Automated Pavement Subsurface Profiling Using Radar: Case Studies of Four Experimental Field Sites

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Accurate knowledge of pavement layer thicknesses and material properties is important to pavement management. Often this information is unknown or records are inaccurate, inaccessible, or out of date. The traditional method for obtaining pavement layer data is core sampling, which is time-consuming, labor-intensive, and intrusive to traffic; it also provides information only at the core location. The capability of ground-penetrating radar to provide accurate and continuous pavement layer thickness and property information has been investigated. Four Texas Strategic Highway Research Program asphalt pavement test sites were tested with radar. The accuracy of the radar predictions for asphalt thickness was within ±0.32 in. using the radar data alone, and within ±0.11 in. when one calibration core was used per site. The accuracy of the radar predictions for base thickness was within ±0.99 in. The nominal layer thickness ranged from 1 to 8 in. of asphalt and 6 to 10 in. of base. The actual asphalt layer thickness was shown to vary by more than 20 percent from values assumed from prior records and earlier cores. These variations have been shown to lead to errors of up to 95 percent in base moduli back-calculated from falling weight deflectometer data. The radar results were shown to be repeatable over time and independent of survey speed at up to 40 mph. The radar data were analyzed automatically using software that operated directly on the raw radar waveforms and produced numerical layer thickness profiles. The resulting predictions were correlated with direct in situ measurements and core and material samples. The results of this project have shown that ground-penetrating radar data, when properly analyzed, can provide highly accurate measurements of pavement layer properties for project- and network-level applications.

Pavement layer thickness data are important in many aspects of pavement engineering and management. Mechanistic models for pavement performance, and structural tests that use these models for back calculation, require pavement layer thicknesses as input. Pavement thickness measurements are required for quality control of new construction or overlays and for designing mill and recycle projects. The layer thicknesses represent an important element of a pavement management system (PMS) data base; they are needed for load rating, overlay design, and setting maintenance and rehabilitation priorities. Many state highway agencies have layer thickness records that are inaccurate or difficult to access and use.

Traditionally, core samples have provided the only means for accurately evaluating pavement layer thickness. However, sampling is time-consuming and intrusive to traffic. Depending on the spacing of cores, there is always uncertainty about thickness variations between them. For network-level pavement inventories, cores are an impractical and inadequate means for characterizing pavement thickness.

The objective of study reported in this paper was to demonstrate the accuracy, reliability, and practicality of using ground-penetrating radar (GPR) for continuous measurement of pavement layer properties. GPR's capability in this application has been suggested in several research and experimental studies (*1–3*). In fact, ASTM D4748-87 specifies for the measurement of pavement thickness with radar. In these applications, however, the radar data analysis is qualitative and manual. There has not been a systematic investigation comparing predicted to actual thickness for a range of conditions.

Recent studies (*4,5*) have demonstrated the feasibility of accurately predicting the thickness of asphalt overlays on concrete bridge decks. Investigators have used automated signal processing techniques to obtain quantitative results for asphalt thickness. The specific objective of the work presented herein has been to use these automated techniques in the context of a systematic study to determine the accuracy of radar thickness predictions.

Four sites were chosen for investigation, each representing different layer dimensions and material properties. Quantitative methods for determining thickness and moisture content were applied automatically to the radar data, and continuous output of thickness and moisture content was obtained. This output was compared with the results from direct measurements using cores, material samples, and a penetrometer. The repeatability of the measurement and the effects of radar vehicle speed were also studied.

PRINCIPLES OF GROUND-PENETRATING RADAR

Ground-penetrating radar operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna attached to a survey vehicle (see Figures 1 and 2). These pulses are reflected back to the antenna; the arrival time and amplitude are related to the location and nature of dielectric discontinuities in the material (air-asphalt or asphalt-base, etc.). The reflected energy is captured and may be displayed on an oscilloscope to form a series of pulses that are referred to as the "radar waveform." The waveform contains a record of the properties and thicknesses of the layers within the pavement. Figure 3 shows a typical set of pavement waveforms collected during this project.

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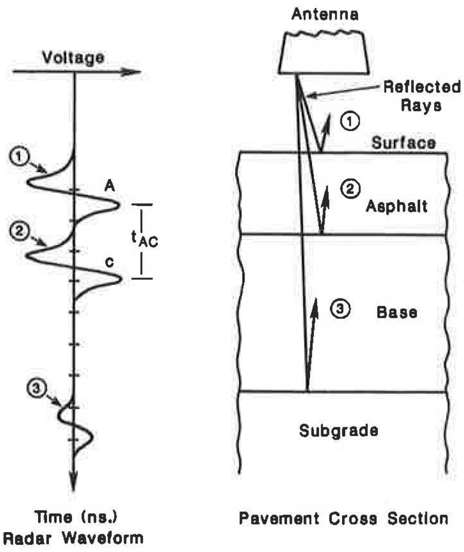

FIGURE 1 Radar pavement model.

The pavement layer thicknesses and properties may be calculated using the amplitude and arrival times of the waveform peaks corresponding to reflections from the interfaces between the layers (see Figure 3). One may calculate the dielectric constant of a pavement layer relative to the previous layer by measuring the amplitude of the waveform peaks corresponding to reflections from the interfaces between the layers. The travel time of the transmit pulse within a layer in conjunction with its dielectric constant determines the layer thickness, as follows:

$$\text{thickness} = \text{velocity} \times \left(\frac{\text{time}}{2}\right) \qquad (1)$$

FIGURE 2 Radar van.

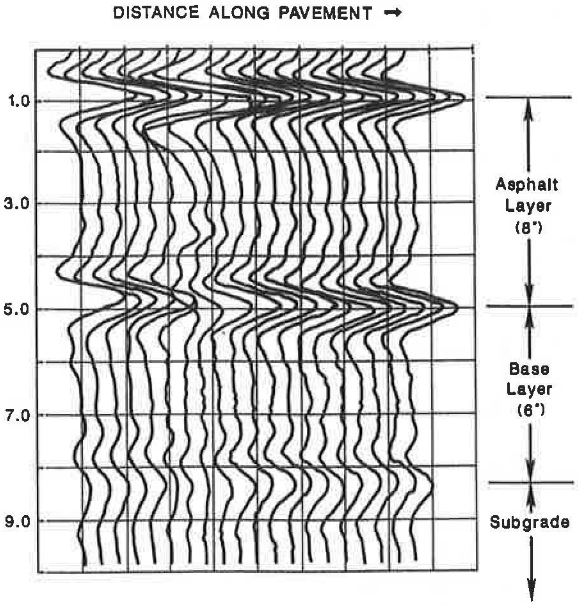

FIGURE 3 Radar pavement data (SH-30, Huntsville, Texas).

Because the measured time between peaks represents the round-trip travel of the radar pulse, the thickness computation is based on time divided by 2. The radar velocity can be computed from the dielectric constant of the medium, ε, as

$$\text{velocity} = \frac{11.8}{\sqrt{\varepsilon}} \left(\frac{\text{inches}}{\text{nanosecond}}\right) \qquad (2)$$

where 11.8 is the radar velocity in free space in inches per nanosecond. Combining Equations 1 and 2, one obtains

$$\text{thickness} = \frac{5.9 \times \text{time}}{\sqrt{\varepsilon}} \qquad (3)$$

where time is measured in nanoseconds and thickness, in inches.

The radar pulse has a finite width, so the layers must be thick enough for the reflections from each layer to appear without overlap from the surrounding layer. This minimum thickness can be calculated from the radar pulse width (in nanoseconds) and the radar velocity in the medium. For the 1-GHz horn antennas commonly used for this application, this thickness is approximately 2.5 in. in asphalt. Ground-coupled dipole antennas such as those used for geotechnical applications have transmit pulses two to three times longer, and their resolution is limited to much thicker layers.

For thicknesses less than this minimum resolution, a numerical procedure called deconvolution is required. This procedure decomposes overlapping reflections into their individual components and thus allows for thickness determination. Deconvolution analysis carried as part of this project on preliminary field data collected at the Texas Transportation Institute (TTI) annex showed that layer thicknesses as low as 1 in. could be predicted accurately.

The computation of thickness using Equation 1 presumes that the layer in consideration is homogeneous and that its dielectric constant is known. Computation of the surface layer dielectric constant can be made by measuring the ratio of the radar reflection from the asphalt to the radar amplitude incident on the pavement. This ratio, called the reflection coefficient, can be expressed as follows:

$$\text{reflection coefficient } (1-2) = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \qquad (4)$$

where the subscripts 1 and 2 refer to the successive layers. The incident amplitude on the pavement can be determined by measuring the reflection from a metal plate on the pavement surface, because the metal plate reflects 100 percent. Using these data, rearranging Equation 4, and noting that the dielectric constant of air is 1, one obtains the asphalt dielectric constant, ε_a, as follows:

$$\varepsilon_a = \left[\frac{A_{pl}+A}{A_{pl}-A}\right]^2 \qquad (5)$$

where A is the amplitude of reflection from asphalt and A_{pl} is the amplitude of reflection from metal plate (negative of incident amplitude). A similar analysis can be used to compute the dielectric constant, ε_b, of the base material. The resulting relationship is

$$\varepsilon_b = \varepsilon_a \left[\frac{(F-R2)}{(F+R2)}\right]^2 \qquad (6)$$

where

$F = \dfrac{4\sqrt{\varepsilon_a}}{1-\varepsilon_a}$ and

$R2$ = ratio of reflected amplitude from the top of the base layer to the reflected amplitude from the top of the asphalt (*5*).

Note that these analyses make two important assumptions: (a) the layers are homogeneous, and (b) the layers are nonconductive. The first assumption is violated when the layers within the asphalt are not uniform, such as may occur because of overlays or differences in properties of successive lifts of the initial pavement. When these layers are not uniform, intermediate reflections will occur within the asphalt and the use of Equation 3 for the entire asphalt layer will be incorrect. This error can be corrected by recognizing the layering within the asphalt and incorporating this layering into the pavement model.

The second assumption is generally true for asphalt but less so for the base materials. The presence of moisture, salts, and clays produces losses that make Equation 4 less valid. Therefore, one can conclude that asphalt thickness can be accurately measured directly from the radar data if layering is taken into account. On the other hand, the absolute measurement of base properties might be subject to error unless conductivity is taken into account.

The moisture content of the base is determined from its dielectric constant using a common mixture law called the complex refractive index model (*6*), which is expressed as

$$\sqrt{\varepsilon_m} = \sum V_i\sqrt{\varepsilon_i} \qquad (7)$$

where

ε_m = relative dielectric constant of the mixture,
v_i = volume fraction of Component i, and
ε_i = relative dielectric constant of Component i.

The components of the base material are solid particles, water, and air. The dielectric constants of water and air can be taken as 81 and 1, respectively.

To determine moisture content from this model, one must assume the bulk density of the material and the dielectric constant of the solids. Once these assumptions are made, the moisture content (percent by total weight) can be computed from Equations 5 and 7, making various substitutions for porosity and percent saturation in terms of bulk density, to obtain the following:

$$\text{moisture content} = \frac{\sqrt{\varepsilon_b} - 1 - \frac{\gamma_d}{\gamma_s}(\sqrt{\varepsilon_s}-1)}{\sqrt{\varepsilon_b} - 1 - \frac{\gamma_d}{\gamma_s}(\sqrt{\varepsilon_s}-22.2)} \qquad (8)$$

where

ε_b = base dielectric constant (determined from Equation 6),
ε_s = solids dielectric constant (varies from 4 to 8 depending on source material),
γ_d = dry density (pounds per cubic foot), and
γ_s = density of solids (~165 pcf).

These equations serve as the basis for analysis of the data collected during this study.

DESIGN AND CONDUCT OF TEST PROGRAM

A program was designed to collect radar data on in-service pavements and to correlate the predictions from the radar data with direct measurement. Four Strategic Highway Research Program (SHRP) General Pavement Studies (GPS) sites were selected for evaluation, as described in Table 1. The sites were asphalt pavement, because this is the type of pavement for which thickness is the greatest unknown.

TABLE 1 PAVEMENT PROPERTIES FROM INVENTORY DATA

Site	Asphalt Thickness (in.)		Type	Base Thickness (inches)	Dry Density (pcf)
	Top Course	Bottom Course			
SH 30	1.0	7.0	Bituminous treated soil	6.0	115
SH 19	1.0	6.0	Lime-treated fine-grained soil	6.0	---
SH 105	1.0	none	crushed stone	10.0	133
SH 21	2.0	6.0	crushed stone	10.0	131

Each test section was 1,500 ft long: 500 ft preceding the GPS site, 500 ft of the site itself, and 500 ft beyond the site. It was understood that verification sampling could take place only in the first and last 500-ft sections, because the GPS site could not be disturbed.

Radar data was collected by Infrasense, Inc. (Cambridge, Massachusetts) using a van-mounted horn antenna system provided and operated by Pulse Radar, Inc., of Houston, Texas. Data were collected on June 26 and 27, 1990, and taken back to Infrasense for analysis. On the basis of the analysis, areas within each site were identified for direct sampling. The sites were revisited on July 26 and 27, 1990, for repeat radar measurements in the identified areas and for extraction of direct samples at the selected sampling sites. Extraction of direct samples was carried out jointly by TTI and the Texas Department of Transportation (TexDOT).

Radar equipment setup included a number of calibration tests, including an antenna end reflection test, a metal plate reflection test, and a time calibration test. Traffic control was set up by TexDOT to allow for test speeds ranging from 5 to 40 mph. A 4-ft-wide strip of aluminum foil was taped transversely across the test lane at the beginning of the 1,500-ft test section to provide a start marker within the radar data.

Initial data collection (June 26 and 27) at each site involved four radar passes—one at low speed (5 mph) on the left wheelpath, and one each at 5, 15, and 40 mph in the right wheelpath. Data were collected continuously over the 1,500-ft test.

All radar data were continuously digitized and stored to hard disk using a Compaq 386 computer housed in the van. The radar data were subsequently analyzed using the PAVLAYER software developed by Infrasense. This software automates the application of Equations 1 through 8 to the raw radar data as shown in Figure 3. The results in this paper are based on this analysis.

Locations for ground truth were determined after a preliminary analysis of the radar data. This analysis revealed locations and areas where significant variations in thickness and dielectric constant occurred. The sample sites were located so that a reasonable range of values could be obtained at each. Ground truth data were also available from field data collected previously as part of the SHRP.

Three types of tests were carried out: (a) 4-in.-diameter wet-core samples to determine asphalt layer thickness, (b) 6-in.-diameter dry cores to obtain samples for base moisture content, and (c) penetrometer tests to determine base thickness. TTI conducted the wet-core and penetrometer testing and collected the samples and conducted the moisture content tests on samples obtained using the TexDOT dry-core rig. Under certain conditions when the penetrometer progress was slow [e.g., State Highway (SH) 21 and SH-105], attempts were made to determine base thickness visually in the dry-core holes, with occasional success.

DESCRIPTION OF DATA AND RESULTS

The data analysis was carried out using Equations 1 through 6. Asphalt pavement thickness is calculated by (a) determining the radar velocity in the asphalt using the asphalt dielectric constant determined from the surface reflection using Equation 5, and (b) computing the thickness from the velocity and the arrival time of the reflection from the bottom of the asphalt using Equation 4. The base layer thickness was calculated in a similar fashion, except the radar velocity in the base material was determined from the base material dielectric constant computed from the magnitude of the reflection at the asphalt-base interface using Equation 6. The base moisture constant was computed from the base dielectric constant using Equation 8. All of these calculations are completely automated in PAVLAYER so that continuous thickness and moisture profiles with hundreds of waveforms can be computed in a few minutes on a 386 machine.

Typical asphalt thickness, base thickness, and moisture content profiles obtained from the radar data collected during this study are shown in Figure 4. The following sections present and discuss comparisons of these predictions with traditional direct measurements.

Asphalt Layer Thickness

Table 2 shows the thickness data predicted from the radar analysis versus the thicknesses measured from core samples for three of the four sites. Two types of radar predictions are presented in the two columns of the table. The column labeled "radar alone" represents predictions using Equations 3 and 5 without benefit of any core data. The column labeled "core calibration" represents an adjustment of the "radar alone" values on the basis of a calibration of the asphalt dielectric constant using the first core at each site.

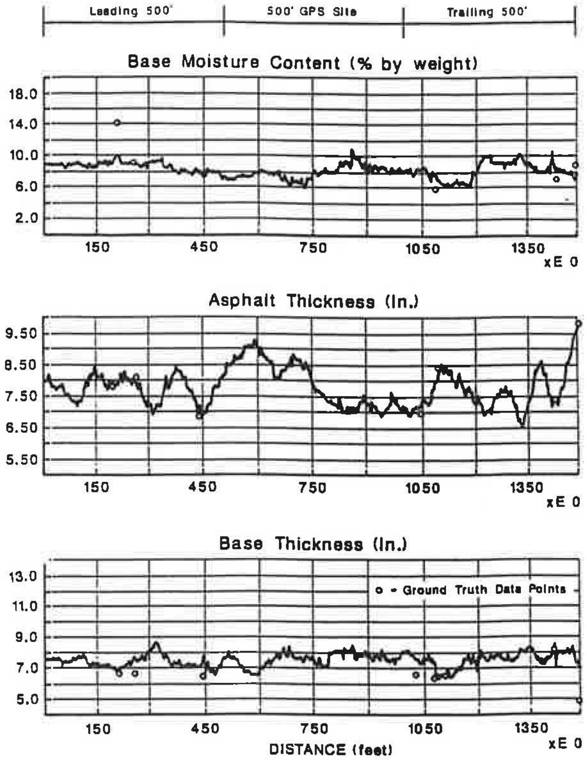

FIGURE 4 Typical data, 5-ft intervals (from GPR data, SH-30).

TABLE 2 PREDICTED VERSUS MEASURED ASPHALT THICKNESS

Site/ Location (ft)	Predicted Asphalt Thickness (in)		Measured Asphalt Thickness (in)
	(radar alone)	(core calibration)	
SH 30-			
210	7.8	7.8	7.8
250	8.0	8.0	8.1
445	6.8	6.8	6.7*
450	6.9	6.9	6.7*
455	6.9	6.9	6.8*
460	6.9	6.9	6.8*
1040	7.2	7.2	7.0*
1062	7.3	7.3	7.0*
1067	7.2	7.2	7.2*
1072	7.3	7.3	7.1*
1105	8.4	7.0	8.5
1441	7.0	7.0	7.4
1495	9.5	9.5	9.8
SH 19-			
25	6.5	6.1	6.1
61	6.6	6.2	6.3
445	6.6	6.2	6.2*
450	6.6	6.2	6.2*
455	6.4	6.0	6.4*
460	6.4	6.0	6.2*
1011	6.9	6.5	6.5
1040	6.4	6.0	6.1*
1062	6.6	6.2	6.2*
1067	6.8	6.4	6.5*
1072	6.9	6.4	6.4*
1078	7.3	6.8	6.8
1150	7.1	6.6	6.8
1193	6.6	6.2	6.3
SH 105-			
5	2.5	2.3	2.3
165	2.5	2.3	1.9
203	2.1	1.9	1.5
255	2.8	2.6	2.0
445	1.9	1.7	1.9*
450	1.9	1.7	1.9*
455	1.9	1.7	1.8*
460	2.0	1.8	1.9*
1040	2.1	1.9	1.8*
1060	2.1	1.9	1.6*
1185	1.6	1.5	1.6

*These values were taken from SHRP field reports.

The thickness data for the fourth site, SH-21, are presented in Table 3. The data from this site revealed two distinct layers of asphalt, the second layer having a higher dielectric constant than the first. Table 3 presents three types of radar prediction: (a) a prediction that ignores this layer information (no calibration), (b) a prediction that considers this layering in the radar analysis (internal calibration), and (c) a prediction that calibrates the asphalt dielectric constant using one core (core calibration).

Tables 2 and 3 present predicted versus measured asphalt thickness for 50 locations on the four pavement sections. To assess the accuracy of the prediction, a linear regression was carried out between predicted and measured values. Two analyses were conducted: one in which the predicted values were based on the best radar data without benefit of core calibration (i.e., middle column of Table 3 for SH-21), and one in which the predicted values incorporated the use of one calibration core per site. The results are as follows:

TABLE 3 PREDICTED VERSUS MEASURED ASPHALT THICKNESS (SH-21)

Site/ Location (feet)	Thickness Predictions (in.)			Measured Thickness from core (in)
	no calib.	internal calib.	core calib.	
SH 21-				
27	8.8	8.2	8.0	8.0
105	9.3	8.7	8.5	8.5
293	9.9	9.3	9.0	9.0
445	9.9	9.3	9.0	8.2*
450	9.8	9.2	9.0	8.5*
455	9.4	8.8	8.6	8.8*
460	9.1	8.5	8.2	9.0*
1035	10.0	9.1	9.1	8.5
1040	9.4	8.8	8.5	8.1*
1084	9.3	8.6	8.4	8.4
1114	9.6	8.9	8.7	8.0
1146	9.2	8.5	8.3	8.1

*These values were taken from SHRP field reports.

$$(T_a)_{\text{measured}} = K1 + K2(T_a)_{\text{predicted}} + \text{random error} \tag{9}$$

where

$(T_a)_{\text{measured}}$ = asphalt thickness measured directly,
$(T_a)_{\text{predicted}}$ = asphalt thickness computed from radar, and
$K1$ and $K2$ = regression constants.

The regression fit yields the following result (N = 50 observations):

Parameter	*Radar Alone*	*Core Calibration*
$K1$	−0.25 in.	−0.012 in.
$K2$	0.998	0.994
R^2	0.98	0.99
Standard error	0.32 in	0.11 in.

The results of this regression indicates that there is an excellent one-to-one relationship between radar prediction and actual thickness (R^2 = 0.98 and 0.99) for both cases. These results also indicate that there is a small (0.25 in.) tendency to overpredict the asphalt thickness with radar measurements alone, a tendency that is corrected when the calibrating core is used. This error is probably due to the increasing asphalt dielectric constant with depth, which is not considered in the radar analysis. In terms of accuracy, the results show a potential predictive accuracy of ±0.32 in. with radar alone and of ±0.11 in. with the use of calibrating cores.

The radar-based asphalt thickness data as validated with coring demonstrate that significant variation in layer thickness can occur in short distances such as shown on SH-30. The surfacing thickness reported as 8 in. was in fact measured to vary from 7.0 to 9.5 in. (−12.5 to +15 percent). In fact, SHRP researchers will use a 7.0-in. thickness value, as determined from their cores, to interpret falling weight deflectometer (FWD) tests and to model the performance of the sections. As can be seen in Figure 4, this assumption is substantially in error (up to 2.5 in.) for most of the GPS section. Sample back calculations show that a +2.5-in. error on a pavement assumed to be 7 in. thick produces a 95 percent error in the back-calculated base modulus (*7*).

Base Thickness Predictions

Predicted versus measured base thickness values were correlated for 42 locations on the four pavement sections. The base thickness predictions for the SH-21 site were made using the two-layer asphalt model used for asphalt thickness predictions. To assess the accuracy of the predictions, a linear regression was carried out between predicted and measured values.

$$(T_b)_{\text{measured}} = K1 + K2(T_b)_{\text{predicted}} + \text{random error} \tag{10}$$

where $(T_b)_{\text{measured}}$ is the base thickness measured directly and $(T_b)_{\text{predicted}}$ is the base thickness computed from radar.

The regression fit yields the following results:

$K1 = 2.47$ in.

$K2 = 0.63$

$R^2 = 0.72$

Standard error = 0.99 inches

Number of observations = 42

These results indicate more scatter (lower R^2) than that observed in the asphalt thickness predictions. The accuracy, as measured by the standard error, is not as good as the asphalt thickness measurements.

Factors that explain the lower accuracy and greater scatter of the base thickness predictions are

- Small errors that occur in the determination of the asphalt dielectric constant have a much greater effect on the computation of the base dielectric constant (see Equation 6) and on the resulting base thickness prediction.
- Geometric attenuation (loss of energy due to spreading of the radar beam) and depth variations in base material properties have not been considered in the analytic model.
- Base thickness ground truth methods are themselves imprecise. For example, thickness determination from cone penetrometer data is based on the interpretation of a 1- to 2-in. transition zone that appears between the base and the subgrade.

Base Moisture Content Predictions

Equation 8 was used for calculating moisture content by using one moisture content sample at each site to estimate a dry density and solids dielectric constant. These estimates were treated as constants for the site in the computation of moisture content at other locations. Using this method, the root-mean-square deviation between predicted and measured moisture content at 21 locations was 1.9 percent by weight.

An alternative application of radar to the measurement of base moisture variations is in looking at moisture content changes over time. The repeat survey carried out as part of this program was used to experiment with this concept. For most of the sites, the moisture content computations were identical for each of the two surveys. For one site, however, a significant change in moisture content occurred over a 100-ft length of the site. This result is shown in Figure 5. This result clearly shows that there is a localized pavement section whose base properties have changed during the month between the two surveys.

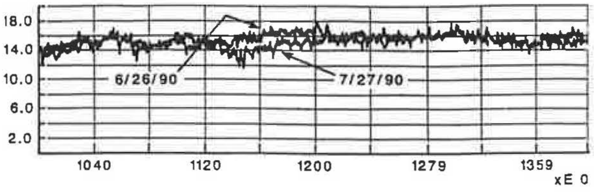

FIGURE 5 Detection of change in base moisture content, percent by weight (from GPR data, SH-30).

Effect of Survey Speed

Surveys at each site were conducted at three speeds: 5 mph, 15 mph, and 40 mph. The objective was to evaluate the sensitivity of the radar prediction to vehicle travel speed. In principal, vehicle speed should affect only the density of the collected data. On the basis of the data rate of the radar system, the three speeds would generate data at distance intervals ranging from 1 to 3 ft. To test for the presence of any other speed effects, the data collected at each of the driving speeds were analyzed at 5-ft intervals and compared. The comparison showed identical results (*8*).

CONCLUSIONS

The results of this effort have provided quantitative confirmation of the accuracy and repeatability of ground-penetrating radar for predicting asphalt and base layer thicknesses in pavement. The accuracy, as represented by regression fits of 50 and 42 data points, respectively, shows standard errors of 0.32 in. for asphalt layer thickness, 0.11 in. for asphalt thickness when one calibration core per site is used, and 0.99 in. for base layer thickness. Asphalt thicknesses ranging from 1 to 10 in. were measured with radar.

These results can be achieved using short-pulse horn antenna equipment in conjunction with a radar analysis model that incorporates the properties of the asphalt and base layers. The radar model must also account for the overlap of reflected pulses that occurs with asphalt fewer than 2.5 in. thick.

The results show that the radar predictions using these methods are repeatable and that the radar survey speed can be up to 40 mph without any effect on the results.

The radar and direct measurement results, as described herein, clearly illustrate the presence of otherwise unpredictable variations in pavement layer thickness. These variations were shown to be as high as 2.5 in. over a 40-ft distance. Such variability can produce large errors in prediction of layer moduli using FWD and similar tests and can lead to incorrect pavement assessment and overlay design. This variability and its consequences will also have a significant effect on the validity of the pavement performance prediction models to be produced by SHRP.

The results also suggest that changes in base moisture content over time can be clearly revealed by repeated radar surveys. Measurement of spatial variation of moisture content is also possible, if the composition and dry density of the base material is relatively uniform.

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