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Research

Ground Penetrating Radar Survey of Pavement Thickness on Mn/ROAD Sections

Mn/ROAD

Office of Minnesota Road Research

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The research shows that highway speed horn antenna ground penetrating radar equipment and automated analysis software can accurately measure asphalt thickness. To accurately measure concrete and base thickness, lower speed ground coupled equipment also must be used.

In the project, researchers collected radar data for pavement layer thickness at the 40 Mn/ROAD research pavement sections to obtain accurate as-built pavement layer thickness data on the sections. A blind comparison between radar asphalt thickness data and available cores shows an R-squared of 0.98. For concrete thickness, the R-square was 0.76. The report details results for base and subbase thickness and for the layer thicknesses of the four aggregate sections.

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GROUND PENETRATING RADAR SURVEY OF PAVEMENT THICKNESS ON MN/ROAD SECTIONS

Final Report

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Ground Penetrating Radar Survey for Pavement Thickness Evaluation at Mn/ROAD

Final Report of Second Stage Data Analysis Results

EXECUTIVE SUMMARY

The objective of this work is to obtain accurate as-built pavement layer thickness data on the 40 Mn/ROAD research pavement sections. Since coring and other destructive testing was not acceptable, ground penetrating radar (GPR) was selected for this purpose.

Radar data for pavement layer thickness was collected at the Mn/ROAD research facility on July 7, 1994. The data was collected on all 40 test sections in the two outside wheelpaths of each section. Two types of radar equipment were used: (a) air-coupled equipment normally operated at driving speeds, and (b) ground-coupled equipment normally operated at 5-10 mph. The data was analyzed using PAVLAYER© to determine layer thicknesses. The software is self-calibrating and the analysis was carried out without core data. Layer thickness results are presented as graphic pavement cross section plots, and in ASCII files.

A report of first stage results was submitted on August 29, 1994 for comparison of computed asphalt and concrete thicknesses at 74 locations to available core data. The core data was subsequently provided by Mn/ROAD, and correlations between core and PAVLAYER data were carried out.

A blind comparison between radar asphalt thickness data and cores has shown an R-squared of 0.98. For concrete thickness, the R-squared was 0.76. The average deviation between radar and core data was 0.24 inches for asphalt, and 0.53 inches for concrete. To improve the accuracy of the concrete data, a calibration factor based on this correlation was applied to the final analyzed data.

Subsequent to the above analysis, complete results have been obtained for asphalt and concrete layer thickness, for base and subbase thickness, and for the layer thicknesses of the four aggregate sections. Thicknesses have been reported at 10 foot intervals, and are presented in ASCII file format and as continuous plots.

This project has shown that for the Mn/ROAD pavement conditions: (a) accurate asphalt thickness data can be obtained using highway speed horn antenna ground penetrating radar equipment and automated analysis software; and (b) accurate thickness data can also be obtained for concrete and base thickness, but lower speed ground coupled equipment must also be used.

1. Introduction

Radar generates short pulses of electromagnetic energy which penetrate into the pavement structure and reflect back from the material interfaces. The amplitude and arrival time of these return reflections are used to determine the thickness and properties of the pavement layers.

Two types of radar antennas were used in this study: highway-speed air-coupled horn antennas and a low-speed ground-coupled antenna. The air-coupled horn antenna is suspended above the pavement surface and mounted to a vehicle which travels at normal driving speed. Two types of air-coupled horn antennas were used: a 1 GHz and a 500 MHz. The 1GHz antenna has been routinely used for pavement layer thickness surveys for several years. The 500 MHz was a new prototype, which has greater capability for depth of penetration. Both units are manufactured by Pulse Radar, Inc. (PRI), of Houston, Texas (see Figure 1).

Figure 1: Radar Equipment used in this Study provided by Pulse Radar, Inc. Houston, TX

The ground coupled antenna is dragged along the pavement surface, and the survey speed is limited to 5-10 mph. The ground-coupled antenna achieves a greater depth of penetration than the air-coupled antenna, but it lacks the shallow resolution for pavement layers less than 5-6 inches. Also, the antenna data can not be self calibrated, so either it has to be operated in conjunction with an air-coupled antenna, or calibration cores are required. The antenna used in this study was a 500 MHz antenna and control system manufactured by Geophysical Survey Systems, Inc. (GSSI), of Salem, NH.

With both sets of equipment, the data was continuously digitized, displayed and stored on a microcomputer (PC) as it is collected. The data acquisition system used is RDAS©, supplied by PRI. The data from the radar survey was post-processed using PAVLAYER©, supplied by INFRASENSE, to determine the thickness of the surface and base layers.

2. Data Collection

Data was collected in the outside wheelpath of both the high volume and low volume test sections. Data collection speed was 15-20 mph for the air-coupled systems, and 5-10 mph for the ground coupled antenna. The survey vehicle, data acquisition system, radar equipment and operator were supplied to INFRASENSE by Pulse Radar. The PRI survey vehicle was outfitted with a DMI sensor attached to the speedometer connection to the transmission. The pulses from the DMI sensor are transmitted to the PC where they are counted by the software and stored with the radar data. This pulse count is later converted to distance when the data is played back and analyzed.

The horn antenna radar equipment generates 50 scans per of data per second. At the speed of 15-20 mph, this translates into approximately 2 scans per linear foot of survey. The ground-coupled radar equipment operated at 51 scans per second. Due to the lower travel speed, however, data collection was approximately 4 scans per linear foot.

Weather conditions were dry with temperatures in the 70's. It had rained over the previous days, and severe thunderstorms occurred immediately after completion of the survey. The equipment was set up on at approximately 9:30 AM at the west end of the high volume section. The first task was to evaluate the influence of the GPR equipment on the Mn/ROAD pavement sensors. Baseline readings were obtained by Mn/ROAD personnel on selected sensors in this area using a MnDOT van to supply a loading. Similar readings were taken at the same sensors using the PRI survey vehicle with the GPR system operating. No noticeable differences were determined in the sensor readings, and it was concluded that the GPR equipment had no influence on the sensors.

The sensor evaluations were completed at 11:30 AM, and the pavement thickness survey was carried out during the remainder of the day. Eleven survey runs were carried out as described below:

Run #	Section	Equipment	Start Station	End Station	WP
1	High Vol	1GHz horn	1246+00	1102+84.5	North
2	High Vol	1GHz horn	1246+00	1102+84.5	South
3	Low Vol south	1GHz horn	213+00	157+00	North
4	Low Vol south	1GHz horn	213+00	157+00	South
5	Low Vol north	1GHz horn	108+00	61+00	North
6	Low Vol north	1GHz horn	108+00	61+00	South
7	High Vol	500MHz horn	1246+00	1102+84.5	North
8	High Vol	500MHz ground	1246+00	1102+84.5	North
9	High Vol	500MHz ground	1246+00	1102+84.5	South
10	Low Vol south	500MHz ground	213+00	157+00	South
11	Low Vol north	500MHz ground	108+00	61+00	North

These survey runs covered a total of 102,500 linear feet (31,250 meters) of continuous data collection.

Tables 1 and 2 summarize the sections that were surveyed and the relationship of the radar survey distance to highway stationing.

3. Data Analysis

Upon completion of the survey, the data was copied to digital tape and brought to INFRASENSE's office for processing. The analysis principles are described and sample data is presented in Appendix 1 of this report. Appendix 2 presents plots of all the analyzed data. The software used to carry out the analysis was PAVLAYER©.

The following are the steps in data analysis:

1. Preview the data in a color display to divide the pavement into homogeneous subsections. This preview revealed the boundaries where changes in pavement structure occurred between test cells.

2. Set up radar waveform processing parameters

3. Run radar waveform processing. This procedure automatically carries out the following:

   (a) increments to the next location at the user-specified interval

Table 1

MnRoad High Volume, Section Descriptions

Station		Radar Distance		Cell Number	Length	Type	Nominal Structure
From	To	From	To				
124580	124030	20	570	23	550	Asphalt	8.75/4.0PASB/3.0base
124000	123450	600	1150	22	550	Asphalt	7.75/18.0base
123420	122870	1180	1730	21	550	Asphalt	7.75/23.0base
122830	122280	1770	2320	20	550	Asphalt	7.75/28.0base
122280	121730	2320	2870	19	550	Asphalt	7.75/28.0base
121710	121160	2890	3440	18	550	Asphalt	7.75/12.0base/9.0base
121140	120590	3460	4010	17	550	Asphalt	7.75/28.0base
120590	120040	4010	4560	16	550	Asphalt	7.75/28.0base
119995	119445	4605	5155	15	550	Asphalt	10.75/subgrade
119445	118895	5155	5705	14	550	Asphalt	10.75/subgrade
118885	118345	5715	6255	13	540	Concrete	9.5/5.0base (p=20,w=24)
118345	117835	6255	6765	12	510	Concrete	9.5/5.0base (p=15,w=24)
117835	117307	6765	7293	11	528	Concrete	9.5/5.0base (p=24,w=24)
117296	116756	7304	7844	10	540	Concrete	9.5/4.0PASB/3.0 (p=20,w=24)
116750	115345	7850	9255	crossover	1405		
115335	114795	9265	9805	9	540	Concrete	7.5/4.0PASB/3.0base (p=15,w=40)
114795	114255	9805	10345	8	540	Concrete	7.5/4.0PASB/3.0base w/trans steel in pass lane @ 4'
114255	113715	10345	10885	7	540	Concrete	7.5/4.0PASB/3.0 base (p=20,w=27)
113705	113195	10895	11405	6	510	Concrete	7.5/5.0 (no drain)/subgrade (p=15, w=27)
113150	112610	11450	11990	5	540	Concrete	7.5/3.0 (no drain)/27 base
112560	112010	12040	12590	4	550	Asphalt	8.75 asph/subgrade
111954	111404	12650	13200	3	550	Asphalt	5.75asph/4.0base/33base
111394	110844	13210	13760	2	550	Asphalt	5.75asph/4.0base/28base
110834	110284	13770	14320	1	550	Asphalt	5.75asph/33base

Table 2

MnRoad Low Volume, Section Descriptions

Station		Radar Distance		Cell	Length	Type	Nominal Structure
From	To	From	To				
South Sections							
21300	20900	0	400	transition	400	Asphalt	10.5
20900	20350	400	950	32	550	Aggregate	1"chip seal/12"agg
20335	19785	965	1515	31	550	Asphalt	3"/4"base/12"base
19765	19215	1535	2085	30	550	Asphalt	5"/12"base
19195	18645	2105	2655	29	550	Asphalt	5"/10"base
18625	18075	2675	3225	28	550	Asphalt	3"/13"base
18055	17505	3245	3795	27	550	Asphalt	3"/11"base
17490	17050	3810	4250	26	440	Asphalt	6"/subgrade
16935	16385	4365	4915	25	550	Asphalt	5"/subgrade
16350	15800	4950	5500	24	550	Asphalt	3"/4"base
15800	15700	5500	5600	Transition	100	Asphalt	
North Sections							
10800	10745	0	55	transition	55		
10745	10235	55	565	40	510	Concrete	7.0"/5.5"/7.0" tapered over 5"base, p=15
10230	9696	570	1104	39	534	Concrete	6"/5"base, p=20
9690	9180	1110	1620	38	510	Concrete	6"/5"base, p=15
9165	8637	1635	2163	37	528	Concrete	6"/12"base, p=12, no dowels
8622	8112	2178	2688	36	510	Concrete	6"/5"base, p=15
8012	7470	2788	3330	35	542	aggregate	1"chip seal/12" aggregate
7470	6920	3330	3880	34	550	aggregate	12" aggregate
6900	6350	3900	4450	33	550	aggregate	12" aggregate
6350	6200	4450	4600	transition	150	Asphalt	
6200	6100	4600	4700	transition	100	Concrete	

(b) internally calibrates the surface layer dielectric constant

(c) computes the arrival time and amplitude of the layer interface reflections

(d) computes dielectric constant and thickness of all detected layers.

4. Convert to ASCII file and plot results.

For the first stage results, the data analysis for the asphalt sections was carried out at 1 foot longitudinal intervals in order to have data in close proximity to the cores. For the concrete sections, the analysis was carried out at 10 foot longitudinal intervals. The analysis was carried out for the 36 pavement test cells and for the transition sections between the cells. The analysis for the transition sections provided data at locations where core data was available from MnDOT.

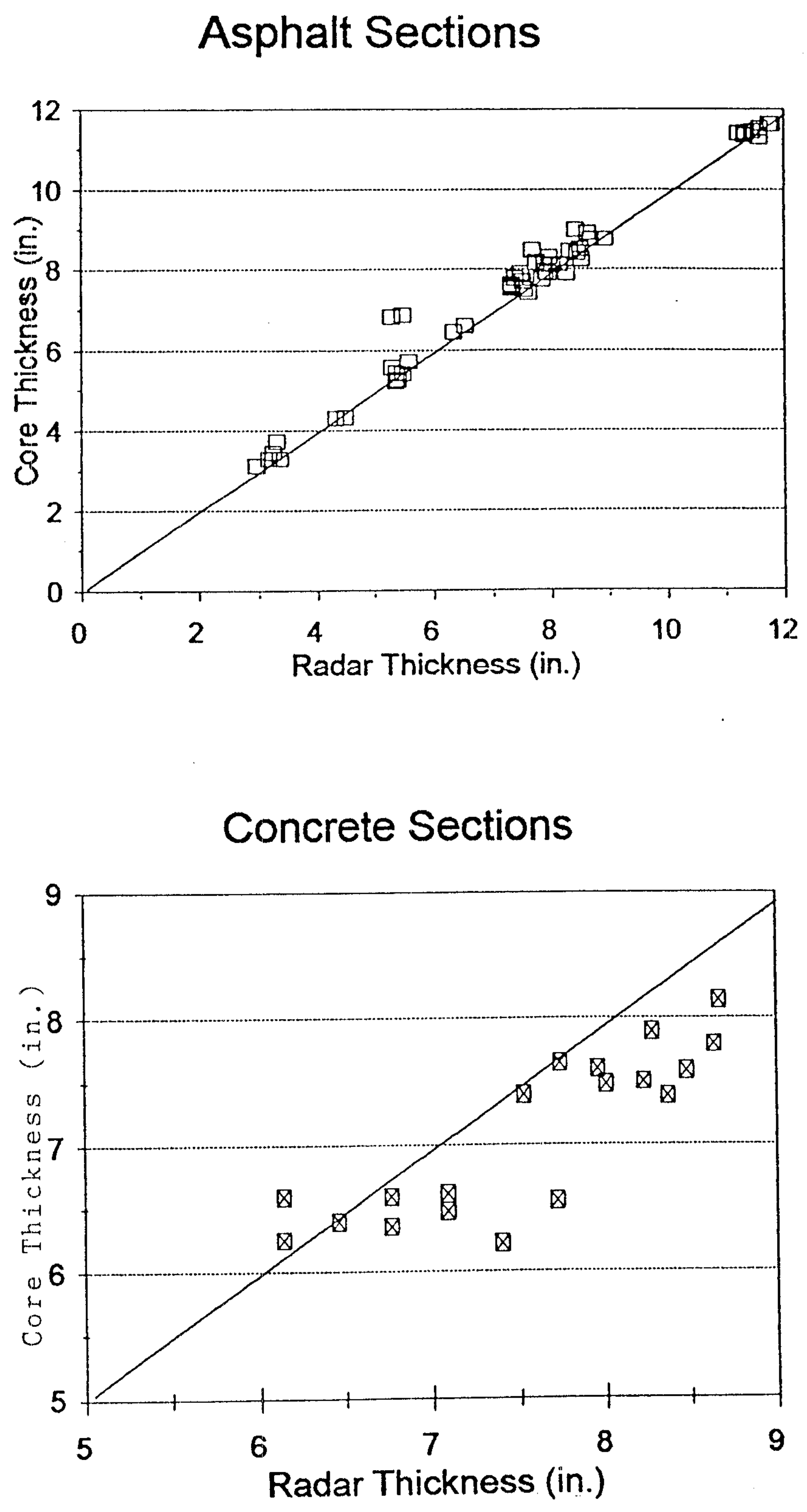
The asphalt and concrete thickness values were computed and tabulated at survey locations where cores were taken by MnROAD. These locations were provided to INFRASENSE upon completion of the field survey. Since all radar surveys were in the outer wheelpaths, only the cores with transverse offsets of +/- 8-10 feet from the centerline were considered. The computed thickness values vs. the core values for 52 asphalt core locations and 22 concrete core locations are discussed below.

4. Discussion of Results

The 1GHz data for the asphalt sections produced clear well-defined interfaces (see data samples in Appendix 1). The analysis of this data was straightforward. The continuous thickness results shown in Appendix 2 reveal important information regarding thickness variations within each test cell. The results show thickness deviations on the order of 1-2 inches within cells which have otherwise been assumed to be homogeneous. This precise thickness detail will be useful in the interpretation of FWD test results.

(a) Correlation with Cores

The first stage asphalt and concrete thickness data was correlated with core data provided by Mn/Road. The core locations and the correlated data are shown in Appendix 3. Figure 2 plots the radar data vs. the core data for both asphalt and concrete sections. The figure is labeled "blind" correlation, since the calculations were made prior to the availability of core data.



Asphalt Sections

Concrete Sections

Figure 2 Correlation of Blind Radar Data to Cores

Figure 2 shows an excellent correlation between asphalt radar and core data. A statistical analysis shows an R-squared of 0.98. The average absolute deviation between radar and core data is 0.24. There are only 2 discrepant points (cores #194 and #196, cell 26) where the deviation exceeded one inch. These core values are not consistent with four other cores taken in cell 26. The radar data compared well with these four other cores. It is possible, therefore, that there may be an error in the reporting of the core data for core nos. 194 and 196.

The radar concrete thickness data correlates well with the core data, but not as well as the asphalt data. With the concrete, the R-square of the correlation is 0.76, and the average absolute deviation between radar and core data is 0.53 inches. The radar data for concrete systematically over-predicts the thickness (see Figure 2). This suggests that a correction can be applied to improve the accuracy. Two corrections have been applied based on this correlation: a 7.2% reduction for the High Volume sections and a 6.1% reduction for the Low Volume sections.

(b) Appearance of a thin layer below the asphalt in cells 24 and 27

The data from cells 24 and 27 showed evidence of a thin (1-2") layer below the 3" asphalt surface layer. Sample data is presented in Appendix 1 showing the two, closely spaced layer interfaces. A discussion with a Mn/ROAD Grading and Paving inspector suggested a possible explanation for this observation. The inspector indicated that during construction, the south low volume road was used as a haul road and the base layer of these sections experienced considerable amount of construction traffic. The high quality 100% crushed granite base may have become supercompacted under traffic and now shows up as a thin layer of material with higher density. In the inspector's experience, this Class 6 material will set up and become hard under continued traffic, and may thus appear as a second "bound" layer above the base.

(c) Data for concrete thickness evaluation

The data from the concrete sections collected using the 1 GHz horn antenna revealed the layer interfaces only in cells 7, 8, and 9. For the remaining concrete sections, there was inadequate contrast between the concrete and base material, and insufficient penetration through the concrete to obtain useful thickness data. Therefore, the 500 MHz data was used in combination with the 1 GHz horn data to compute the concrete thickness. The 500 MHz antenna has much more penetration, but much lower resolution. Therefore, the accuracy is not expected to be as good as that for the horn antenna.

Using this combined antenna method, the data from the 1 GHz horn was used to calibrate the concrete dielectric constant. The data from the 500 MHz ground coupled antenna was then used to detect the concrete/base interface. The combination allowed for the computation of the concrete thickness. The contrast between the concrete and base was still weak, even with the deeper penetrating 500 MHz antenna. For example, in cells 10, 11, 12, and 13, only the bottom of the base could be detected, but not the bottom of the concrete. Due to this weak interface, the concrete thickness data is not expected to be as precise or as accurate as the asphalt thickness data.

(d) Base and subbase thickness evaluation

In most cases the 500 MHz antenna data was the source of data for the computation of base and subbase thicknesses. The method used was the same as that applied to the concrete sections, as described above. For base thickness calculation, the horn antenna data was used to determine the asphalt thickness and the dielectric constant of the top of the base layer. The 500 MHz data was used to locate the bottom of the base layer(s), and a linearly increasing dielectric constant vs. depth was assumed through the base for the calculation of base thickness.

In nine cells (2, 3, 18, 23, 24, 27, 28, 31, and 32), the base was thin enough, and/or provided enough contrast so that the thickness of one or more base layers could be calculated directly from the 1 GHz data.

(e) Horn Antenna Equipment for Deeper Penetration

Experience with the 1GHz horn antenna has shown that its depth of penetration may be limited in different circumstances. Therefore, a prototype 500 MHz horn antenna was tested as part of this project in an effort to extend the depth of penetration using highway speed equipment. This equipment is currently under development by Pulse Radar, Inc., and it has only been tested to a limited extent in the field. Unfortunately, operational problems were experienced with the prototype equipment, and insufficient time and resources were available on site to make repairs. Further efforts to achieve deeper penetration were therefore carried out using the 500 MHz ground coupled antenna as described above.

5. Conclusions

This project has shown that accurate asphalt thickness data can be obtained using highway speed horn antenna ground penetrating radar equipment and automated analysis software. A blind comparison between radar asphalt thickness data and cores has shown an R-squared of 0.98 and an average deviation of 0.24 inches. No calibration cores were required to achieve this level of accuracy.

Accurate concrete thickness data can also be obtained, but to achieve this, lower speed (5-10 mph) equipment is also required in combination with the horn antenna. The blind concrete thickness data is not as accurate as the asphalt thickness data (R-square = 0.76, average deviation = 0.53), but the accuracy can be improved through the use of calibration cores.

Under certain conditions of thickness and dielectric contrast, the thickness of concrete and granular base layers can be determined using the highway speed horn antenna. However, the lower speed, ground coupled equipment, used in combination with the horn antenna, provides the most reliable means for base thickness determination under a full range of conditions.

6. References

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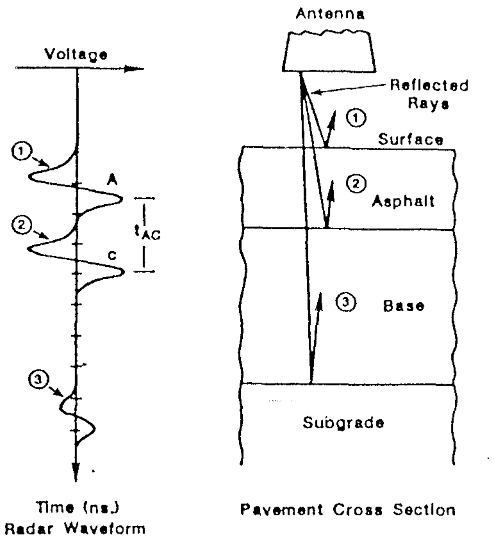
[4] Maser, K. R., "Ground Penetrating Radar Surveys to Characterize Pavement Layer Thickness Variations at GPS Sites". Report SHRP-P-397, Strategic Highway Research Program, 1994

Appendix 1

Radar Data Analysis for Pavement Layer Thickness and Moisture Content
and
Radar Data Samples from Mn/ROAD Test Cells



Time (ns.)
Radar Waveform

Pavement Cross Section

FIGURE 1 Radar pavement model.

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

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

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

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

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

$$\text{thickness} = \frac{5.9 \times \text{time}}{\sqrt{\varepsilon}} \tag{3}$$

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

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

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

The computation of thickness using Equation 1 presumes that the layer in consideration is homogeneous and that its dielectric constant is known. Computation of the surface layer dielectric constant can be made by measuring the ratio of the

FIGURE 2 Radar van.

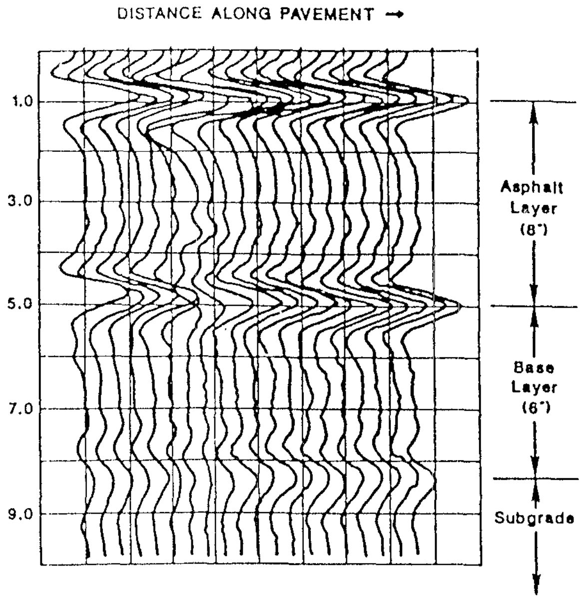


FIGURE 3 Radar pavement data (SH-30, Huntsville, Texas).

radar reflection from the asphalt to the radar amplitude incident on the pavement. This ratio, called the reflection coefficient, can be expressed as follows:

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

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

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

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

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

where

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

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

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

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

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

$$\sqrt{\varepsilon_m} = \sum V_i \sqrt{\varepsilon_i} \tag{7}$$

where

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

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

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

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

where

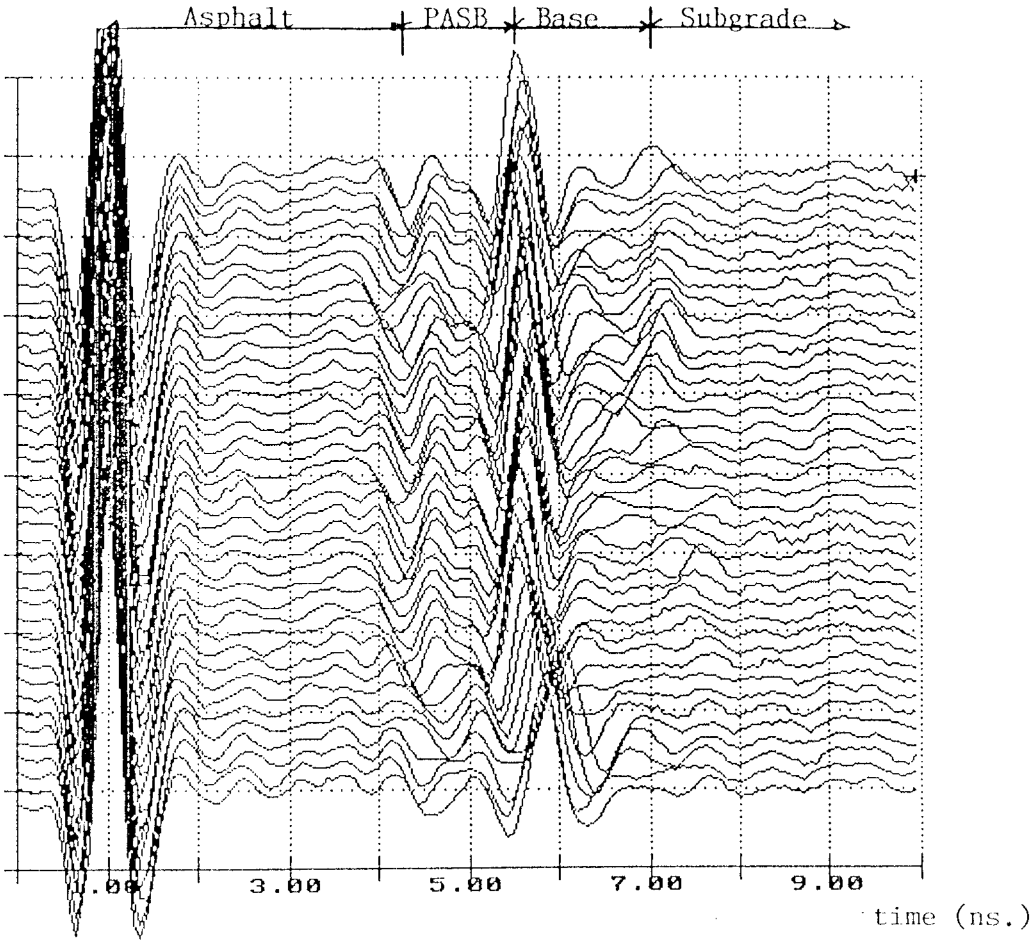
ε_b = base dielectric constant (determined from Equation 6),
ε_s = solids dielectric constant (varies from 4 to 8 depending on source material),
γ_d = dry density (pounds per cubic foot), and
γ_s = density of solids (~165 pcf).

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

SAMPLE RAW DATA FROM 1 GHZ HORN ANTENNA

C:\MNROAD\DATA\
HS1.DAT

From ==> 50
To ==> 440 _

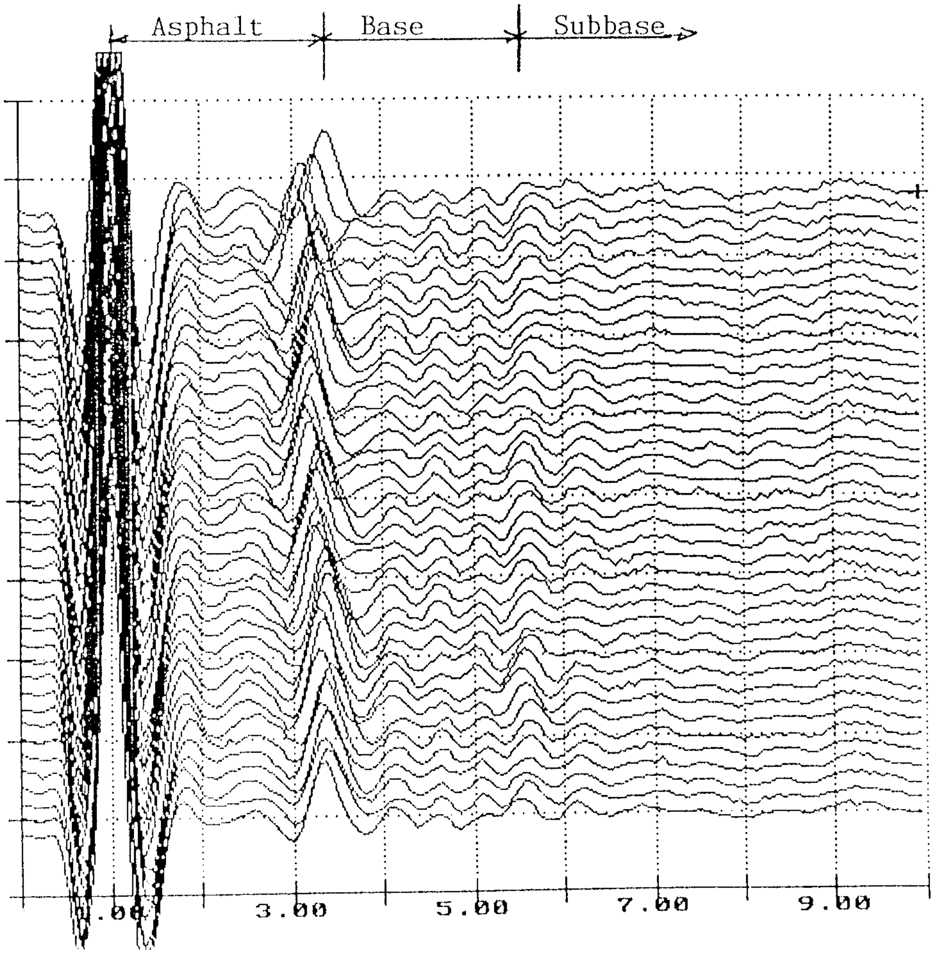


Sample radar data –
Cell 23

C:\MNROAD\DATA\
HS1.DAT

From ==> 12700

To ==> 13090



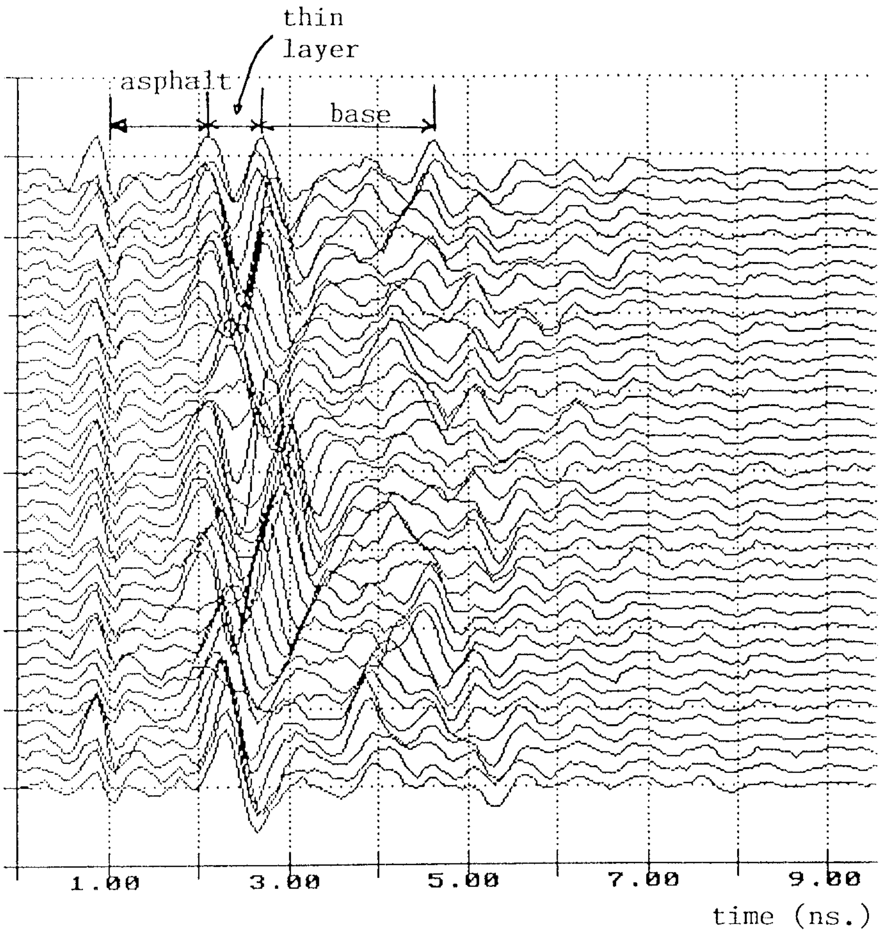
Sample radar data–
Cell 3

c:\mnroad\lv1.d
at

From ==> 4950
To ==> 5340 _

RAW RADAR DATA
FROM CELL 24

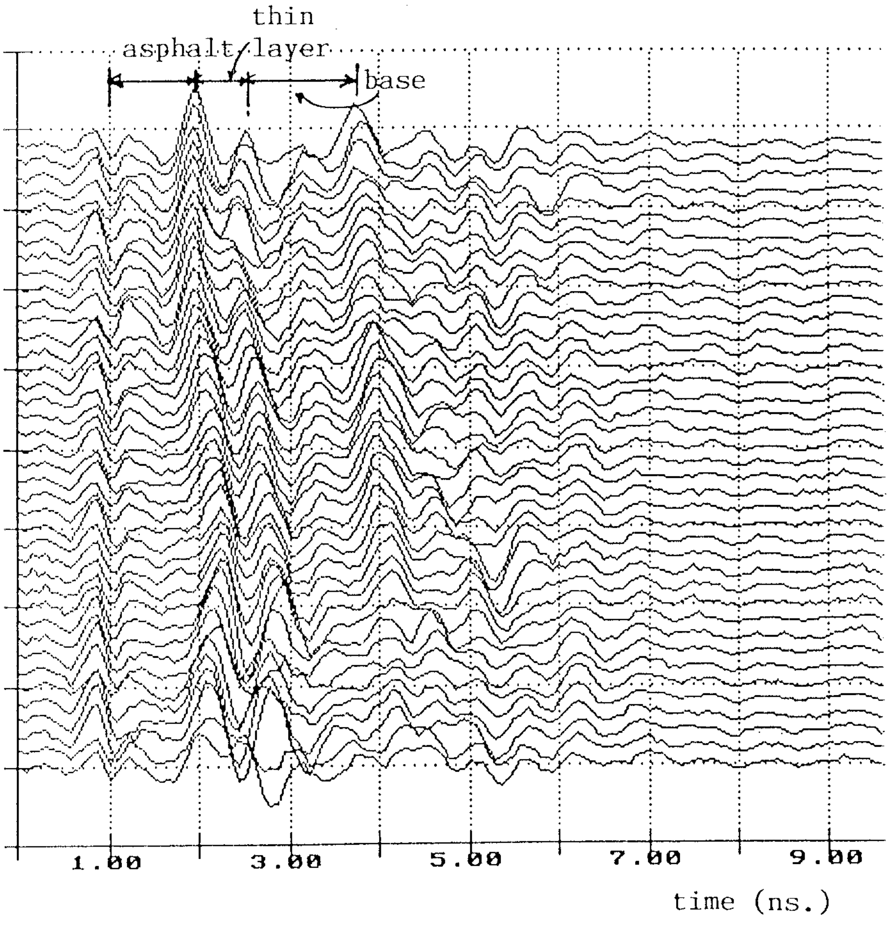
(a) at 10' intervals
over 400'



c:\mnroad\lv2.d
at

From ==> 5300
To ==> 5378 _

(b) at 2' intervals
over 80'

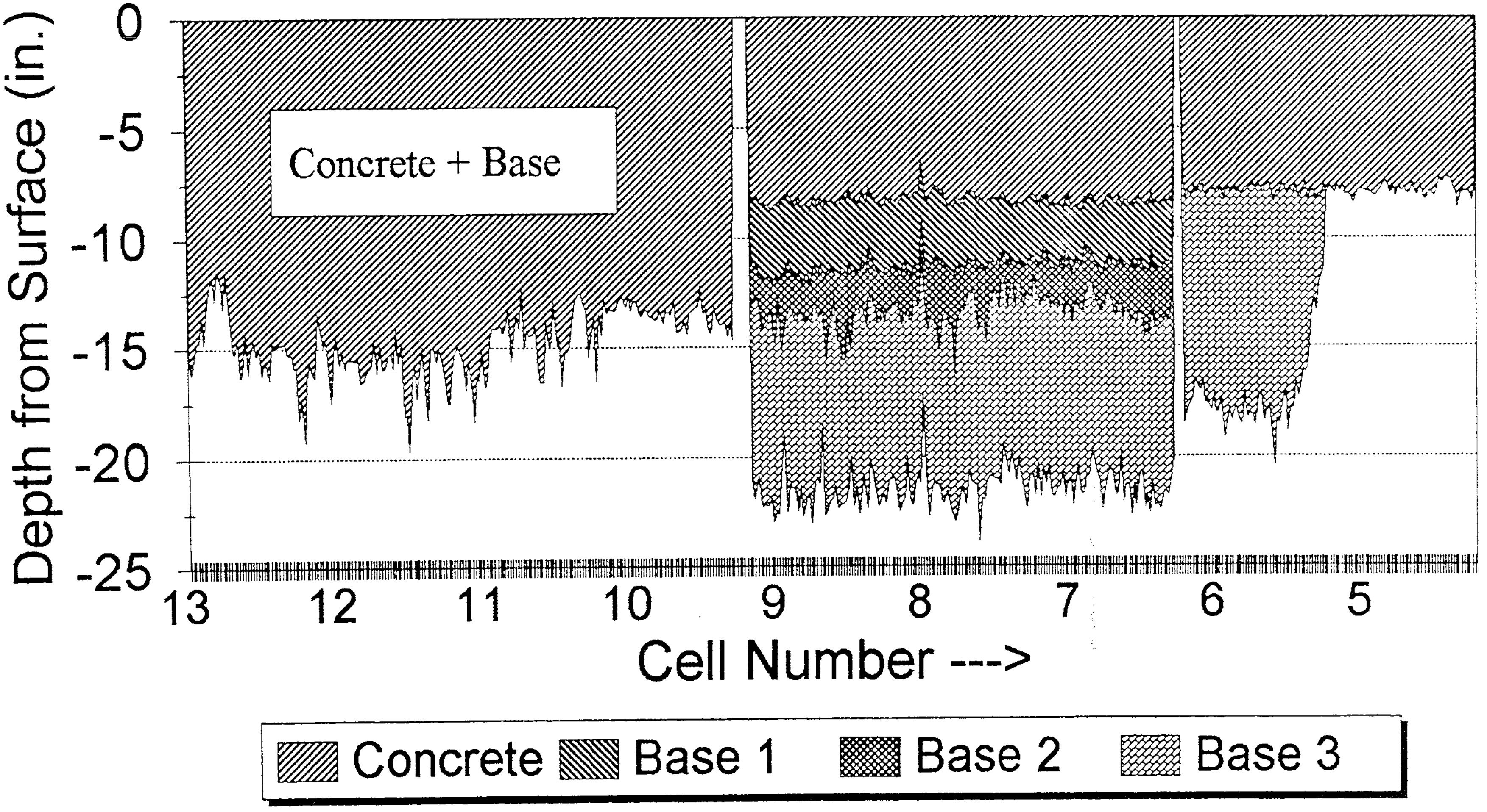


Appendix 2

Plots of Asphalt and Concrete Thickness Results

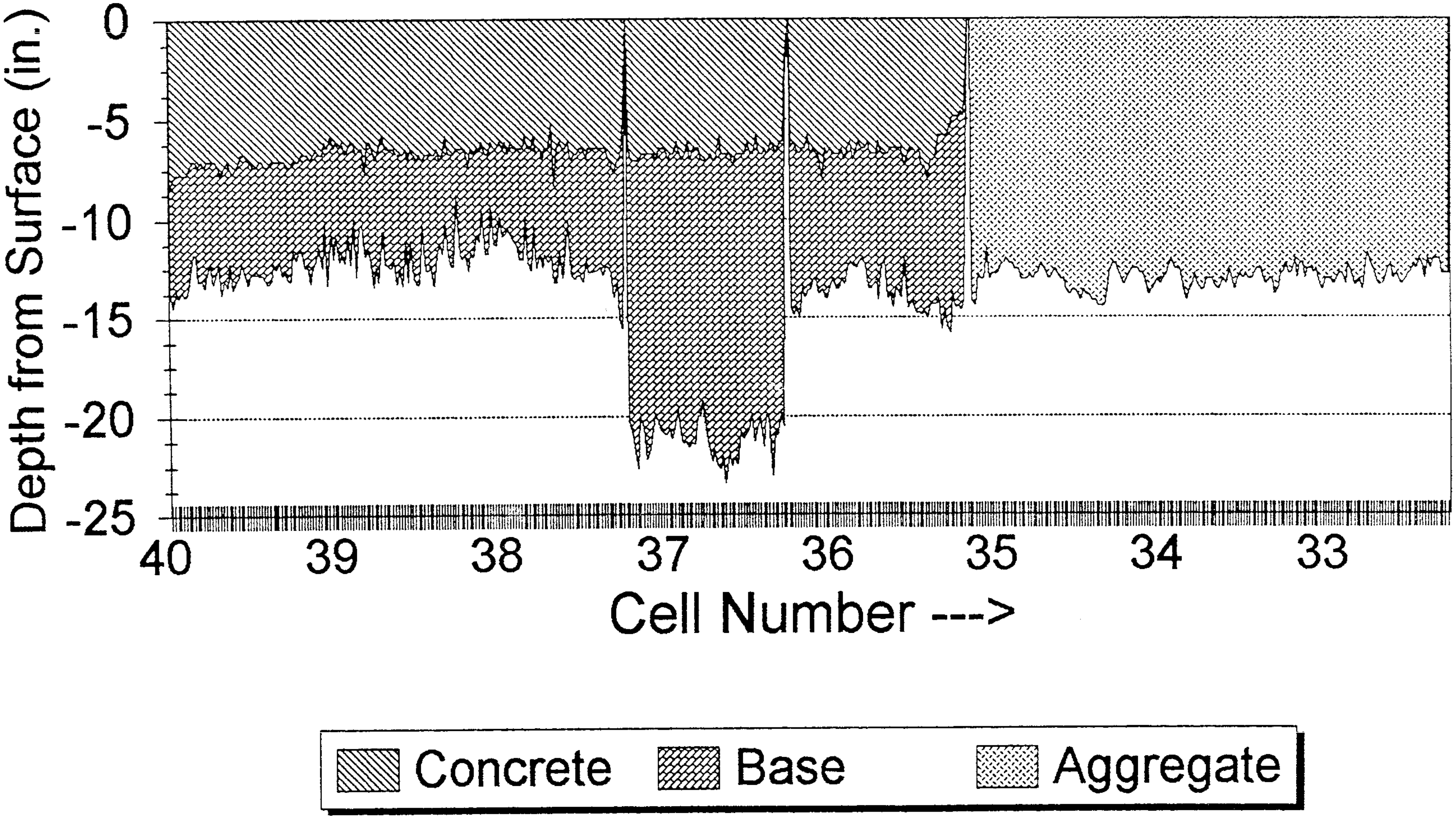
High Volume Road

Concrete and Base Thickness (north wp)



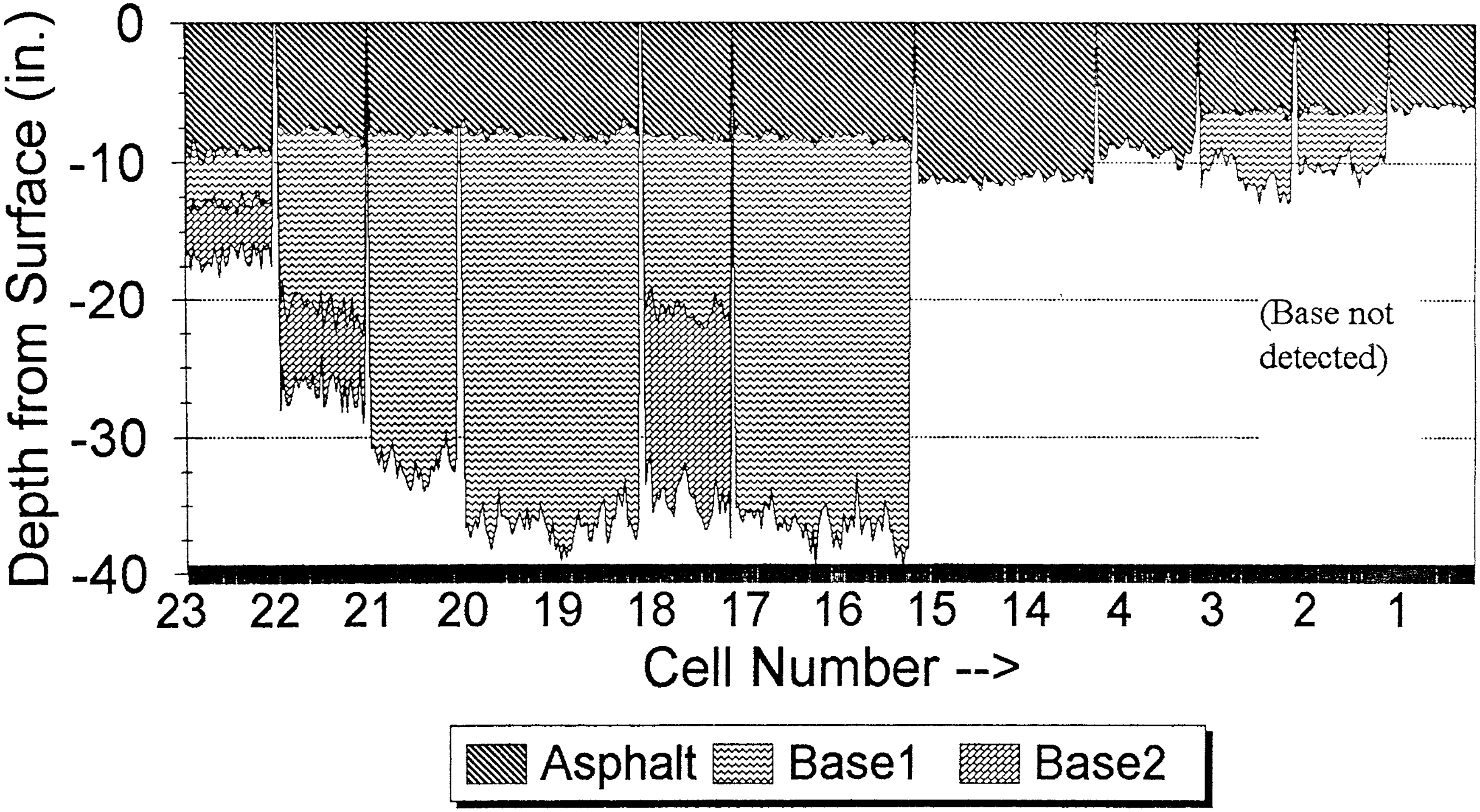
Low Volume Road, North Section

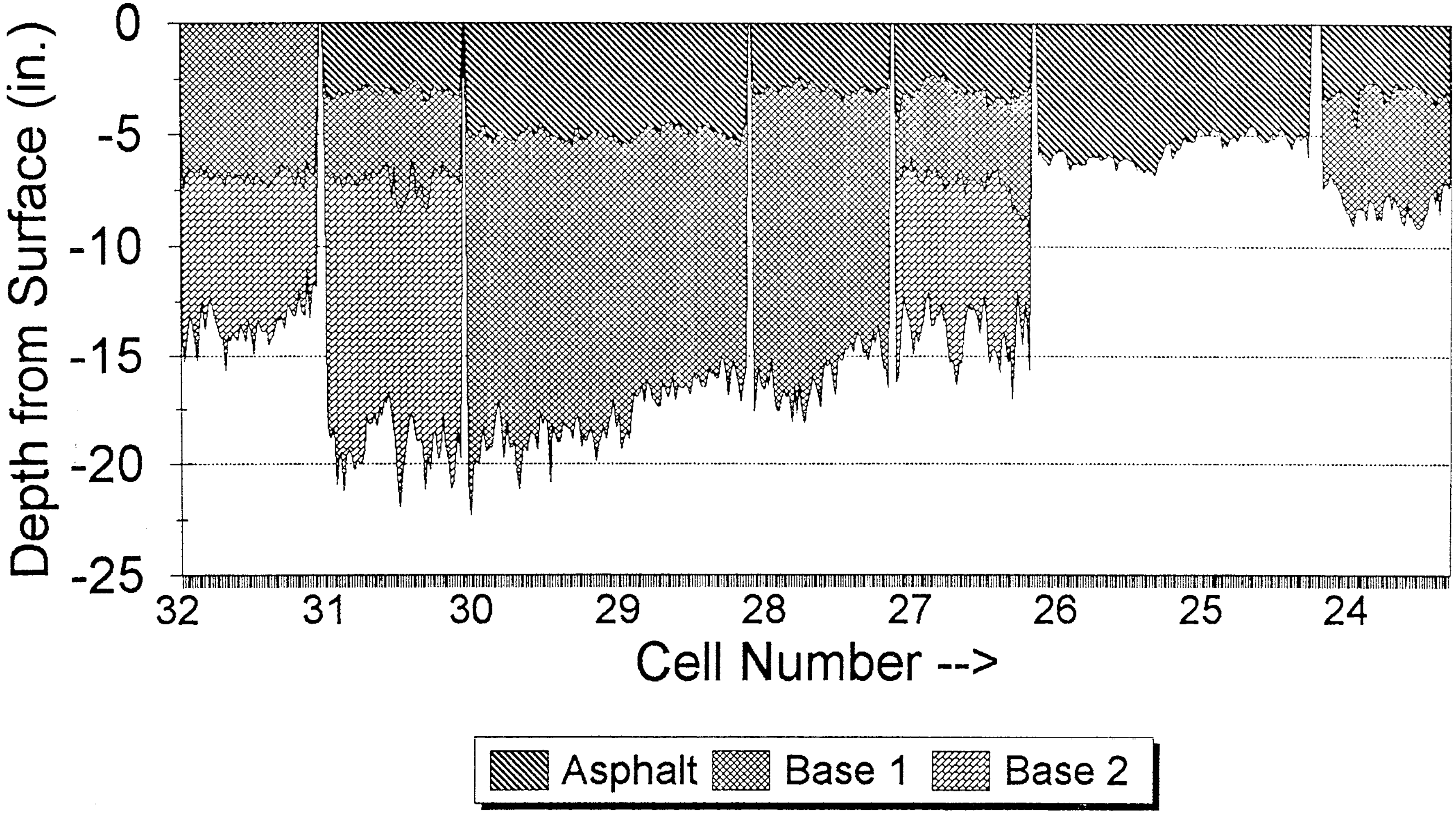
Concrete/Base/Aggregate Thickness



High Volume Road

Asphalt and Base Thickness (north wp)





Low Volume Road, South Section

Asphalt and Base Thickness (north wp)

Appendix 3

Table of Asphalt and Concrete Thickness Values at Core Locations

Radar Thickness vs. Asphalt Core Data

Cell #	Core ID #	Station (ft. x 100)	Radar Distance (feet)	Thickness (in.)		Absolute Difference (inches)
				Radar	Core	
14	54	1189.16	5684	11.34	11.35	0.008
14	56	1189.18	5682	11.47	11.44	0.026
14	58	1194.24	5176	11.58	11.30	0.280
14	60	1194.22	5178	11.24	11.41	0.165
15	65/66	1194.66	5134	11.76	11.64	0.117
15	67/68	1194.68	5132	11.8	11.64	0.156
15	70	1199.74	4626	11.36	11.43	0.067
15	72	1199.72	4628	11.6	11.52	0.076
16	77/78	1200.61	4539	8.93	8.75	0.181
16	79/80	1200.63	4537	8.68	8.77	0.086
17	85/86	1206.11	3989	8.52	8.27	0.249
17	87/88	1206.13	3987	7.97	8.30	0.329
18	101/102	1211.81	3419	8.45	8.41	0.036
18	103/104	1211.83	3417	7.68	8.48	0.798
19	109/110	1217.51	2849	8.26	7.90	0.363
19	111/112	1217.53	2847	7.95	7.90	0.051
19	118	1222.59	2341	8.32	8.45	0.134
19	120	1222.57	2343	8.51	8.51	0.002
20	122	1223.01	2299	8.15	8.14	0.005
20	124	1223.03	2297	7.75	8.18	0.427
20	130	1228.09	1791	7.39	7.79	0.400
20	132	1228.07	1793	7.48	7.89	0.413
21	138	1228.91	1709	7.54	7.50	0.043
21	140	1228.93	1707	7.61	7.43	0.182
22	150	1234.71	1129	8.63	8.92	0.287
22	152	1234.73	1127	8.43	8.98	0.553
18	98	1211.81	3419	7.9	7.94	0.044
18	100	1211.83	3417	7.85	7.76	0.086
20	125/126	1223.01	2299	7.89	8.13	0.244
20	127/128	1223.03	2297	8.02	8.11	0.093
21	134	1228.91	1709	7.33	7.59	0.263
21	136	1228.93	1707	7.32	7.53	0.209
21	141/142	1233.99	1201	7.52	7.71	0.190
21	143/144	1233.97	1203	7.33	7.63	0.301
25	189/190	169.14	4386	5.41	5.28	0.134
25	191/192	169.12	4388	5.37	5.21	0.159
26	194	169.61	4339	5.29	6.82	1.534
26	196	169.63	4337	5.48	6.88	1.399
28	225	186.04	2696	3.25	3.45	0.203
28	228	186.02	2698	3.17	3.30	0.133
29	238	191.74	2126	5.38	5.44	0.060
29	240	191.72	2128	5.48	5.42	0.059
31	254	198.06	1494	3.32	3.72	0.397
31	256	198.08	1492	3.31	3.73	0.420
25	185	164.06	4894	6.35	6.45	0.099
25	187	164.08	4892	6.54	6.60	0.064
26	197/198	169.61	4339	5.3	5.57	0.268
26	199/200	169.63	4337	5.59	5.73	0.138
31	257/258	198.06	1494	2.96	3.13	0.171
31	259/260	198.08	1492	3.36	3.31	0.049
31	262	203.14	986	4.49	4.33	0.162
31	264	203.12	988	4.33	4.31	0.016

Mean: 0.237 inches

Radar Thickness vs. Concrete Core Data

ML Cores - Low Speed Lane, Outside WP

Cell #	Field ID #	Station (ft. x 100)	Radar Distance (feet)	Concrete Thickness (in.) Radar	Core	Deviation
5	2	1126.24	11976	8.37	7.39	13.3%
5	8	1131.37	11463	7.96	7.60	4.7%
6	11	1132.00	11400	8.23	7.50	9.7%
6	17	1137.02	10898	7.53	7.40	1.8%
7	26	1142.42	10358	8.64	7.80	10.8%
8	29	1142.67	10333	8.01	7.48	7.1%
8	36	1147.90	9810	8.28	7.90	4.8%
9	40	1148.09	9791	8.48	7.59	11.7%
8	36	1147.90	9810	8.28	7.90	4.8%
9	40	1148.09	9791	8.48	7.59	11.7%
9	45	1153.29	9271	7.74	7.65	1.2%
					Average:	7.2%

Low Volume, North Section, North WP

Cell #	Field ID #	Station (ft. x 100)	Radar Distance (feet)	Concrete Thickness (in.) Radar	Core	Deviation
37		86.38	2162	6.77	6.36	6.4%
37		86.40	2160	6.77	6.36	6.4%
38		91.91	1609	7.72	6.56	17.7%
39		97.00	1100	7.40	6.22	19.0%
36		81.24	2676	7.09	6.62	7.1%
40		102.47	553	7.09	6.48	9.4%
36		86.13	2187	6.14	6.25	-1.8%
37		91.60	1640	6.14	6.60	-7.0%
38		96.87	1113	6.46	6.40	0.9%
39		102.17	583	6.77	6.60	2.6%
40		107.42	58	8.67	8.15	6.4%
					Average:	6.1%

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