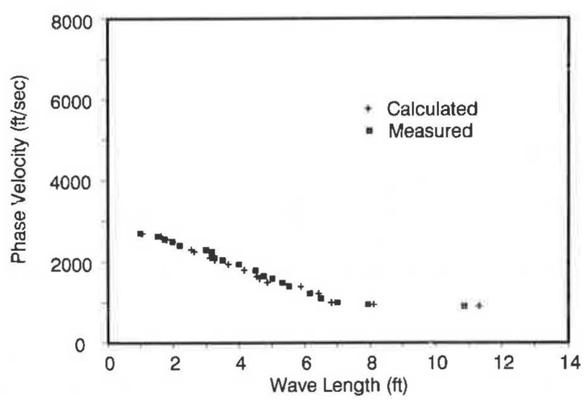

FIGURE 15 Dispersion curves, Site 4.

and unit weight (125 pcf) were assumed for crushed stone, dense-graded aggregate (DGA), and subgrade materials. For PCC and AC, corresponding values of those parameters were 0.15, 145 pcf and 0.25, 135 pcf, respectively. The initial shear wave velocities for surface layer and the half-space were determined by using the procedure developed by Vidale (*14*). Layer velocities were assumed for base and sub-base materials for initializing the optimization process. The calculated dispersion

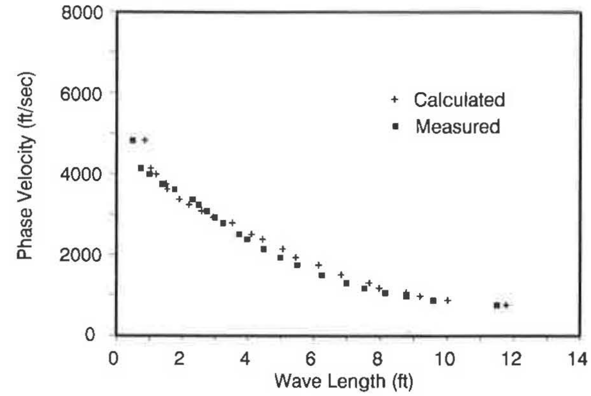

FIGURE 16 Dispersion curves, Site 5.

TABLE 2 SHEAR WAVE VELOCITIES FROM SASW TESTS

Material	Shear Wave Velocity (ft/s)				
	Site 1	Site 2	Site 3	Site 4	Site 5
PCC	8400	——	——	——	——
AC	——	3080	3000	4340	3500
CS	700	650	580	——	——
DGA	——	——	480	420	600
Broken Shale	——	——	770	——	——
Subgrade	875	850	1200	960	850

—— Data not applicable

curves also are shown in Figures 12–16. From those figures it can be gathered that the agreement between theoretical and experimental curves is quite good for all wavelengths. The thickness of the surface layer was only 2.5 in. in the case of Site 2. This thin layer produced vibration similar to that of a flexural-type of a plate, as indicated by Jones (*13*). A plate vibration solution was used in this case to match the dispersion curve for wavelengths between 0 and 3 ft. However, a layered solution was used for wavelengths greater than 3 ft. The back-calculated shear wave velocity profiles for the five sites are given in Table 2.

COMPARISON AND DISCUSSION OF RESULTS

Sites 1 and 2 were very close to each other, and the depth to limestone bedrock was on the order of 4 ft. The SASW results for the crushed stone, compacted subgrade, and limestone compared well between the two sites, whereas the results for the FWD test did not. At Site 1, the stiff concrete pavement layer appeared to mask the stiffness of the underlying bedrock. At Site 2, where a thin AC pavement existed, the values of modulus for bedrock were much higher. Recall that the average error in the back calculation for the FWD was large (20.8 percent) and that this error was primarily due to the two data points near the source. For the SASW test, a different dynamic model had to be used to fit the dispersion curve for the close-in data. Thus, at least two separate modes of deformation existed for this site (one for near-source behavior and one for far-field behavior) and that a single model for the back calculation by the FWD method was not adequate. At both sites, the values of moduli for the crushed stone base by the SASW method were much higher than those obtained by the FWD method. Values of moduli for the compacted subgrade by FWD at those two sites differed significantly.

Site 3 is similar to Sites 1 and 2 in that a bedrock subgrade is at shallow depths. However, at Site 3, the AC pavement is much thicker than at Site 2, 13 in. versus 2.5 in. This site also proved difficult for the FWD test because the moduli for the pavement and crushed stone base layers are significantly smaller than expected for a newly constructed pavement.

At Site 4 the base consists of an 18-in.-thick layer of DGA. Values of modulus for this layer by the SASW were similar to the values for DGA at Site 3, but corresponding values from FWD were significantly higher.

Site 5 is an interesting one in that a PCC pavement had been broken and seated prior to being overlain by an 8-in. thick AC pavement. The sizes of the broken pieces were on the order of 12 to 24 in. Data in the SASW test for the overlay and broken concrete pavement require close transducer spacings (typically 6 in. to 24 in.) and are obtained by using accelerometers that have good response at high frequencies. The likelihood of having the wave propagation measured on an intact piece of broken pavement is great, and, hence, a large value of modulus is obtained. The FWD test takes the overall action into account by measuring the deflections and, hence, gave a much smaller value for the moduli for the broken pavement. It is important to recall the assumptions associated with both methods, that is, that each layer is uniform and continuous in all directions. Clearly, this assumption is invalid when broken and seated pavements are tested. (Obviously, this assumption also is invalid when badly cracked pavements of any kind are tested.)

Besides Table 1, moduli obtained by both methods are compared in Figure 17, where the FWD values are plotted versus the SASW values. The diagonal curve represents equal values by both methods. Many of the data points lie on or near the curve. In general, the SASW method gives the larger values.

CONCLUSIONS

The assumptions associated with the models used for back calculation of layer moduli need to be kept in mind as the data for pavement systems are analyzed. Both the deflection basin method and the surface wave propagation velocity method give similar values of layer moduli when the assumptions associated with the models are satisfied. The model associated with the surface wave propagation velocity method is more flexible in that many more layers may be handled and the existence of a very stiff subgrade (bedrock) at shallow depths does not pose any problem. The back-calculation schemes associated with the deflection basin method for well-conditioned sites generally are strong in calculating subgrade moduli and pavement moduli but are weak in calculating base moduli because of the high modulus contrast that typically

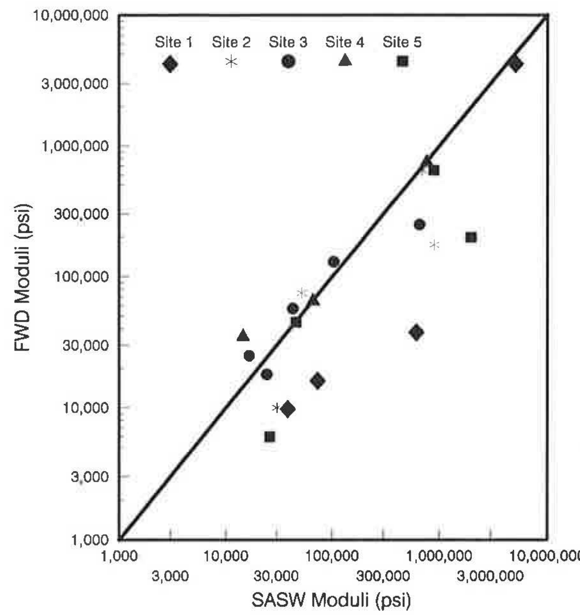

FIGURE 17 Comparison of moduli from FWD and SASW tests.

exists. Finally, the moduli calculated are for the layers in the idealized model used in the back-calculation scheme and are not inherent engineering properties for the layers in the real pavement system.

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