TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. TX-91-930-5F	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Use of Radar Technology for Pavement Layer Evaluation

5. Report Date

February 1991
September 1990/Revised

6. Performing Organization Code

7. Author(s)

Ken Maser (Infrasense, Cambridge, MA)
Tom Scullion, Bob Briggs (Texas DOT)

8. Performing Organization Report No.

Research Report 930-5F

9. Performing Organization Name and Address

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

10. Work Unit No.

11. Contract or Grant No.

Study No. 2-18-88-930

12. Sponsoring Agency Name and Address

Texas Department of Transportation
Transportation Planning Division
P.O. Box 5051
Austin, Texas 78763

13. Type of Report and Period Covered

September, 1989
Final-September, 1990

14. Sponsoring Agency Code

15. Supplementary Notes

Research performed for the State of Texas
Research Study Title: District Level Pavement Management System

16. Abstract

This report describes the use of non-contract Ground Penetration Radar to measure asphalt surfacing thicknesses at speeds ranging from 5 to 40 mph. On four SHRP sites in Texas, it was determined that by using radar alone it was possible to predict asphalt thicknesses to ± 7.6 mm (0.32 inches). The accuracy in predicting granular base thickness was ± 25 mm (0.99 inches). The impact of using actual layer thicknesses on FWD analysis is demonstrated.

17. Key Words

Ground Penetrating Radar, Thickness Determination, Flexible Pavements, Field Testing, Deflection, Research, Stiffness, Management

18. Distribution Statement

No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 19	22. Price

Form DOT F 1700.7 (8-69)

USE OF RADAR TECHNOLOGY FOR PAVEMENT LAYER EVALUATION

by

K. R. Maser
T. Scullion
R. C. Briggs

Research Report 0930-5F

Research Study Number 2-18-88-930

Study Title "District Level Pavement Management System"

Conducted for

Texas Department of Transportation

by

Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

February 1991
September 1990/Revised

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

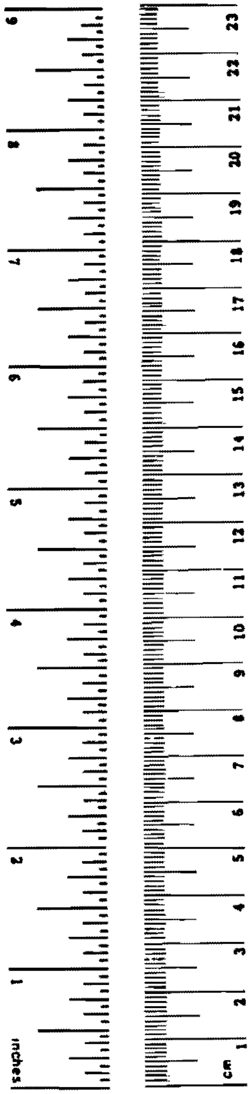
VOLUME

fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

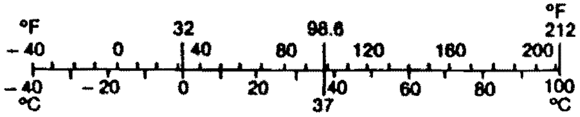
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

---

* SI is the symbol for the International System of Measurements

ABSTRACT

Use of Radar Technology for Pavement Layer Evaluation

by

K. R. Maser*, T. Scullion**, and R. C. Briggs***

This report describes the use of non-contact Ground Penetration Radar to measure asphalt surfacing thicknesses at speeds ranging from 5 to 40 mph. On four SHRP sites in Texas it was determined that by using radar alone it was possible to predict asphalt thicknesses to ± 7.6 mm (0.32 ins). However when a single calibration core was taken on each site the accuracy improved to ± 2.8 mm (0.11 ins). The accuracy in predicting granular base thickness was ± 25 mm (0.99 inches). The impact of using actual layer thicknesses on FWD analysis is demonstrated.

*Infrasense, Cambridge, Mass.
**Texas Transportation Institute, Texas A&M University,
College Station, Texas
***Texas DOT, Austin, Texas

IMPLEMENTATION STATEMENT

This study demonstrated that Ground Penetration Radar has the ability to accurately measure surface layer thicknesses for flexible pavements. This technology can be considered for implementation within the Texas DOT Pavement Management System. However, it is proposed that additional pavement types be studied. The SHRP sections represent a best case senario with homogeneous asphalts laid at the same time. In-service pavements often have multi-layered surfacings.

DISCLAIMER

PREFACE

Project 930 "District Level PMS" was initiated in September 1987 to provide continuation in the Department's ongoing Pavement Management effort. Other reports in this study include:

Report 930-1 "Micro-PES Release 1.0, User's Manual" presents a user's manual for a microcomputer system developed for the Texas DOT for analyzing the annual Pavement Evaluation System pavement condition data. Analysis tools include a procedure to make one-year Maintenance and Rehabilitation (M&R) estimates, the RAMS-District Optimization Program, and a procedure for estimating routine maintenance requirements.

Report 930-2 "Pavement Management, Where Do We Go From Here?" presents a plan on how the Texas DOT can proceed with its PMS efforts to meet both Federal and Departmental requirements. The departmental requirements were identified by interviews with the Administration, senior engineers and the staff of six Districts. Also a questionnaire was completed by all 24 Districts.

Report 930-3 "RAMS-D01 as a Decision Analysis Tool," describes the evaluation of the RAMS District Optimization Program in selecting projects to maximize network benefit. A case study was conducted in which the decisions made by a specific Texas District to allocate its maintenance and rehabilitation funds were compared with those determined from the optimization algorithm. The case study indicated that the RAMS-D01 Program has great potential for assisting the Districts in project programming.

Report 930-4 "An Initial Evaluation of the Feasibility of a GIS to Support PMS Applications," presents a review of GIS technology together with a pilot test of how it can be applied to support PMS applications in Texas. A GIS was developed to report the Pavement Evaluation System data collected in Angelina County in the Lufkin District.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Texas State Department of Transportation for their support of this work. The author would like to acknowledge Mr. Arash Sotoodehnia of INFRASENSE for his contribution to software development; Mssrs. Paul Chan and John Ragsdale of TTI for their assistance in providing data and in the conduct of the field tests; Mssrs. Carl Rascoe, Dave Turner, and Steve King of Pulse Radar, Inc. for their assistance in providing and operating the radar equipment used in this study; and Mssrs. Rob Harris, and Henry Thomason of the Texas DOT for their support and interest in this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Importance of Pavement Profile Data

Automated pavement evaluation equipment is enhancing the ability of pavement engineers and managers to assess the condition of their pavements and to make prudent decisions regarding programs, priorities, and rehabilitation strategies. The evaluation equipment in use today focuses on longitudinal profile, rutting, surface distress, and skid resistance. While these conditions are important, they only represent surface measurements. Most of the mechanisms of pavement behavior are dependent on the subsurface properties. These properties include layer thicknesses and moisture contents. Therefore, this subsurface information is important both to understand the cause of current conditions as well as to predict the future performance of a pavement.

Knowledge of layer thicknesses is also critical in the interpretation of pavement structural test data, such as that produced by the Falling Weight Deflectometer (FWD). Incorrect assumptions regarding thickness in the data analysis will produce erroneous results, and lead to incorrect conclusions regarding the pavement strength and the optimum rehabilitation design.

Excessive moisture infiltration at particular locations also represents a conditions which will eventually lead to pavement failure. Detection of this condition could lead to preventive maintenance which would address the cause of moisture infiltration, and prolong the life of the pavement. Measurement of transverse thickness variations would reveal the depth and cause of rutting, which would suggest the most appropriate form of maintenance.

To date, core samples have provided the only means for accurate pavement layer thickness evaluation. However, these are time consuming and destructive. Furthermore, depending on the spacing of cores, there is always uncertainty regarding thickness variations between cores. For network level pavement inventories, cores are impractical and inadequate as a means for pavement thickness characterization. The only means for obtaining moisture content of base and subbase material is by extraction of direct samples using some type of dry sampling procedure. Due to the impracticality of this approach, such measurements are not routinely made, except for research purposes.

This paper presents a summary of work performed in Texas over the past three years. It summarizes information presented elsewhere by Maser and Scullion (1991) and Briggs et al (1991). The paper is divided into the following sections:

1. Principles of Ground Penetration Radar
2. Design of test program
3. Description of data and results
4. Impact of thickness variations on FWD analysis
5. Conclusions and recommendations

Objectives and Scope of this Study

The objective of this study is to demonstrate the accuracy, reliability, and practicality of using ground penetrating radar for measurement of pavement layer properties. Ground penetrating radar has the inherent capability of measuring pavement layer thickness and subsurface moisture properties. This capability has been suggested in a number of research ad experimental studies (e.g. Berg and Larsen, 1984; Rosetta, 1980), and specifically suggested as a means for improvement of FWD backcalculations (Eckrose, 1989). In fact, an ASTM specification exists (ASTM, 1987) for the measurement of pavement thickness with radar. In these applications, however, the radar data analysis is qualitative and manual. Also, there as not been a systematic investigation which compared predicted to actual thickness for a range of conditions.

Recent studies (Carter et. al, 1986; Maser, 1989) have demonstrated the feasibility of accurately predicting the thickness of asphalt overlays on concrete bridge decks. These investigators have employed automated signal processing techniques to obtain quantitative results for asphalt thickness. The specific objective of the work presented in this paper has been to employ 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 thickness and moisture content determination were applied automatically to the radar data, and continuous profiles of thickness and moisture content were obtained. The results from these profiles were compared to 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.

The following sections describe the principle of radar relevant to this application, the design and execution of the test program, the results obtained and their sensitivity to the procedures used, and the implications of these results in pavement management.

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, as shown in Figure 1, 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 a typical set of pavement waveforms collected during this project.

The pavement layer thicknesses and properties may be calculated by measuring the amplitude and arrival times of the waveforms 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 corresponding to reflections from the interfaces between the layers.

A discussion of the principles of Ground Penetration Radar applied to highways has been given elsewhere (Maser 1989, Maser and Scullion 1991). By automatically monitoring the amplitudes and time delays between peaks it is possible to calculate layer dielectrics, layer thicknesses and to estimate the moisture content of granular base courses. The equations used in this study are shown below (see Maser and Scullion 1991 for derivation).

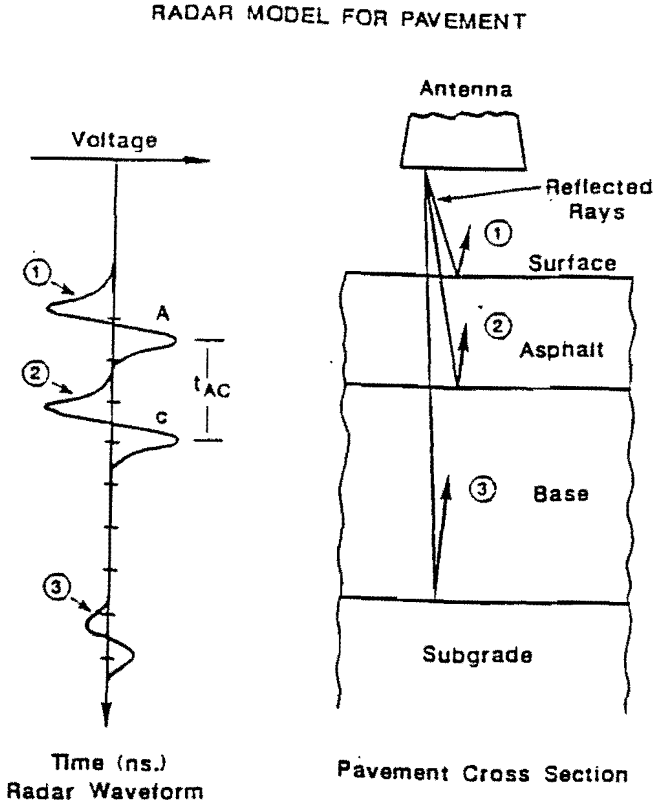


Figure 1. Ground Penetration Radar Model for a Pavement.

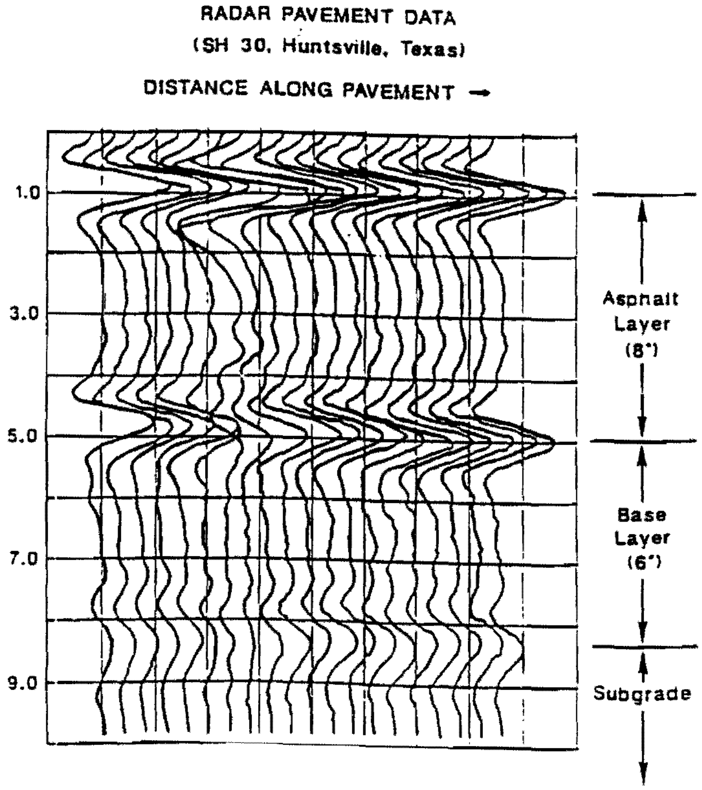


Figure 2. Typical Radar Pavement Data (SH 30, Texas).

$$\text{Layer thickness} = (5.9 \times \text{time delay})/\sqrt{\epsilon} \tag{1}$$

where, layer thickness is in inches, time delay (between peaks) in nanoseconds and ϵ is the relative dielectric constant of the medium.

$$\epsilon_a = \left[\frac{(1 + A/A_{pl})}{(1 - A/A_{pl})}\right]^2 \tag{2}$$

where A = amplitude of reflection from asphalt

A_{pl} = amplitude of reflection from a metal plate

$$\text{Base Moisture Content} = \frac{\sqrt{\epsilon_b} - 1 - \gamma\,(\sqrt{\epsilon_s} - 1)}{\sqrt{\epsilon_b} - 1 - \gamma\,(\sqrt{\epsilon_s} - 22.2)} \tag{3}$$

where: ϵ_b = base dielectric constant

ϵ_s = solids dielectric constant (varies from 4 to 8 depending on source material)

γ = dry density γ_d (lbs/ft^3) divided by density of solids γ_s (~ 165 lbs/ft^3)

Note equation 3 assumes that the density along a highway remains constant. This clearly is not the case and will limit the accuracy of moisture content estimation. However, the moisture content is the major factor which influences measured base dielectric constant ϵ_b. The relative dielectric constants of air, dry granular base and water are approximately 1, 6, and 81 respectively. High base dielectrics are almost certainly attributable to high moisture contents. The accuracy of equation 3 is yet to be determined.

The above equations serve as the basis for analysis of the data collected during this study, as described below.

DESIGN AND CONDUCT OF THE 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. The program consisted of three elements: site selection, radar data collection, and ground truth measurements, as discussed below.

Site Selection

In-service pavement sites were selected from amongst candidates for which the actual conditions were reasonably known, so that the range of conditions could be selected. This requirement was satisfied by sites designated by the Strategic Highway Research Program (SHRP) for its Long Term Pavement Performance (LTPP) Program. Since the LTPP sites could not be disturbed with intrusive sampling, the designated test areas were adjacent to the LTPP sites. The selected sites were asphalt pavement, since this is the type of pavement where thickness represents the greatest unknown. Asphalt thicknesses ranging from 25 mm to 230 mm (1 to 9 inches) were considered. Based on this evaluation, the following sites were selected:

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 456 m (1500 ft.) long, including 152 m (500 ft.) preceding the LTPP site, the LTPP site itself, and beyond the LTPP site. It was understood that verification sampling could only take place in the first and last 152 m (500 ft.) sections.

Radar Data Collection

Radar data was collected using a van-mounted or antenna system provided and operated by Pulse Radar, Inc. of Houston, Texas. The antenna used was a 1 GHz horn antenna which was mounted on a boom behind the vehicle and suspended approximately 300 mm (12 ins) above the pavement surface. Data was collected on June 26-27, 1990 for repeat radar measurements in the identified areas, and for extraction of direct samples at the selected sampling sites. Radar equipment setup included a number of calibration tests, including an antenna and reflection test, a metal plate reflection test, and a time calibration test. A 1.2 m (4 ft.) wide strip of aluminum foil was taped transversely across the test lane at the beginning of the test section. This provided a clear start indicator within the radar data, which is particularly important for the high speed pass.

Initial data collection (June 26-27) at each site involved four radar passes - one at low, 8 km/hr (5 mph) speed on the left wheelpath, and one each at speeds of 8, 24, and 64 km/hr (5, 15, and 40 mph) in the right wheelpath. Data was collected continuously over a 456 m (1500 ft.) section. The repeat radar measurements (July 27) were conducted at low speed only, over the right wheelpath.

Ground Truth Data Collection

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 such that a reasonable range of values could be obtained at each site.

Three types of tests were carried out: (1) 101 mm (4 inch) diameter wet core samples to determine asphalt layer thickness, (2) 152 mm (6 inch) diameter dry cores to obtain samples for base moisture content determination, and (3) dynamic cone penetrometer tests to determine base thickness. Visual observation of base thickness supplemented the penetrometer results.

DESCRIPTION OF DATA AND RESULTS

Typical asphalt thickness, base thickness, and moisture content profiles obtained from the radar data collected during this study are shown in Figure 3. The following sections present and discuss comparisons of these predictions with more traditional direct measurements. The discussion of the data will address the accuracy of each of the three predictions, and the magnitude and source of any systematic errors. This discussion will also address the effect of radar survey speed, the repeatability of the measurement, and the prediction of temporal changes in the base moisture content.

Asphalt Layer Thickness

Table 2 summarizes the thickness data predicted from the radar analysis vs. 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" represent predictions using the theoretical equations without benefit of any core data. The column labeled "core calibration" represents an adjustment of the "radar alone" values based on calibration with the first core at each site.

Note that additional core data is presented beyond what was obtained in this program. This additional data, which was previously obtained as part of the SHRP program, was useful here since the radar surveys traversed the locations where the core samples had been taken.

The thickness data for the fourth site, SH 21, is 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 predictions: (a) a prediction which ignores this layer information (no calib.): (b) a prediction which calibrates the asphalt dielectric constant using one core (core calib).

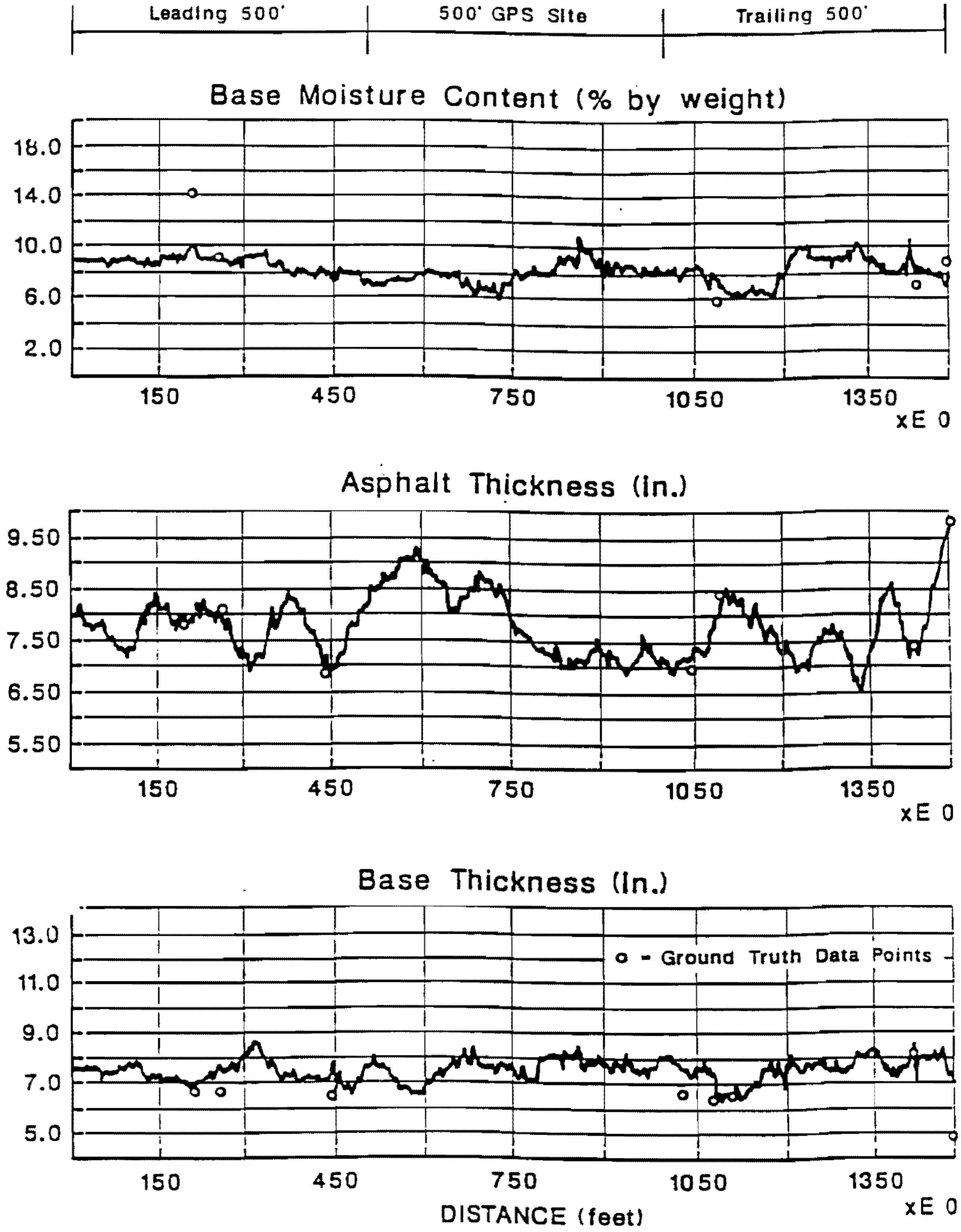


Figure 3. Typical Profiles Computed from GPR Data for SH 30 in Texas.

Table 2. Predicted vs. 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.

Table 3. Predicted vs. Measured Asphalt Thickness (SH 21).

Site/ Location (feet)	Thickness Predictions (in.)			Measured Thickness from core (in)
	No Calibration	Internal Calibration	Core Calibration	
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.

Tables 2 and 3 present predicted vs. measured asphalt thickness for 50 locations on the four different pavement sections. In order 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 the benefit of a core, the other in which the predicted values incorporated the use of one calibration core per site.

The results are as follows:

$(T_a)_{measured} = K1 + k2(T_a)_{predicted} + \text{random error}$

where: $(T_a)_{measured}$ = asphalt thickness measured directly

$(T_a)_{predicted}$ = asphalt thickness computed from radar K1 and K2 are regression constants

The regression fit yields are following result:

Parameter	Radar Alone	Core Calibration
K1	-0.25 inches	-0.012 inches
K2	0.998	0.994
R-squared	0.98	0.99
Standard Error	0.32 inches	0.11 inches

Number of observations = 50

The results of this regression indicates that there is an excellent one-to-one relationship between radar prediction and actual thickness (R-square = 0.98 and 0.99) for both cases. These results also indicate that there is a small, 6 mm (.25 inches), tendency to overpredict the asphalt thickness with radar measurements alone, a tendency which is corrected when the calibrating core is used. This error is likely due to the increasing asphalt dielectric constant with depth, which is not considered in the radar analysis. In terms of accuracy, the results show, to one standard error, a potential predictive accuracy of ± 7.6 mm (0.32 inches) with radar alone, and of ±2.8 mm (0.11 inches) with the use of calibrating cores.

The radar-based asphalt thickness data as validated with coring demonstrates that significant variation in layer thickness can occur in short distances such as shown on SH 30. The surfacing thickness reported as 203 mm (8 inches) was in fact measured to vary from 177.8 to 241.3 mm, 7 to 9.5 inches (-12.5% to +15%). In fact, SHRP researchers will be using a 177.8 mm (7.0 inches) thickness value, as determined from their cores, to interpret FWD tests and to model the performance of the sections. As can be seen in Figure 3, this assumption is substantially in error (up to 63 mm or 2.5 inches) for most of the SHRP section. The significance of this error will be discussed later.

Base Thickness Predictions

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

The regression fit yields the following result:

K1 = 2.47 inches
K2 = 0.63
R-squared = 0.72
Standard Error = 0.99 inches
Number of observations = 42

The accuracy, as measured by the standard error, is not as good as the asphalt thickness measurements. It is important to note that the accuracy of radar for base thickness prediction is being assessed using techniques which are known to be imprecise. The best base thickness ground truth data for this study was obtained from a cone penetrometer penetration curve. In every case there is a transition zone between the base and the subgrade. The radar clearly detected these transitions, but it is difficult to define whether the radar was responding to the top, middle, or bottom of this transition zone.

BASE MOISTURE CONTENT

Spatial Variation

As can be seen in equation (3), the calculation of moisture content directly from the radar data involves 3 variables - moisture content, dry density, and solids dielectric constant. Consequently, in order to calculate moisture content from the radar data alone it is necessary to make assumptions regarding the other two properties. For the purposes of this study, data from one moisture content sample at each site was used to estimate a dry density and solids dielectric constant. These estimates were then treated as constants for the site in the computation of moisture content at other locations.

The results from this study showed that once this calibration was made, the predicted moisture content at other locations is reasonably close to that which was measured, with a few exceptions. Looking at the 1 data points that were computed independently, the RMS deviation between predicted and actual moisture content is 1.9% by weight.

For most of the sites, the moisture content computations were identical for each of the two repeat surveys. For one site, however, a significant change in moisture content occurred over a 30 m (100 foot) length of the site. This result is shown in Figure 4. This result clearly shown that there is a localized pavement section which has experienced a change in base properties during the 1 month period between the two surveys.

Impact of Vehicle Speed

Three surveys were made at 8, 24, and 64 km/hr (5, 15, and 40 mph). The radar equipment used in this study recorded 25 wave forms per second. A comparison of the three resulting profiles showed identical profiles confirming that data collection speed does not affect radar results.

Impact of Thickness Variations

A detailed evaluation of the impact of these variation in layer thickness was presented earlier by Briggs et. al, (1991), a summary is presented here. This study compared the influence of assuming constant vs. using a measured variable layer thicknesses on the backcalculated layer moduli.

The actual surface and base thicknesses were extracted from the GPR results at each of the FWD test locations. A comparison of assumed and measured thicknesses is given in Table 4 below.

Table 4. Assumed vs. Measured Thicknesses for Sections 483559.

ASSUMED VS. MEASURED THICKNESSES - SHRP SECTION 483559		
ASSUMED THICKNESSES: 7.0 in. HMAC, 6.0 in. Base		
MEASURED THICKNESSES		
DISTANCE (ft.)	HMAC (in.)	BASE (in.)
0	8.2	7.2
50	9.0	7.0
100	9.1	7.0
150	8.2	7.8
200	8.7	7.5
250	8.3	7.2
300	7.6	7.0
350	7.1	8.0
400	7.4	7.8
450	7.2	7.8
500	7.4	8.0

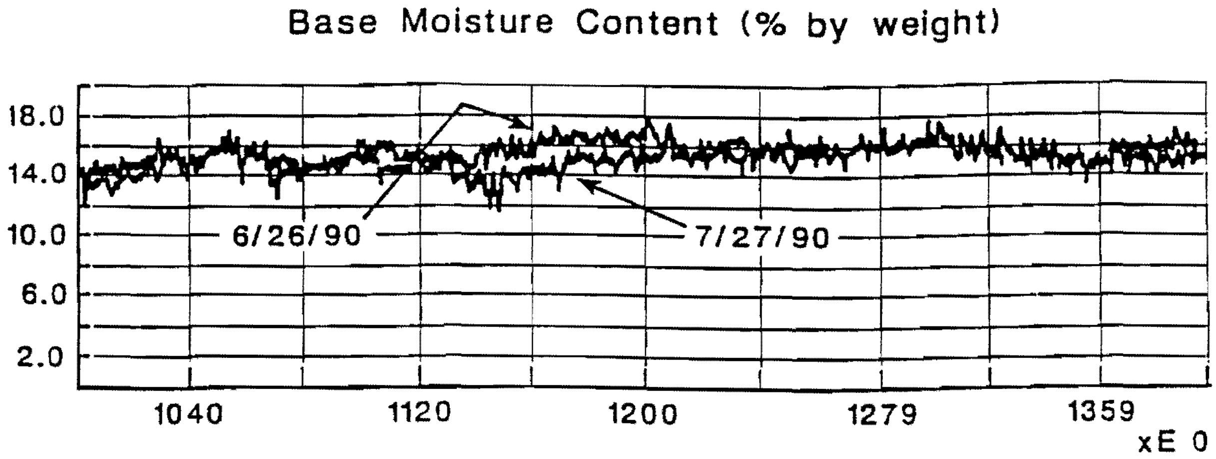


Figure 4. Information Computed from GPR Data for SH 30 in Texas.

In the backcalculation process the MODULUS 4.0 backcalculation system (Uzan 1990) was used to match measured and theoretically calculated deflection bowls. MODULUS 4.0 automatically calculates a stiff subgrade layer and uses it in generating a deflection data base for the section being analyzed. The final layer moduli values are those that minimize error between measured and theoretically calculated bowls. The impact of varying layer thicknesses as opposed to the single assumed thickness are demonstrated by large reductions in the final error per sensor and reduction is the variability of the backcalculated asphalt moduli as shown in Table 5.

Table 5. Comparison of Backcalculated Surface Modulus and Error per Sensors Using Assumed and Measured Thicknesses.

BACKCALCULATION RESULTS				
DISTANCE	ASSUMED THICKNESS		MEASURED THICKNESS	
	Surface Modulus E1 (PSI x 10^6)	Error Per Sensor	Surface Modulus E1 (PSI x 10^6)	Error Per Sensor
0	2.29	4.07	1.11	2.90
50	3.42	3.01	1.44	1.62
100	3.57	5.36	1.31	2.40
150	1.73	2.42	1.86	0.49
200	2.39	3.44	2.04	1.41
250	1.81	3.32	1.62	1.99
300	1.43	3.73	1.66	0.80
350	1.74	3.06	1.79	1.42
400	2.06	2.72	1.74	0.99
450	1.58	4.31	1.59	1.18
500	1.34	2.95	1.59	0.88
Avg	**2.12**	**3.5**	**1.61**	**1.4**
C.O.V. %	**35%**		**15%**	

The use of the measured surface and base thicknesses substantially reduced the variability of the backcalculated surface modulus, the coefficient of variation reduced from 35% to 15%. This trend was repeated for the base moduli.

The conclusion for this analysis was that:

1. Variations found in layer thicknesses on SHRP sites in Texas are large enough to cause up to 100 percent error in the backcalculated modulus of the surface layer of the pavement, if not taken into account.
2. These variations also resulted in up to 80 percent error in the base materials.
3. These variations did not appreciable affect the backcalculated modulus of the subgrade.
4. Deflection basins alone cannot be used to identify or quantify changes in pavement layer thicknesses which are severe enough to adversely affect the accuracy of the backcalculated moduli.

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 pavements. The accuracy, as represented by regression fits of 50 and 42 data points respectively, shows a standard error of 7.6 mm (0.32 inches) for the asphalt thickness without taking a core, but reduced to 2.8 mm (0.11 inches) when one calibration core per site is used, and 25 mm (0.99 inches) for the base layer thickness. Asphalt thicknesses ranging from 25 to 250 mm (1 to 10 inches) were measured with radar as part of this study.

These results presented above are achievable using short pulse, horn antenna equipment in conjunction with a radar analysis model which incorporates the properties of the asphalt and base layers. The radar model must also account for the overlap of reflected pulses which occurs with asphalt less than 64 mm (2.5 inches) thick.

The regression results revealed a systematic tendency to predict higher thickness values than are observed from direct measurements. This observation makes sense, in that certain assumptions in the radar analysis model would tend to lead to higher-than-actual thickness values. The regression lines developed as part of this program provide a statistical means for correcting for this systematic error in the near term. Future analytic models, such as those being developed at TTI and M.I.T., can provide more accurate predictions by incorporating improved models of the physical properties of asphalt and base.

The results presented herein show that the radar predictions using the above methods are repeatable, and that the radar survey speed can be up to 64 km/hr (40 mph) without any impact 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 64 mm (2.5 inches) over a 12 m (40 foot) distance. Such 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 repeat 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.

REFERENCES

1. American Society for Testing and Materials (1987) "Standard Test Method for Determining the Thickness of Bound Pavement Layers using Short Pulse Radar" ASTM Standard D4748-87.
2. Berg, F., Jansen, J.M., and Larsen, H.J.E., (1986) "Structural Pavement Analysis based on FWD, Georadar, and/or Geosonar Data", Proc. 2nd International Conference ont he Bearing Capacity of Roads and Airfields, Plymouth, U.K.
3. Briggs, R.C., Scullion, T., and Maser, K.R., "Asphalt Thickness Variation on Texas SHRP Sections and Effect on Backcalculated Moduli" Symposium on NDT and Backcalculation, Nashville, Tennessee, August, 1991.
4. Eckrose, R.A., Ground Penetrating Radar Supplements Deflection Testing to Improve Airport Pavement Evaluations" Non-Destructive Testing of Pavements and Back Calculation of Moduli, ASTM STP 1026, A.J. Bush III and G.Y. Baladi, Eds., ASTM.

5. Carter, C.R., Chung, T., Holt, F.B., and Manning, D.G. (1986) "Automated Signal Processing System for the Signature Analysis of Radar Waveforms from Bridge Decks" Canadian Electrical Engineering Journal, Vol. II, No. 3.
6. Halabe, U.B., Maser, K., and Kausel, E. (1989) "Condition Assessment of Reinforced Concrete Using Electromagnetic Waves" Final Technical Report prepared for the U.S. Army Research Office under Contract DAAL 03-87-K005, Center for Construction Research and Education, Massachusetts Institute of Technology, Cambridge, Massachusetts.
7. Maser, K.R., Brademeyer, B., and Littlefield, R. (1988) "Pavement Condition Diagnosis Based on Multisensor Data" Transportation Research Record No. 1196, Transportation Research Board, Washington, D.C.
8. Maser, K.R., (1989) "New Technology for Bridge Deck Assessment" Phase I Final Report prepared for the New England Transportation Consortium, Center for Transportation Studies, Massachusetts Institute of Technology, Cambridge, Massachusetts.
9. Maser, K.R., and Roddis, W.M.K (1990) "Principles of Radar and Thermography for Bridge Deck Assessment", ASCE Journal of Transportation Engineering, Vol. 116, No. 5, Sept/Oct., 1990.
10. Maser, K.R., and Scullion, T., "Automated detection of Pavement Layer Thicknesses and Subsurface Moisture Using Ground Penetrating Radar", TRB Paper, January 1991.
11. Rosetta, Jr., J.V. (1980) "Feasibility Study of the Measurement of Bridge Deck Overlay Thickness using Pulse Radar", Report R-35-80, Prepared for the Massachusetts Department of Public Works by Geophysical Survey Systems, Inc. Salem, New Hampshire.
12. Uzan, J., Scullion, T., Michalek, C.H., Parades, M., and Lytton, R.L. (1988). "A Microcomputer Based Procedure to Backcalculate Layer Moduli from FWD Data," Res. Report 2-18-87-1123-1, Texas Transportation Institute, College Station, Tx.

KEY WORDS

Ground radar
Field testing
Flexible pavements
Research
Management
Deflection
Stiffness