Pavement Thickness Variability and Its Effect on Determination of Moduli and Remaining Life

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Variation in layer thickness can result in variations in the structural characteristics and in-service performance of a pavement. Pavements can vary substantially in thickness within one pavement management section. Discrete thickness measurement approaches, such as coring, may miss significant changes in the continuous thickness profile. The effects of variable asphalt pavement layer thickness on the composite back-calculated moduli and remaining life before overlay are investigated. In-service pavements selected to cover a range of thickness, structural, and functional conditions were investigated. Ground-penetrating radar was used to measure continuous thickness profiles of pavement sections so that the actual thickness variability of in-place pavements was used as the basis for the study. Discrete pavement thickness was obtained by destructive coring. Dynaflect testing was performed to measure pavement deflection. By using the continuous thickness profile obtained from the radar survey, the effect of variability of asphalt cement-bound layer thickness on the remaining life before overlay and back-calculated moduli of the asphalt cement-bound layers was investigated. The effect of variability of thickness on remaining life prior to overlay is very pronounced.

Knowledge of asphalt layer thickness is important in many areas of pavement management. The layer thicknesses, which represent an element of the Pavement Management System (PMS) data base, are required for load rating, overlay design, and setting of maintenance and rehabilitation priorities. A rational Project Optimization System requires correct pavement thickness data for performance prediction modeling. Negative economic effects and reductions in remaining life are consequences of both underestimates and overestimates of actual pavement thickness. For direct overlay projects an underestimate of existing pavement thickness will result in a conservative overlay design with excessive cost, whereas an overestimate will result in a design that will not achieve the desired service life. For milling and recycling projects, an underestimate of existing thickness may falsely indicate that a direct overlay would be more cost-effective, whereas 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.

Layer thickness can be determined from historical data base records or coring. Thicknesses from historic data base records are frequently inaccurate or nonexistent, whereas coring is destructive, time-consuming, expensive, and intrusive to traffic. Ground-penetrating radar (GPR) is a noncontact technique that has the potential for use in surveying pavement thickness while operating at near highway speed, and the GPR-generated continuous pavement thickness profiles provide important data for pavement management systems.

Asphalt layer thickness is an important variable in the back-calculated moduli of pavements. Minor changes in asphalt layer thickness can produce significant changes in the analytical results of elastic properties of the pavements (*1*). Normally, one or more cores are used to directly measure in situ layer thickness. Variation in construction and natural terrain make some variability in layer thickness inevitable. The impact of variation of asphalt layer thickness on the back-calculated modulus has been investigated by Irwin (*2*) and Rodriguez-Gomez et al. (*3*). In those studies all of the thickness data were based on simulation.

The purpose of this paper is to investigate the effect of variable asphalt layer thickness on the composite back-calculated moduli and remaining life before overlay. The study described here, unlike the previous studies, investigates in-service pavements selected to cover a wide range of pavement thickness, structural, and functional conditions. Furthermore, continuous thickness profiles of pavement sections were obtained from the GPR survey so that the actual thickness variabilities of in-place pavements were used as the basis for the study.

FIELD STUDY

The objective of the site selection was to ensure that the selected pavement segments would be a representative cross-section of a highway population unit managed at the network and project levels, in particular, the highways of the Kansas Department of Transportation (KDOT) road system.

The KDOT PMS classifies paved highways 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 asphalt concrete; (*c*) full design 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 (AADT) counts expressed in terms of daily equivalent 18-kip axle loads (ESALs) in one direction and are categorized as low (less than 87 ESALs), medium (between 87 and 162 ESALs), or high (greater than 162 ESALs) use. Widths are categorized as less than 32 feet or 32 feet and greater.

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<table>
<tr><td colspan="2">Pavement Type</td><td colspan="3">PPC</td><td colspan="3">Comp</td><td colspan="3">FDBit</td><td colspan="3">PDBit</td></tr>
<tr><td colspan="2">Traffic</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td><td>L</td><td>M</td><td>H</td></tr>
<tr><td>Function</td><td>Width</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Interstate</td><td>< 32 ft</td><td rowspan="2" colspan="2">1</td><td rowspan="2">2</td><td rowspan="2" colspan="2">3</td><td rowspan="2">4</td><td rowspan="2" colspan="3">5</td><td rowspan="2" colspan="3"></td></tr>
<tr><td>32 ft</td></tr>
<tr><td rowspan="2">Other</td><td>< 32 ft</td><td rowspan="2">6</td><td rowspan="2">7</td><td rowspan="2">8</td><td rowspan="2">9</td><td rowspan="2">10</td><td rowspan="2">11</td><td>12</td><td>13</td><td>14</td><td>18</td><td>19</td><td>20</td></tr>
<tr><td>32 ft</td><td>15</td><td>16</td><td>17</td><td>21</td><td>22</td><td>23</td></tr>
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FIGURE 1 Kansas highway network road categories.

For the purpose of the present study pavement type is the most important road characteristic because the objective depends on the effect of variable asphalt layer thicknesses. Therefore only the asphalt pavement types (Comp, FDBit, PDBit) are of interest. The 23 road categories used for the entire Kansas road network were reduced to 10 road categories for inclusion in the study, as indicated by the shaded cells in Figure 1.

The primary criterion in selecting the specific road segments to represent each category was that the in-service segments chosen have documented construction history, maintenance history, and current pavement surface condition. This allowed a choice of road segments with a range of physical characteristics. Additional criteria were to have multiple asphalt overlays in place on several sites. The sites selected covered a range of subbase materials (bituminous-treated, lime-treated, crushed limestone, natural gravel, and cement-treated bases).

Table 1 lists the pavement structures of the sites included in the thickness survey. The individual layers of the structure in Table 1 were obtained from data in the KDOT pavement management data base. Discrepancies were found between KDOT pavement management data base records and the in-place pavements with regard to pavement type. Site 15 was classified in the records as a fully designed bituminous category. From the cores it was clear that the site is a partially designed pavement. Site 23 was classified in the records as a partially designed bituminous category. The cores showed that the site is a fully designed pavement. Maintenance histories earlier than 1970 were not available. Before 1970 the KDOT 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 was to add 0.1 in. for each year of pavement service prior to 1970. This accounts for pavement thickness build-up because of repeated applications of seal coating. This adjustment is included in Table 1.

DATA COLLECTION

GPR was used to obtain continuous thickness data at the selected sites. Each site was 1,000 ft long, and GPR data were acquired at longitudinal intervals of 5 ft. Each site was tested with one pass of the radar van, in the inner wheelpath of the outside lane. At Site 3 radar surveys were conducted in both the inner wheelpath and between the wheelpaths of the passing lane. By subtracting the two computed thicknesses, rut depth throughout the section can be computed. All radar data were digitized and stored on hard disk by using an IBM-compatible 386 computer housed in the van. The radar thickness data were subsequently analyzed by Infrasense, Inc., Cambridge, Massachusetts, by using its PAVLAYER customized software for the radar pavement application. Continuous thickness profiles were generated for each site. Figure 2 shows the thickness profile for Site 21.

Locations for coring were determined after preliminary analysis of the continuous thickness profiles generated from the radar data. This analysis revealed locations where significant variations in thickness occurred. The first 10 field sites listed in Table 1 were cored to determine total asphalt-bound thickness and individual mixture layer thickness.

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

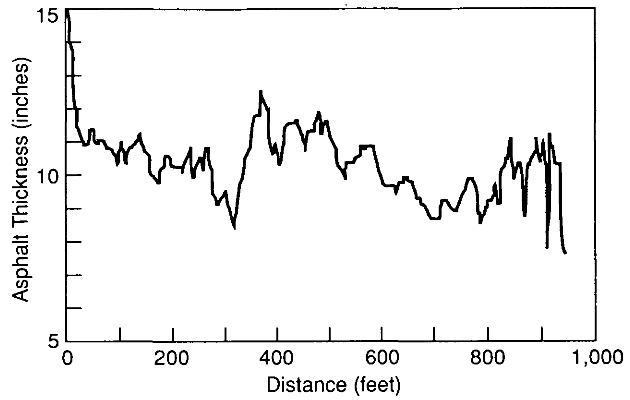

FIGURE 2 Continuous asphalt thickness profile for Site 21.

DEFLECTION TESTING

KDOT evaluates pavement structural condition by using the Dynaflect system. Dynaflect deflection measurements were made at 50-ft intervals located within each 1,000-ft test site in the inner wheelpath. This is far in excess of the number of tests required for routine pavement evaluation. The large quantity of data was obtained to allow assessment of variable thickness on deflection and hence on modulus. The Dynaflect system consists of a dynamic force generated mounted on a small two-wheel trailer with a control unit. It applies a cyclic dynamic load that generates a force with an amplitude of 1,000 lb on each wheel at a fixed frequency of 8 Hz. The load is applied at two points, and surface deflections are measured by geophones.

DATA ANALYSIS

After the continuous radar survey was completed, cores were obtained from the pavement and total and mixture layer thicknesses were recorded. Deflection measurements, coupled with asphalt concrete thickness layers, were used to estimate the composite back-calculated moduli. The moduli were subsequently used to determine the 1986 AASHTO design guide (*4*) layer coefficients of the composite asphalt concrete layers. The above layer coefficients were subsequently used to calculate the effective structural number, allowing the determination of the AASHTO remaining life before overlay of flexible pavements.

Variability of Asphalt-Bound Layer Thickness

A measure of variability of asphalt concrete layer thickness can be expressed in terms of the mean squared deviation from the mean thickness, that is, the variance, as defined in Equation 1, where x_i is the thickness of core i, $\bar{x}$ is the mean of all core thicknesses, and n is the sample size. However, the variability of the layer thickness can be more easily interpreted in terms of two statistical measures related to the variance. These are the standard deviation (Equation 2) and the coefficient of variation, defined as the standard deviation of the mean (Equation 3).

$$\text{Variance} = \sigma^2 = \sum_{i=1}^{n} \frac{|(x_i - \bar{x})|}{n - 1} \quad (1)$$

$$\text{Standard deviation} = \sigma = \sqrt{\sigma^2} \quad (2)$$

$$\text{Coefficient of variation} = V = \frac{\sigma}{\bar{x}} \quad (3)$$

The standard error (i.e., standard deviation) of the mean thickness, $\sigma_{\bar{x}}$, for a particular sample size can be estimated by (*5*)

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \quad (4)$$

where n is the number of cores, and σ is the population standard deviation of individual sampling units. Because it is not possible to know beforehand what the population standard deviation will be, σ is replaced with S_R, the standard deviation of thickness from the radar survey for the 1,000-ft test section (about 200 points).

In a random sampling of n cores, if the sampling process were repeated a large number of times, the distribution of the resulting sample means would approximate a normal distribution, as predicted by the central limit theorem. The average value of these sample means would be expected to equal the true thickness of the pavement section. Because of the normality assumptions, 68 percent of the sample mean thickness values would be expected to fall within ± 1.0 standard deviation of the actual thickness, and 95 percent of the thickness values will fall within ± 1.96 standard deviations of the actual thickness. In a more precise way, it can be expected that at the 68 percent confidence level that thickness from a particular location estimate is within ± 1.0 standard deviation of the actual thickness and at the 95 percent confidence level that the estimated thickness is within ± 1.96 standard deviations of the actual thickness.

To state the desired accuracy of a particular estimate, it is first necessary to specify an acceptable degree of error between the estimated and actual thicknesses, and then a degree of confidence that represents an acceptable difference or error between the estimated thicknesses and actual thicknesses is selected:

$$\epsilon = Z\sigma_{\bar{x}} \quad (5)$$

where ϵ is the acceptable error, and Z, the standard normal value, is a parameter based on the desired degree of confidence. Taking S_c as the standard deviation of thickness from the cores, the number of cores required is then equal to

$$n = \left(\frac{S_c Z}{\epsilon}\right)^2 \quad (6)$$

For a particular pavement type it is useful to know how many cores are required to achieve a specified acceptable error. Table 2 shows the pavement thickness data statistics comparing continuous GPR profiles, discrete destructive cores, and KDOT data base records. By using the radar standard deviation measured over the entire test section as a measure of variability, for composite pavement (Sites 3, 4, and 11) the highest variability is 0.40 (Site 3) and the lowest variability is 0.21 (Site 11). For FDBit (Sites 5, 12, 17, 23, 17SHRP) the lowest variability is 0.61 (Site 17) and the highest variability is 1.3 (Site 17SHRP). For PDBit (Sites 15, 18, and 21) the lowest variability is 0.38 (Site 15) and the highest variability is 1.07 (Site 21). This variability is based on the radar-generated continuous thickness profiles, sampling approximately

TABLE 2 Pavement Layers from KDOT Data Base

Road Category	AVERAGES at Core Sites		DIFFERENCES Between Radar and Cores		STANDARD DEVIATION			KDOT DATA BASE	
	Radar (in.)	Cores (in.)	Inches	%	Radar at core sites	Radar complete section	Cores	KDOT Data (inches)	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

TABLE 3 Number of Required Cores per 1,000 ft for 0.25-in. Acceptable Error

Pavement Type	Number of Cores: 95 Percent Confidence Intervals	Number of Cores: 68 Percent Confidence Intervals
COMP	3	1
FDBit	29	8
PDBit	32	8

200 points on each 1,000-ft roadway section. Using average standard deviations and setting an acceptable error of 0.25 in. for illustration, the numbers of cores required within a 1,000-ft section were computed by using Equation 6 and Z values of 1.96 for 95 percent confidence intervals and 1.0 for 68 percent confidence intervals. The results are presented in Table 3.

The high number of cores obtained at the 95 percent confidence limit indicates that with the exception of composite pavements, a considerable amount of destructive coring is needed to achieve the 95 percent confidence limit. In contrast the radar can be used to obtain the same confidence limit without destructive coring.

Deflection Testing and Interpretation

Deflection testing and interpretation refer to the direct use of representative pavement surface deflections and deflection basin parameters as a means of quantifying the structural adequacy (or lack thereof) of a pavement structure without relating that adequacy to the fundamental properties of the pavement and the materials with which it was constructed (*6*). Deflection basin parameters are widely used for three major applications: (*a*) to check the structural integrity of in-service pavements, (*b*) to define critical pavement response, and (*c*) to calculate the in situ layer moduli.

For the present study the deflection basin parameters were used to calculate the in situ combined layer (all asphalt-bound layers) moduli. Hall and Mohsenni (*7*) outlined the limitations of existing back-calculation methods for estimating the modulus of an asphalt concrete overlay of a PCC pavement. For this reason, modulus back-calculation in the present study was limited to FDBit and PDBit pavements. Deflection testing was conducted at five sites; two were FDBit (Sites 5 and 17) and three were PDBit (Sites 15, 18, and 21). The mean, standard deviation, and coefficient of variation of the five Dynaflect sensors at each site were determined, and the variability across the sites was studied (Table 4). Since the coefficient of variation has a normalizing effect, Houston and

TABLE 4 Sensor Values

Site	Std.* Dev.	Coefficients of Variation (%) S1	S2	S3	S4	S5	Average for site
5	0.63	8.3	8.0	7.4	8.1	7.3	7.8
15	0.38	14.0	12.9	14.6	16.1	21.3	15.7
17	0.61	35.9	21.4	23.1	25.4	22.2	25.6
18	0.44	14.6	15.3	16.6	17.6	19.4	16.7
21	1.07	19.7	15.3	16.6	17.6	19.4	20.8
Average Across Sites		18.5	14.6	15.7	17.0	17.9	16.7

* Complete Radar Data

Perera (*8*) commented that an average coefficient of variation of greater than 13 percent is the result of a material or site change.

The average coefficient of variation for the five Dynaflect sensors across the sites is 18 percent and is the result of site differences. The sites showing the greatest variability for the Dynaflect test were Sites 17 and 21, having average coefficients of variation of 25.6 and 20.8 percent, respectively. Table 4 shows that the variability in pavement thickness, as measured by the standard deviation for the complete section radar profile, generally correlates ($r = 0.46$) with the variation in deflection sensor values. The exception is Site 5, which was found to be thick and stiff. Thus, the deflection variation is small, as would be expected for a stiff pavement. The 0.63-in. standard deviation in thickness is also a small variation in the total pavement thickness of 20 in.

Four parameters were computed from the Dynaflect measurements, in which S_1, S_2, S_3, S_4, and S_5 are deflections at sensors 1, 2, 3, 4, and 5, respectively.

1. Dynaflect maximum deflection (DMD) = S_1,
2. Surface curvature index (SCI) = $S_1 - S_2$,
3. Base curvature index (BCI) = $S_4 - S_5$, and
4. Spreadability (SPD) = $100\,(S_1 + S_2 + S_3 + S_4 + S_5)/5S_5$.

Dynaflect maximum deflection is a measure of the pavement structural capacity and support conditions. The surface curvature index is predominantly an indicator of the structural condition of the surface layer. The base curvature index measures base support conditions. Spreadability measures the load-carrying capacity and the stiffness ratio of the pavement structure. Furthermore, Dynaflect maximum deflection has been shown to indirectly measure the subgrade modulus.

For each site the average values of DMD, SCI, BCI, and SPD were determined. Table 5 presents the results. Comparing the DMD and SCI values in Table 5 with the layer thicknesses in Table 2, the DMD and SCI values generally increase with decreasing thickness. This is typical for flexible pavement layers in good condition. Thus, Dynaflect measurements indicated that all test sections were typical of in-service flexible pavements without obvious defects in structural condition.

Back-Calculation of Layer Moduli

Back-calculation is a computational procedure that uses elastic-layer theory to define a plausible set of layer moduli that would theoretically result in a deflection basin that matches the measured deflection basin to within a specified tolerance. However, more than one set of moduli may satisfactorily produce a layered structure response that duplicates the measured deflection basin. If the tolerance is sufficiently tight and the deflection basin data are reliable, a reasonable set of comparable moduli can be found. Although it cannot be said that the moduli of the pavement materials are absolutely correct (*8*), they can be used to adequately model the behavior of the pavement under actual traffic loading.

TABLE 5 Dynaflect Parameters

Site	Mean			
	DMD	SCI	BCI	SPD
5	2.9	0.1	0.3	158
15	8.8	1.9	0.9	217
17	4.9	1.1	0.4	156
18	11.0	2.5	1.1	145
21	7.6	1.0	0.9	220

Layer thickness is an important independent variable in the back-calculation of moduli. As the layer becomes thinner, the layer thickness input must be more precise. Although it is almost certain that some of the layers in a pavement system are nonlinear in their response to loading, pavements are modeled as linearly elastic systems in back-calculation algorithms.

The deflections calculated from the Dynaflect tests were used as inputs to MODULUS (*9*), a program that back-calculates the elastic composite modulus of the total asphalt layer. The numbers of pavement layers were determined from coring and radar waveforms. Two-layer or three-layer back-calculation analysis was performed as appropriate for the pavement structure determined by radar and corings. Two analyses were made:

1. Back-calculation using the thickness and structure obtained from the radar survey, and
2. Back-calculation using the thickness and structure obtained from destructive coring.

The following assumptions were made:

1. All asphalt layers were considered to be a single composite layer, giving one modulus for all asphalt-bound materials. Poisson's ratio was assumed to be equal to 0.35 for asphaltic concrete.
2. The material in each layer was linear, homogeneous, and isotopic.
3. The layers overlaying the elastic half space were weightless, finite in thickness, but infinite in the horizontal plane.
4. Inertia effects were neglected.
5. The boundary conditions were as follows:
   a. Layers were in continuous contact. There were no normal stresses outside the loaded area at the top of asphalt concrete layer; the surface was free from shearing stress.
   b. Horizontal strains across the interface were equal.
   c. Temperature effects were neglected.

A paired *t*-test was used to determine whether there was a significant difference between pavement moduli back-calculated from core thickness and radar thickness. With the exception of Site 5, the results of the paired *t*-test show that composite moduli of pavement are not significantly influenced by the procedure used to measure thickness. That is, radar and core data result in similar moduli. The anomalous behavior for radar on Site 5 is explained by the profile-generating software PAVLAYER. As used in the present study, the software model assumes constant dielectric properties for the pavement with respect to depth. For very thick pavements, such as at Site 5, which is 20 in. thick, this assumption does not match the actual trend of higher moisture content with depth. The radar method thus overestimated the thickness, resulting in a significant difference on the *t*-test. This difficulty occurs only on very thick pavements and can be corrected by use of a single calibration core when generating the profile as shown for Site 5 in Table 2 (footnote *d*).

Remaining Life Before Overlay

The remaining life of the existing pavement structure before the construction of an overlay is a difficult parameter to determine accurately. Remaining life is the estimated number of years or axle loads from a given date (usually from the last survey date) needed by a pavement section to accumulate distress equal to the threshold value.

In the present analysis the 1986 AASHTO design guide and a nondestructive testing approach were used. The remaining life before overlay was estimated by using a pavement condition factor, which is the percentage of remaining life before overlay found by comparing the effective structural number of the existing pavement (SN_{xeff} determined from radar survey and destructive coring) to the original structural number SN_0. The pavement condition factor C_x is calculated as

$$C_x = SN_{xeff}/SN_0 \quad (7)$$

given that SN_{xeff} equals $a_1D_1 + a_2D_2m_2 + a_3D_3m_3$, where

a_i = layer coefficients of pavement layers,
D_i = thicknesses of individual layers, and
m_i = drainage coefficients of individual layers.

Given C_x, the remaining life, RL_x, is determined from the 1986 AASHTO design manual, Figure 5.13, Remaining Life Estimate Predicted from Pavement Correction Factor (*4*). The SN_0 of the original pavement was assumed to be 4.50 on the basis of the standard assumption by KDOT for new pavement construction.

Only the asphalt concrete layers were considered in the computation of SN_{xeff}. This is because the thicknesses of other layers such as untreated base were not available from either the radar survey or destructive coring. At some sites the base consisted of stabilized asphalt, so the total thickness was used as the asphalt concrete layer.

By using the composite moduli obtained by using radar and core thicknesses, the layer coefficients of the asphalt material were determined by using AASHTO design manual Figure 2.5, Chart for Estimating Structural Layer Coefficient of Dense-Graded Asphalt Concrete Based on the Elastic (Resilient) Modulus (*4*). The value was then multiplied by the layer thickness obtained from the radar survey and destructive coring to obtain the effective structural number SN_{xeff}. The condition factor of the pavement C_x is then determined by Equation 7.

Figures 3 and 4 show the remaining life before overlay of selected sites. When C_x was greater than 1, the remaining life before overlay was assumed to be 100 percent. Figure 3 illustrates the

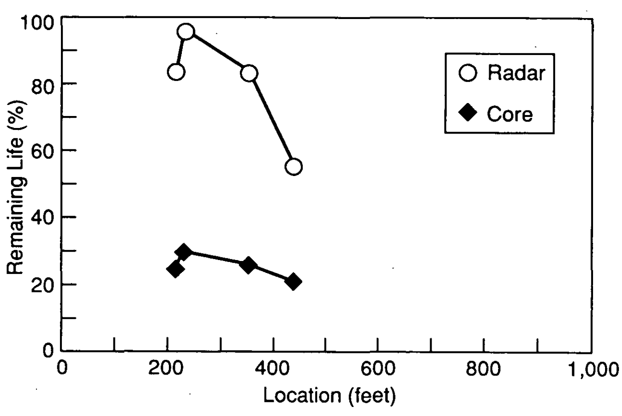

FIGURE 3 Remaining life before overlay for Site 18.

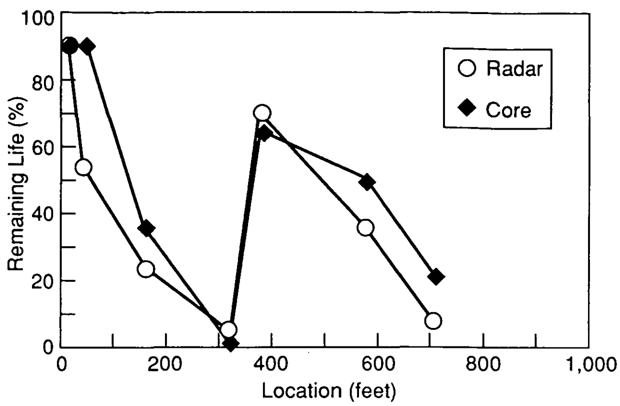

FIGURE 4 Remaining life before overlay for Site 21.

remaining life prediction for Site 18. The estimates of remaining life before overlay obtained by the radar approach were far greater than those obtained by the coring approach. The maximal difference in the remaining life estimates was about 70 percent. On this site there was a difference of 10 percent between the radar-based thickness and the core-based thickness, with radar giving the higher values. This shows how a small thickness difference may result in a larger difference in predicted remaining life.

Figure 4, in contrast, shows consistent behavior by using core and radar thickness data. When radar indicated a greater thickness, the radar-based remaining life was higher. When cores indicated a greater thickness, the core-based remaining life was higher. The thickness measurements at this site alternated; there were locations where the radar values were greater and there were locations where the core values were greater. Therefore, the remaining life pattern tracks the thickness pattern, as can be seen by comparing Figures 2 and 4.

The remaining life estimates obtained by this approach are relative. Depending on the design life, the life before overlay are obtained by multiplying the design life by the remaining life estimates.

CONCLUSION

1. A comparison of the composite layer moduli of asphalt concrete layers computed at discrete points shows that the thickness predictions from radar can be used as input for the back-calculation of the layer moduli. The paired *t*-test showed that radar-based moduli and the core-based moduli are statistically equivalently matched to the same discrete locations.
2. The predictions can also be used to investigate the effects of variable thickness of asphalt concrete layers on the back-calculation of layer moduli.
3. The combined use of GPR (continuous thickness) predictions and deflection studies can provide a standard by which the practical accuracy of composite back-calculation layer modulus results can be interpreted and used for further analysis and characterization of asphalt concrete pavement layers.
4. Most important, the continuous thickness profile, combined with deflection data, improves the interpretation and characterization of the structural integrity of an entire length of pavement. The use of discrete core thickness, which in some cases does not

correspond to the location of the measured deflections, will result in an inaccurate interpretation of the structural conditions of the site. This can lead to incorrect rehabilitation or maintenance decisions. The use of historical thickness information from a pavement management data base likewise may lead to incorrect decisions by forcing the choice of one, frequently inaccurate, thickness for an entire section.

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REFERENCES

1. Eckrose, R. A. Ground Penetrating Radar Supplements Deflection Testing To Improve Airport Pavement Evaluation. In *Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli,* STP 1026 (A. J. Bush and G. Y. Baladi, eds.). ASTM, Philadelphia, 1989, pp. 563–573.
2. Irwin, L. H., W. S. Yang, and R. N. Stubstad. Deflection Reading Accuracy and Layer Thickness Accuracy in Backcalculation of Pavement Layer Moduli. In *Symposium on Nondestructive Testing of Pavements and Backcalculation of Moduli,* STP 1026 (A. J. Bush and Baladi, G. Y., eds.). ASTM, Philadelphia, 1989, pp. 229–244.
3. Rodriguez-Gomez, J., C. Ferrugut, and S. Nazarian. Impact of Variability in Pavement Parameters on Backcalculated Moduli. *Proc., Conference on Road and Airport Pavement Response Monitoring Systems.* West Lebanon, N.H., 1991, pp. 261–275.
4. *Guide for Design of Pavement Structures.* AASHTO, Washington, D.C., 1986.
5. Mace, A. E. *Sample-Size Determination.* Reinhold Publishing Corp., New York, 1964.
6. Richter, C. A., and L. H. Irwin. *Application of Nondestructive Testing to Pavement Evaluation and Overlay Design.* Cornell Local Roads Program, Ithaca, N.Y., 1987.
7. Hall, K. T., and A. Mohsenni. Backcalculation of Asphalt Concrete-Overlaid Portland Cement Concrete Pavement Layer Moduli. In *Transportation Research Record 1293,* TRB, National Research Council, Washington, D.C., 1991, pp. 112–123.
8. Houston, S. L., and R. Perera. Impact of Natural Site Variability on Nondestructive Test Deflection Basins. *Journal of Transportation Engineering,* ASCE, Vol. 117, No. 5, 1991, pp. 550–565.
9. Uzan, J., R. L. Lytton, and P. F. Germann. General Procedure for Backcalculation of Moduli. In *Symposium on Nondestructive Testing of Pavement and Backcalculation of Moduli,* STP 1026 (A. J. Bush and Baladi, G. Y., eds.). ASTM, Philadelphia, 1989, pp. 217–228.

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