Radar Pavement Thickness Evaluations for Varying Base Conditions

W. M. KIM RODDIS, KENNETH MASER, AND ANDREW J. GISI

Accurate knowledge of pavement layer thicknesses is important in many aspects of pavement management. Often this information is unknown, and records are inaccurate, out of date, or difficult to access. To date, the only method for obtaining pavement layer data has been core sampling. That is time-consuming, labor intensive, intrusive to traffic, and limited in coverage. This study investigated the capability of ground-penetrating radar to provide accurate subsurface pavement profile information. Eleven sites were selected to represent the population of pavement types present in Kansas, with a particular emphasis on variations in base type and road history. The radar results show substantial variations in pavement thickness within each 1,000-ft test section, and in general, higher values of pavement thickness than were reported in available records. These predictions, when correlated with data from 73 ground truth cores, show an accuracy of ±5 percent to 10 percent, depending on the treatment of the data. The asphalt thicknesses in this study ranged from 2.5 to 20 in. The radar data were analyzed automatically using software that operated directly on the raw radar waveforms. This software is based on an electromagnetic model of the pavement layer structure. The resulting predictions were correlated with core samples obtained in cooperation with the Kansas Department of Transportation. The results show that a radar system that combines air-launch horn antenna equipment with appropriate software can provide an effective alternative to coring for pavement thickness measurements. In addition, this system provides more information to the agency, is cost competitive, and is safer to use because it does not require lane closures.

Knowledge of asphaltic pavement layer thickness is important in many areas of pavement management. Accurate thickness data are needed throughout the roadway network to improve pavement performance predictions, establish structural load carrying capacities, and develop maintenance and rehabilitation priorities. On a project level, accurate knowledge of pavement thickness is required for overlay design and to interpret the results of structural tests such as dynaflect and the falling weight deflectometer (FWD). For new construction, it is important to ensure that the thickness of materials being placed by the contractor is close to specification.

Accurate project level determination of pavement thickness for overlay design is of particular value for the Kansas road system. Overlays dominate the Kansas Department of Transportation's (KDOT's) current and projected paving activities, with reconstruction and new construction playing a lesser role. A rational project optimization system requires correct pavement thickness data for effective and efficient overlay design.

W. M. K. Roddis, Department of Civil Engineering, University of Kansas, Lawrence, Kans. 66045. K. Maser, Infrasense, Inc., 19-R Brookline Street, Cambridge, Mass. 02139. A. J. Gisi, Kansas Department of Transportation, Materials and Research Center, 2300 Van Buren Street, Topeka, Kans. 66611.

Negative economic effects are the consequence of both underestimates and overestimates of the actual pavement thickness.

For a direct overlay project, an underestimate of existing thickness will result in an overly conservative overlay design with an excessive cost. On the other hand, an overestimate will result in a nonconservative design that will not achieve the desired service-life. For a mill and recycle overlay project, an underestimate of existing thickness may falsely indicate that a direct overlay would be more cost-effective. An overestimate may result in an inadequate amount of material for reuse. Possible equipment breakthrough on the reduced structure of the milled pavement may also occur. The consequences of inaccurate thickness information may thus be seen to be severe, especially for the case of milling and recycling, which is an increasingly common project type.

Layer thicknesses may be determined from historical records. However, records are often highly inaccurate or nonexistent. The only acceptable method for pavement thickness measurement at present is through core samples and test pits. These are time-consuming, destructive to the pavement system, dangerous to the field employees, and intrusive to traffic. In addition, they only provide data at the location of the test, and assumptions must be made regarding variations between cores. Recent studies (*1,2*) at Strategic Highway Research Program (SHRP) sites have shown that variations of up to 2.5 in. in asphalt thickness can be found between cores taken at 50-ft spacing. When such variations exist and are not detected, large errors in dynaflect or FWD test interpretation and in overlay design can occur.

Ground-penetrating radar is a noncontact technique that has the potential for surveying pavement thickness while operating at highway speed. Until recently, the radar data required manual and qualitative interpretation (ASTM D4748-87, *3–5*). Recent research has resulted in automated data interpretation and allowed verification (*1,2*). Radar-generated continuous pavement thickness profiles provide important data for pavement management at network and project levels. These data would lead to better decisions regarding highway safety, use of funds, and life cycle designs for repair and rehabilitation.

The main objective of this study was to assess the applicability of the radar thickness profiling technology to KDOT's pavement evaluation and management program, both at the network and project levels. To meet this objective, it was necessary to establish the capabilities of radar technology for accurately generating continuous pavement profiles for asphalt overlaying a variety of base conditions. The testing for this study consisted of the collection of radar data on in-service pavements and the correlation of the predictions from the radar data with direct measurement. This work included test site selection, radar data collection, analysis of radar waveforms, selection of direct measurement locations, collection of direct samples, and correlation between radar data and direct measurement.

SITE SELECTION

The pavement population of the Kansas road system was considered when determining the site test matrix. The objective of site selection was to ensure that the selected pavement segments would constitute a representative cross-section of the state's asphaltic pavement population. In-service sites were selected from among candidates for which the actual pavement construction and conditions were reasonably well known, so that the range of conditions could be reliably selected.

Characteristics of Pavement Population

The pavement management system for the Kansas highway network classifies roads into 23 categories by pavement type, function, traffic level, and width, as illustrated in Figure 1. The pavement types are (a) portland cement concrete (PCC); (b) composite pavement (Comp), PCC pavement or brick that has been overlaid with asphaltic concrete; (c) full-depth bituminous pavement (FDBit), designed and constructed to carry expected traffic; and (d) partial design bituminous pavement (PDBit), not designed or constructed to carry expected traffic. The two functional classifications of the road categories are "Interstate" and "other." The traffic levels are based on annual average daily traffic counts expressed in terms of daily equivalent 18 kip axle loads in one direction and categorize roads as low (L), medium (M), or high (H) use. Widths are categorized as less than 32 ft or 32 ft or greater. These 23 road categories used for the entire Kansas road network were reduced to 10 road categories for inclusion in the radar survey according to the following rationale.

Pavement type is the most important road characteristic for this study because the objective is asphalt thickness determination. In addition, the radar response is most directly affected by the arrangement of the layered materials that make up the pavement cross-section. Only the three pavement types including an asphalt surface are of interest here, eliminating Categories 1, 2, 6, 7, and 8 from further consideration.

Because construction and use for Interstate roads differ from construction and use of other roads, survey sites were selected from both function types.

Pavement Type		PCC			Comp			FDBit			PDBit		
Traffic		L	M	H	L	M	H	L	M	H	L	M	H
Function	Width												
Interstate	< 32 ft	1		2	3		4		5				
	32 ft												
Other	< 32 ft	6	7	8	9	10	11	12	13	14	18	19	20
	32 ft							15	16	17	21	22	23

FIGURE 1 Kansas highway network road categories.

Traffic levels were not of direct interest for survey site selection. However, traffic level was used as an indirect indicator of road condition and maintenance history, but no systematic link between traffic level and condition resulted. Most pavements surveyed were in good condition with some transverse cracking, typical of KDOT's road population. For each pavement type and function selected, a pair of sites was selected, one from the highest traffic level and one from the lowest traffic level. This eliminated categories 10, 13, 16, 19, and 22 from further consideration. Category 9 was eliminated from the study because the site that had been radared was not available for coring because of ongoing reconstruction work.

Road width does not have a direct effect on radar survey results, but inclusion of narrow and wide roads more completely represented road types in Kansas. The narrow width, high traffic road categories (14 and 20) were not included to mitigate traffic control problems.

The 10 categories shown shaded in Figure 1 are those included in the radar survey. All three pavement types in the state network are included. The functional classifications, different roadway widths, and spectrum of traffic levels encountered in the state network are covered by the categories selected.

Criteria for Site Selection

Of primary importance in selecting specific road segments to represent each category was that the in-service segments chosen had well-known construction history, maintenance history, and current condition. This allowed a choice of road segments with the desired range of characteristics. It also facilitated the interpretation of the radar signatures of different sites of varying maintenance histories.

An additional criterion was to have a multiple asphalt overlays in place on several sites so that the ability of the radar to separately measure several asphalt layers could be examined. For the bituminous pavements, the sites selected covered a range of subpavement materials (bituminous treated, lime treated, crushed stone, naturally occurring gravels, cement treated).

The selected sites were chosen to be geographically clustered. This minimized time spent in travel between sites, and thus maximized productive use of the radar survey equipment. The sites were clustered around Topeka in District I in northeast Kansas. This highway district covers a diverse portion of the state, allowing inclusion of all 10 of the selected road categories.

Pavement Structure of Sites Selected for Radar Survey

Table 1 presents the pavement structure of the 11 sites included in the radar survey. The individual layers that make up the pavement structure are shown according to KDOT's pavement management data base. Two sites of Category 17 were included because of the addition of a SHRP site. Maintenance histories earlier than 1970 are not available. Before 1970 KDOT's standard operating procedure was to apply a seal coat every 3 years. For this reason, when using data base values to determine asphalt thicknesses, KDOT's rule of thumb is to add 0.1 in. for each year of pavement service before 1970. This accounts for pavement thickness build up as a result of repeated applications of seal coating. Table 1 includes this adjustment.

Accuracy of Pavement Management System Data Base

Network planning relies on the information in the pavement data base; therefore, discrepancies between recorded and observed layer information are of interest even though the study was not designed to sample and verify the recorded data. Discrepancies were found between KDOT pavement management data base records and the in-place pavements with regard to pavement type. Of the 11 sites tested, the pavement type differed from that obtained from KDOT records in 2 cases. One site was classified in the records as Category 15, a fully designed bituminous category. In fact, the site is a partially designed pavement. Another site was classified in the records as Category 23, a partially designed bituminous category. In fact the site is a fully designed pavement. Layer data obtained from KDOT records are in general agreement with the core data and thus also contradict the data base road categories for these two sites.

CONDUCT OF RADAR SURVEY

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. These pulses are reflected back to the antenna with an arrival time and amplitude that is 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 2 shows the relationship of the layer thicknesses to the radar waveforms. Figure 3 shows typical pavement waveforms collected during this project.

The pavement layer thicknesses and properties may be calculated by measuring the amplitude and arrival times of the waveform peaks corresponding to reflections from the interfaces between the layers (see Figure 2). The dielectric constant of a pavement layer relative to the previous layer may be calculated by measuring the amplitude of the waveform peaks

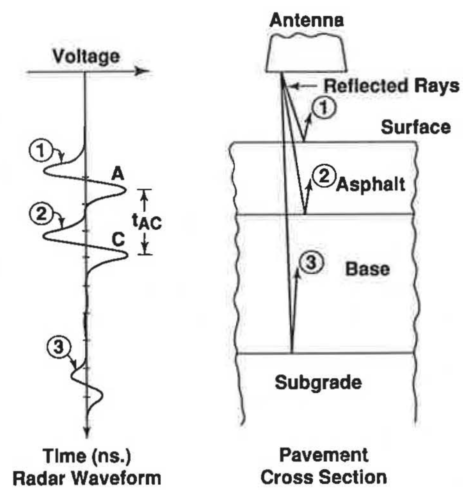

FIGURE 2 Model of radar pavement data.

TABLE 1 Pavement Layers from KDOT Data Base

	Asphalt											
	Layer 1			Layer 2			Layer 3			Base Layer		
Road Category	(in.) Thick	Material	Year	(in.) Thick	Material	Year	(in.) Thick	Material	Year	(in.) Thick	Material	Year
3	3.0	BM2	1979	1.0	BM1	1979			1950-70	9.0	PCCPAV	1950
4	1.0	BM1	1980	3.0	BM2	1980				9.0	PCCPAV	1956
5	0.75	BM2	1981	1.0	HM31	1973	1.0	HM3	1973	16.0	ACB3	1973
11	1.0	BM1	1984	2.0	BM7	1984				9.0	PCCPAV	1968
12	1.5	BM1	1979							2.0	BITCOV	1979
15	1.5	BM2A	1990	1.5	BM2	1983	2.3	Maint	1947-70	2.0	BITCOV	1947
17	4.0	BM3	1975							9.0	BM4	1975
18	2.0	BM2	1988	0.75	BM2	1988	2.3	Maint	1947-70	6.0	BM2A	1947
21	2.0	BM1B	1990	1.5	BM1	1981	1.8	Maint	1952-70	2.0	BITCOV	1952
23	1.5	BM2	1982	1.0	BITCOV	1950	2.0	Maint	1950-70	6.0	AB	1950
SHRP*	4.0	HM3	1972							7.5	ACB3	1972

Legend

AB	Aggregate binder	HM3	Hot mixture 3
ACB3	Asphalt concrete base mix	HM31	Hot mixutre 31
BITCOV	Bituminous cover	HM6	Hot mix
BM1	Bituminous mixture 1	PCCPAV	Portland cement concrete
BM1B	Bituminous mixture 1B	Maint	Maintenance seal
BM2	Bituminous mixture2		
BM2A	Bituminous mixture2A		
BM3	Bituminous mixture3		

*SHRP LTPP GPS 201005 Site, Road Category 17

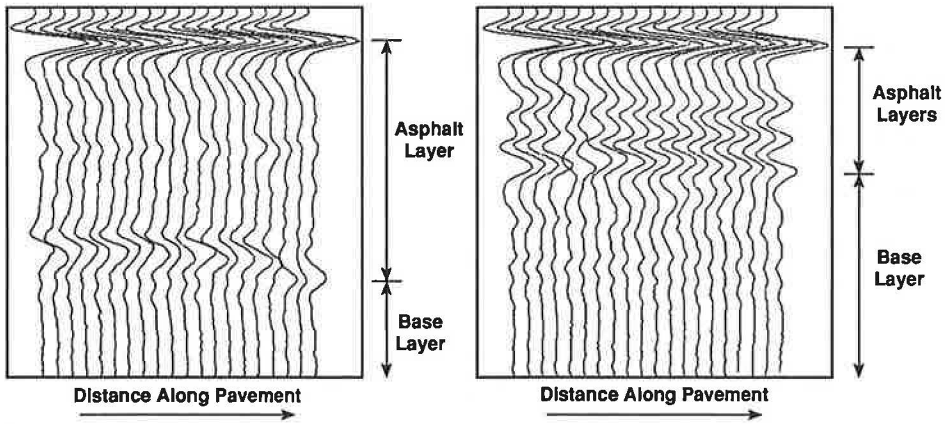

FIGURE 3 Typical waveforms.

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:

$$\text{Thickness} = \text{velocity} \times (\text{time}/2) \qquad (1)$$

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

$$\text{Velocity} = 11.8/\sqrt{\varepsilon}\ (\text{inches/nanosecond}) \qquad (2)$$

where 11.8 is the radar velocity in free space in inches per nanosecond. The result of combining Equations 1 and 2 is

$$\text{Thickness} = (5.9 \times \text{time})/\sqrt{\varepsilon}\ (\text{inches}) \qquad (3)$$

where time is measured in nanoseconds.

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:

$$\text{Reflection coef } (1 - 2) = (\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2})/(\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}) \qquad (4)$$

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, and noting that the dielectric constant of air is 1:

$$\text{Reflection coef (air} - \text{asphalt)} = A/(-A_{pl}) = (1 - \sqrt{\varepsilon_a}) \div (1 + \sqrt{\varepsilon_a}) \qquad (5)$$

where

A = amplitude of reflection from asphalt,
A_{pl} = amplitude of reflection from metal plate (= negative of incident amplitude), and
ε_a = asphalt dielectric constant.

By rearranging Equation 5, one obtains the following expression for the asphalt dielectric constant.

$$\varepsilon_a = [(1 + A/A_{pl})/(1 - A/A_{pl})]^2 \qquad (6)$$

A similar analysis can be used to compute the dielectric constant (ε_b) of the base material. The resulting relationship is

$$\varepsilon_b = \varepsilon_a[(F - R2)/(F + R2)]^2 \qquad (7)$$

where

F = $(4\sqrt{\varepsilon_a})/(1 - \varepsilon_a)$,
$R2$ = ratio of reflected amplitude from the top of the base layer to the reflected amplitude from the top of the asphalt, and
ε_b = base dielectric constant.

Note that in the context of this work, "base" represents any material occurring below the first major asphalt layer. The previous equations serve as the basis for analysis of the data collected during this study.

Radar Data Collection

Radar data were collected by INFRASENSE, Inc., of Cambridge, Massachusetts, using a van-mounted horn antenna system provided and operated by Pulse Radar, Inc., of Houston, Texas. Data were collected June 8 and 9, 1991, and taken back to INFRASENSE for analysis. Based on the analysis, areas within each site were identified for direct sampling. Extraction of direct samples was carried out jointly by KDOT in association with the University of Kansas.

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 KDOT to allow for medium speed (5 to 20 mph) radar runs. Data were acquired at longitudinal intervals of 5 ft. These speeds and sampling intervals were selected for convenience, and do not represent radar system limitations. A 3-ft^2 aluminum plate was placed on the pavement surface at the beginning and end of each 1,000-ft test section to provide reference markers in the radar data. Each site was tested with one pass of the radar van, with the antenna positioned in the left wheel path of the outside (low speed) lane.

All radar data were continuously digitized and stored using an IBM compatible 386 computer housed in the van. The radar data were subsequently analyzed by INFRASENSE using its PAVLAYER (Copyright by INFRASENSE, Inc.) customized software for the radar pavement application. The results presented here are based on this analysis.

RADAR DATA ANALYSIS AND RESULTS

The data analysis was carried out using Equations 1–7. Asphalt pavement thickness is calculated in the following steps: (a) determination of the radar velocity in the asphalt using the asphalt dielectric constant determined from the surface reflection using Equation 6, and (b) computation of the thickness from the velocity and the arrival time of the reflection from the bottom of the asphalt using Equation 3. The base layer thickness was calculated in a similar fashion. 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 7. All of these calculations are automated in the INFRASENSE PAVLAYER software so that a continuous thickness profile with thousands of waveforms can be computed in a few minutes on a 386 machine. Typical asphalt thickness and base thickness profiles obtained from the radar data collected during this study are shown in Figures 4 and 5.

Two different types of radar data analyses were conducted on these tests sections. The first was where the bituminous layers could be treated as a single monolithic layer. The second was where the thicknesses of each significant bituminous layer had to be calculated separately. The decision to use one of the two approaches depended on how clearly the individual bituminous layers appeared in the raw data as shown in Figure 3. Figure 3a shows raw radar data that had the appearance of a single monolithic layer; this site was thus analyzed using the single monolithic layer approach.

In other circumstances the data clearly showed successive reflections from multiple asphalt layers as shown in Figure 3b. This was true for the sites with processed data shown in Figures 4 and 5. In Figure 4, the bituminous surface layers were distinguished from a bituminous base layer. In Figure 5, bituminous surface layers placed at different times are distinguished from one another. Discussed in the following sections are comparisons of these predictions with direct core measurements.

COMPARISONS WITH GROUND TRUTH

Ground Truth Data Collection

Locations for coring were determined after a preliminary analysis of the radar data. This analysis revealed locations and areas in which significant variations in thickness and dielectric constant occurred. The samples were located such that a reasonable range of values could be obtained at each site. The first 10 field sites listed in Table 2 were cored to determine actual asphalt thickness and pavement layer structure. Cores 4 in. in diameter were wet drilled through the pavement. All cores were photographically documented in the field, and layer data were field recorded to an accuracy of approximately 0.125 in. Cores were then examined in the laboratory to confirm layer thickness measurements. Core and test pit data from the 11th site (the SHRP site) were also used because they were available from the SHRP long-term pavement performance data base.

In addition to coring, soil classification and particle size distribution were tested. At one site, dry samples of the as-

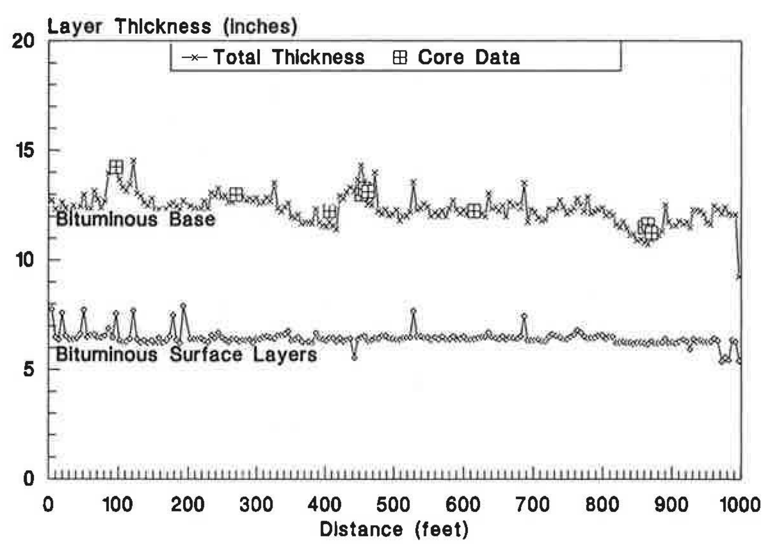

FIGURE 4 Output for two-layer analysis (Category 23).

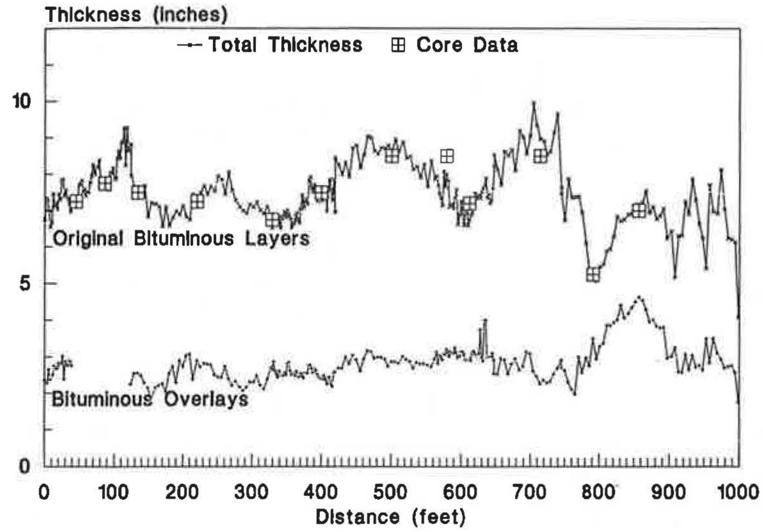

FIGURE 5 Output for two-layer analysis (Category 12).

TABLE 2 Pavement Thickness Data Statistics: Comparison of Radar, Cores, and Data Base

Road Cat.	AVERAGES at Core Sites: Radar (inches)	AVERAGES at Core Sites: Core (inches)	DIFFERENCES Between Radar and Cores: Inches	DIFFERENCES Between Radar and Cores: %	STANDARD DEVIATION: Radar at core sites	STANDARD DEVIATION: Radar complete section	STANDARD DEVIATION: Cores	KDOT DATA BASE: KDOT Data (inches)	KDOT DATA BASE: Differences KDOT-Core
3	4.64	4.41	0.23	5.30	0.23	0.40	0.22	4.0	–0.41
4	3.30	2.79	0.51	18.28	0.27	0.24	0.26	4.0	1.2
5	21.66	19.17	2.49	13.00	0.54	0.63	0.76	18.75	–0.42
5 [d]	19.19	19.17	0.02	0.10					
11	2.82	2.63	0.19	7.31	0.22	0.21	0.22	3.0	0.37
12	7.37	7.41	–0.04	–0.57	0.92	0.80	0.87	3.5	–3.91
15	9.60	8.36[a]	1.23	14.76	0.54	0.38	1.03	7.3[e]	–1.03
17	14.32	14.03	0.30	2.11	0.86	0.61	0.24	13.0	–1.03
18	11.92	10.12[b]	1.79	17.70	0.30	0.44	0.11	11.05[e]	0.93
21	10.91	10.71	0.20	1.87	1.99	1.07	1.04	7.3[e]	–3.41
23	12.46	12.55	–0.09	–0.70	1.35	0.62	0.89	10.5[e]	–2.05
17(SHRP)	14.20	13.35	0.85	6.39	0.16	1.3	[c]	11.5	–1.85

Notes: [a]questionable data due to poorly defined asphalt/soil base
[b]questionable data due to core damage during drilling
[c]insufficient data (less than 5 cores)
[d]calibrated by 1 core
[e]for the period 1950-1970, these figures assume one chip seal every 3 years, with an average thickness of 0.33 inches/chip seal

phalt at various depths were taken to determine moisture contents and hence variations in dielectric constant. For Sites 3, 5, 11, 15, 17, 18, 21, and SHRP, dynaflect tests were performed. This was to evaluate the effect of having such data on KDOT pavement management and overlay decisions.

Description of Data and Results

Figure 6 shows a comparison of all of the core data versus the radar predictions at each of the 73 core locations. The number of distinct asphalt layers observed in the cores varied from 1 to 8. Thirteen of the 73 cores were not intact when removed from the hole. These damaged cores were clustered almost entirely among the sites from Categories 5, 15, and 18. Questions regarding the interpretation of the core data occurred for two of the sites, as discussed next.

In Site 15, the cores revealed a consolidated soil/asphalt layer under the main paving layer. The data reported in Figure 6 represent the thickness of what was believed to be the main paving layer. The cores, however, broke at various locations between the top and the bottom of this layer, and the bottom of consolidated bituminous material was not clearly defined. Similarly, the radar data for this site showed several layers, and it was not clear which interface to define as the bottom. From this perspective, the radar data accurately reflected the pavement condition, but the core measurements were not adequate to provide ground truth.

In Site 18, the cores revealed 5 to 8 pavement layers, 4 of which were about 1 in. thick and located between the depths of 4.5 and 8.5 in. All of the cores were damaged during drilling. The thickness measurements on the fragmented cores may not accurately reflect the pavement thickness. Unfortunately, more reliable in-hole measurements were not made

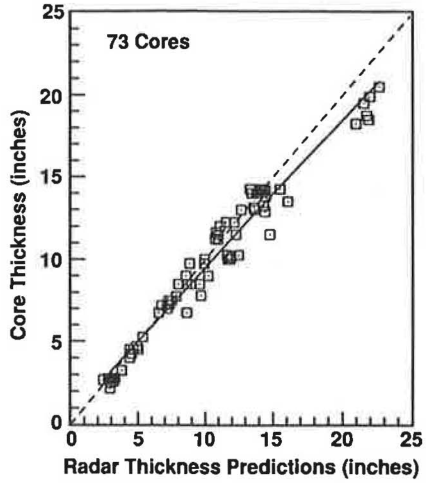

FIGURE 6 Asphalt thickness: radar predicted versus core measurements for 73 cores.

at this site. The radar data for this site suggested a complex layered structure, which was simplified in the analysis as a two-layered structure: the first 6.5 to 7.5 in. thick, the second 4 to 5 in. thick.

Discussion of Data

The radar and core data for the 73 core locations are plotted in Figure 6. The regression line through the data is represented by the following equation.

Core data = $K1 + K2*$(radar prediction)

The regression results are as follows:

- R-squared = 0.97,
- Standard error = 0.87 in.,
- $K1$ = 0.51,
- $K2$ = 0.90.

This regression includes all the data, including those sites (15 and 18) for which the core data were questionable. A regression analysis with these sites removed shows little change in results. Regressions performed for the three different pavement types result in R-squared values of 0.90 for composite pavement, 0.97 for fully designed bituminous pavement, and 0.48 for partially designed bituminous pavement. The composite data yielded a good fit, as expected, because of the clear dielectric interface between the asphalt and the concrete and the low variability in asphalt thickness for this pavement type. The fit for fully designed bituminous data was extremely good, showing a systematic tendency to overestimate asphalt thickness for thicker pavements. The reason for this tendency is discussed in the following section with regard to Site 5, the thickest pavement tested. The fit for partially designed bituminous data was the poorest, as expected, because of the questionable core data from Sites 15 and 18, representing 2 out of the 3 sites for this pavement type.

A regression analysis using the site averages in Table 2 instead of the individual data points yields the following values:

- R-squared = 0.99,
- Standard error = 0.61 in.,
- $K1$ = 0.04 in., and
- $K2$ = 0.93.

This also shows an excellent fit. The average difference between the radar predictions and the core data is 0.72 in., or 8.0 percent. When the data for sites with questionable core data (15 and 18) are eliminated, the results show an accuracy of within 0.5 in. in all but two sites. As discussed later, a single core calibration for Site 5, as would be warranted because of the thickness, would further reduce the average difference to 0.275 in., or 4.75 percent.

It is of interest to compare the standard deviations to see if the radar data can provide a measure of the section variability. The standard deviation has been computed for each site using (a) the core values; (b) the radar data at the core site locations; and (c) all of the radar data (approximately 200 points per section). Using a simple threshold of 0.5 in. to categorize variability, the variability as determined by the radar data corresponds to the variability as determined by the core data 70 percent of the time.

The relationship of these results to the pavement condition and to the application of the data for project and network level pavement management will be discussed in the next section.

DISCUSSION OF RESULTS

Relationship of the Radar Data to Pavement Condition

Data from 73 cores taken at 11 sites showed that the radar predictions were within 10 percent of the core data. This accuracy was achieved using radar data alone and including questionable core data. When poor quality core data are removed from the data set, and when one calibrating core is used for Site 5, the accuracy is increased to 7.5 percent. These are excellent results and show that radar, when properly used, represents an effective alternative to coring in a variety of pavement engineering and management applications.

The largest deviations between radar predictions and core data occurred in Sites 5, 15, and 18. The deviations for Sites 15 and 18 can be attributed to the poor quality of the core data, as discussed earlier. In Site 5, the core data revealed a total of five asphalt layers adding up to 18 to 20 in. in thickness. The radar data did not show any significant contrast between layers, and therefore the dielectric constant for the top layer was used for the entire thickness computation. Common knowledge of pavement conditions would suggest, however, that there is a gradient of moisture content with depth. This gradient would yield an increased dielectric constant and a reduced velocity with depth, which, if accounted for, would produce more accurate thickness computations.

The use of the surface dielectric constant for a 20-in. layer is not realistic, and there are two possible procedures for implementing corrections. The first is to take a calibration core. This core will provide the average radar velocity for the full pavement, and that velocity can be used to compute the thicknesses of the remaining points. Table 2 shows the results of such a calibration. The second approach is to use a moisture/depth function for thick layers as part of the normal analysis procedure. Such a function would require further development and verification.

Analysis of the data reveals a level of accuracy that is somewhat less than that observed in a previous study by Maser and Scullion (*1,2*). In that study, the standard error was ±5 percent (0.33 in.) over a thickness range of 2 to 9 in. In the Maser and Scullion study, the four investigated sites were SHRP general pavement study sites, and were of more recent, higher quality construction. The sites in this Kansas study were thicker, older, and more heavily layered than those studied by Maser and Scullion. Efforts were made in the radar analysis to recognize and compute the contrasting layer properties. In some cases this yielded accurate results (e.g., Category 23). In other cases, there were either too many layers to consider (e.g., Category 18) or the layers did not show up in the data (e.g., Category 5). In these cases, the analysis does not accurately model the progressively increasing moisture content and dielectric constant with depth, resulting in an overestimate in radar velocity and in computed thickness.

Determination of Rutting

One interesting result of this study was a computation of rut depth versus distance using the radar data for Category 3. For that site, radar surveys were conducted in both the left wheelpath and the center of the lane. Analysis of the data showed a uniformly greater asphalt thickness in the center of the lane, as expected, because of rutting. By subtracting the two computed asphalt thicknesses from one another, rut depth versus distance was computed.

Because radar can compute the thicknesses of deeper layers, it is possible to use the above approach to identify the layer in which the rutting is occurring. Investigating this possibility was not in the scope of this program, but could be evaluated in the future.

Implications for Pavement Management

The results of this work have relevance to both network and project level pavement management. Table 2 compares average thickness of bituminous layers found by the three different methods of radar, cores, and data base records. As may be seen in Table 2, the thicknesses given in the data base may differ significantly from those found by coring, and the data base usually underestimates the actual thickness. At the network level, KDOT does not take cores but relies on the data base records. The data generated in this study show that, on the average, for 1,000-ft sections, the radar predictions are within 7.5 percent of what would be obtained from a series of at least 5 cores. Therefore, for network-level pavement management, the results of a radar survey can improve the accuracy of asphalt thickness values used for pavement management decision making.

At the project level, radar-based thickness data can be used to eliminate backcalculation errors that can occur if incorrect thickness assumptions are used. The data show that radar thickness predictions can be expected to be within 7.5 percent to 10 percent of core thickness values for use in conjunction with FWD and dynaflect data interpretation. As shown in the data for Site 5, accuracy improvements can be achieved on certain sections by using a single calibration core.

The radar results also showed an ability to characterize the variability of the pavement thickness over potential project sections. This information would be useful in defining the required spacing of structural evaluation tests.

At the project level, the true thickness and its variation is very important. Project decisions consider amounts of cold milling and hot or cold recycling. The closer the milling gets to the bottom of the existing layer, the more construction related problems are encountered. The pavement is generally cracked and is leaking water into the subgrade soils, creating soft or weak spots. Heavy construction equipment breaks through the pavement in these areas. With accurate pavement thicknesses, it would be possible to avoid getting too close to the subgrade. It is also necessary to be able to evaluate the load carrying capacity of a milled surface to carry traffic during construction. The thickness of the pavement remaining after milling needs to be accurately determined so that failure due to insufficient thickness does not occur. Radar data would thus be of value at the project level.

CONCLUSIONS

The main objective of this study was to assess the application of radar thickness profiling technology to KDOT's pavement evaluation and management program at both the network and project levels. As a result of these and previous studies, the following conclusions can be reached.

1. A radar system that combines air-launch horn antenna equipment with the appropriate software provides an effective alternative to coring for pavement thickness measurements. In addition, this system provides more information to the agency, is cost competitive, and is safer to use because it does not require lane closures.
2. The expected accuracy will range from 7.5 percent to 10 percent for thicknesses from 2.5 to 20 in. The accuracy is improved with the occasional use of a calibration core, particularly in the thicker material.
3. Radar thickness information can be used for the following applications:

- FWD and dynaflect backcalculation,
- Quality control in new construction,
- Thickness estimates for mill and recycle projects,
- Design of overlays, and
- Network-level pavement inventories.

4. It is possible that radar thickness measurement could be used to identify the pavement layer most responsible for rutting. This identification would influence the pavement rehabilitation design.

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