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Pavement Thickness Evaluation by GPR Survey in Idaho

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ABSTRACT

In 1995 and 1996, the Idaho Transportation Department (ITD) conducted a series of ground-penetrating radar (GPR) surveys as a nondestructive testing (NDT) method to evaluate the thickness of asphalt and Portland cement concrete (AC/PCC) pavements in Idaho. GPR surveys employed both air-coupled and combination air and ground coupled systems with their associated equipment and software. A total of 30 miles of AC/PCC pavements were evaluated by GPR surveys. The results obtained were correlated with the site-specific ground-truth data from borings.

Knowledge of pavement layer thickness is needed to predict pavement performance, establish load carrying capacities and develop maintenance and rehabilitation priorities. In addition, for new construction, it is important to ensure that the thickness of materials being placed by the contractor is acceptably close to specification. Core sampling and test pits are destructive to the pavement system, expensive, time consuming and intrusive to traffic. The objective of the ITD study was to evaluate, compare and assess the ability of these two GPR systems to accurately measure the thickness of multiple pavement layers, and document the data nondestructively. This paper reviews the findings of these surveys and provides statistically based data for both AC and PCC pavements.

The overall study has shown that reasonably accurate, dependable determination of pavement thickness can be achieved by using GPR survey for conditions encountered in Idaho.

Key Words: GPR survey, pavement thickness evaluation, NDT testing.

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1. INTRODUCTION

The research study was performed as a part of the ITD Research Project No. 119 (GPR Test Sections). The study considered network (whole section length) and project (500 foot-long section length) level pavement applications. The objective was to assess and analyze the ability of GPR technology as a NDT method of data collection for AC/PCC pavement. GPR surveys employed either air-coupled (A-C) or combination air and ground-coupled (A-G-C) systems, each with associated equipment and component software for interpretation of gathered pavement thickness data (i.e., pavement surface thickness, base thickness and subbase thickness).

ITD provided the descriptions and locations of eight state highway test sections by functional class, route number, beginning and ending mile posts, and whether the pavement type was flexible (AC) or rigid (PCC) pavement for the GPR technology application. ITD also provided a plan and procedures guide for collection of pavement thickness data at normal driving speeds, with no lane closures, for rural and urban highway sections. The plan addressed the speed limit variation from 35 mph to 55 mph. The summary of roadway test sections is provided in Table 1. The total length of network lanes surveyed was 29.269 miles. The total number of 500-foot long sections surveyed was 16.

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Both GPR firms (A-C and A-G-C) were asked to provide the output and documentation of the process involved for statistical and visual validation on the highway network and project level analyses. Both GPR firms additionally had to describe their study results on pavement thickness data, and correlate the findings with the ground-truth data (GTD) obtained from ITD borings drilled in the designated locations of the GPR test sections. The correlation against the GTD was required to determine the accuracy (including both the network and project level data accuracy analyses) of these NDT devices typically used elsewhere in pavement thickness data collection processes. The focus of the study was centered upon the applicability of the GPR system(s) to conditions encountered in Idaho.

2. GPR/NDT PROCEDURES

The development of GPR began in the late 1960's. The earliest study on the use of GPR in areas related to civil engineering was reported in 1974. GPR, more appropriately called short-pulse radar, is the electromagnetic analog of sonic and ultrasonic pulse-echo methods. GPR is governed by a process involving the propagation of electromagnetic energy through materials of different dielectric constants.[1] Coetzee, *et al* [2] provides the following brief description of the procedure:

> "GPR directs pulses of electromagnetic radiation into the ground or pavement structure. A portion of this energy is reflected back to the surface, and picked up by the GPR receiver, at each location in the pavement structure where a significant difference in electrical properties of the materials occur. The electrical property of interest is the material's dielectric constant. GPR is effective for pavement evaluations as long as there is sufficient contrast in the dielectric constant of the paving materials. Additionally, the dielectric constant is frequency dependent. The following dielectric ranges are typical for paving materials at a frequency of approximately 1 GHz:

➢ Air	1
➢ Asphalt Surface / Black (asphalt) Base	5 to 6
➢ Concrete / Cement Stabilized Base	8 to 9
➢ Flexible Base	10 to 11 (highly moisture dependent)
➢ Water	80
➢ Steel	81

> From the list above, it is evident that pavement layers composed of materials having significantly different dielectric constants can be identified. Pavement structures having multiple layers with similar dielectric constants are more difficult to evaluate, and it may not be possible to identify each individual layer and measure its thickness. Additionally, city streets often have utility patches and maintenance practices that can confuse data reduction.
>
> The wavelength of a 1-gigahertz GPR system is approximately three inches. The thickness of layers approximately one-quarter of the radar wavelength or greater can be resolved. Consequently, GPR systems cannot resolve pavement layers less than 1 inch in thickness. The 1-gigahertz system has a depth of penetration of approximately 24 inches. The penetration depth is a function of the overall dielectric constant of the pavement structure. Materials possessing a high dielectric constant tend to attenuate the radar signal, thereby decreasing its effective depth of penetration.
>
> A 500-megahertz GPR system has a wavelength of approximately six inches. Since the signal has a longer wavelength, it can penetrate deeper into the pavement structure. The 500 MHz system is capable of measuring to depths of four to five feet, depending on the dielectric constant of the material. The trade-off is less thickness measurement capability with the 500 MHz system when compared to the 1 GHz system."[2]
>
> "Assuming that the dielectric constant of a given material is uniform and known, the two-way transit time of microwave pulses through the material is directly proportional to the thickness of the material. The presence of observed range of errors in the results likely reflects the fallacy of the assumption inherent in this procedure that the material at all locations has the same relative dielectric constant and errors exceeding ± 0.25 inches is considered acceptable for compliance testing."[1]
>
> "The success of thickness measurement using GPR depends on a reasonably detectable reflection from the backside (or the bottom) of the member (AC or PCC pavement slab), because this allows for the

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precise identification of the reflection and, therefore, the accurate measurement of the transit time. Conditions that would prevent the reflection from being precisely detected include the presence of the relatively high attenuation of the microwave pulses by the pavement materials, insufficient difference between the relative dielectric constants of the pavement materials (surface and base course), and pavements that are too thick. For some pavements, it is likely that there may be only small differences between the relative dielectric constants of the surface course (AC or PCC), base course and the subbase materials, so that this reflection would be very weak and difficult to identify. Consequently, prior to an actual inspection, it is generally difficult to predict how precise the GPR measurements will be in measuring the thickness of a particular pavement."[1]

"Short-pulse radar systems operate by transmitting a single pulse that is followed by a "dead time" in which reflected signals are returned to the receiver. A basic radar system consists of a control unit, a monostatic antenna (*i.e.*, an antenna that is used for both transmitting and receiving), an oscillographic recorder, and a power converter for DC operation. A multi-channel instrumentation tape recorder is recommended due to the relatively fast rate at which the inspection has to be carried out. In operation, as the radiated pulses travel through the material, different reflections will occur at interfaces that represent changing dielectric properties. Each reflected eletromagnetic pulse arrives back at the receiving antenna at a different time that is governed by the depth of the corresponding reflecting interface and the dielectric constant of the intervening material. A receiver circuit reconstructs the reflected pulses at an expanded time scale by a time-domain sampling technique. The resulting replicas of the received radar signals are amplified and further conditioned in the control unit before they are fed to an output. The analog output can be displayed on an oscilloscope, an oscillographic recorder, or a facsimile gray-scale graphic recorder. It can also be recorded on magnetic tape for future processing or analysis. On an oscilloscope or an oscillographic recorder, the received radar signals may appear similar to the waveform depending on the radar system used. The received signal consists of three basic components. At the top is the transmitted pulse that serves as a time reference. Immediately following the transmitted pulse is a strong surface reflection, the shape of which is indicative of the shape of the radar pulse transmitted by the antenna. Then, at a later time equal to the pulse travel time from the surface to an interface and back to the antenna, the interface reflection appears. The vertical scale is the time scale, which can be calibrated by a pulse generator that produces pulses at equally spaced time durations. If the wave speed in the material is known, the time scale can be converted to a corresponding depth scale."[1]

3. GPR METHODOLOGIES USED IN ITD STUDY

The GPR system results provide pavement engineers with subsurface information for "project level" rehabilitation design or "network level" planning. The degree of detail and frequency of measurement depend on the requirements of the user. The research by ITD included both.

At the project level, the objective was to gather detailed information for the selected project. The information included continuous subsurface profiles of the thickness of layers, including determination of base problems, subgrade anomalies, surface and sub-surface cracks, voids, debonding and weakened or stripped areas. Rehabilitation design will utilize assigned appropriate layer thicknesses in overlay thickness calculations. One to three project level sections, 500 feet in length, were identified for detailed evaluation and correlation with GTD within each of the overall network level test sections.

At the network level, the objective was to locate pavement segment profiles and check expected performance by gathering sufficient continuous surface and subsurface course thickness information for future planning purposes and budget estimates.

ITD required the assessment of newly developed GPR technologies for both project and network level applications, including demonstration of the equipment operations, data analysis procedures, and comparison of the analyzed GPR data with measurements made by more traditional (destructive) means. A total of 8 road test sections were identified and surveyed as part of this evaluation by ITD. Test sections represented a wide spectrum of network and project level applications, including interstate, principal and minor arterial in both urban and rural settings, and consisted of both AC and PCC pavements. ITD required a variety of GTD information for direct comparison between GPR and core measurements which consisted of coring road test sections at designated locations, logging the bore holes (maximum depth of 7 ft.) and obtaining samples from the materials encountered.

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3.1 Air-Coupled (A-C) GPR System:

The system employed is the Pulse Radar, Inc. RODAR™ GPR equipment, coupled with Infrasense PAVLAYER™ and DECAR™ software.[3] "The GPR equipment used is designed for mobile applications involving the coverage of large distances and areas. The equipment is based on a 1 GHz air-coupled "horn" antenna (called horn because of its outer appearance, and used in a non-contact manner as it is scanned over the pavement surface) positioned from 12 to 18 inches above the pavement surface. Non-contact arrangement allows for road surveys to be performed at normal driving speeds. It is claimed that "for mobile applications, the horn antenna is superior to the more familiar ground-coupled antenna, since it permits driving speed surveys and since it provides a surface reflection for calibration of the surface material dielectric permittivity. Typical horn antenna system generates 50 scans per second, with a pulse width of approximately 1 nanosecond. The radar analog signal is transmitted to a PC-based data acquisition system where it is digitized and stored to hard disk or tape. A distance measuring instrument (DMI) typically operated off of the survey vehicle transmission, provides position pulses which are encoded into the digitized radar for location referencing. Large quantities of data are obtained quickly and processed efficiently by software programs which move sequentially through the digitized radar waveforms at a specified distance interval, computing the amplitudes and arrival times of the interface reflections which are related to pavement internal dimensions and properties. These amplitudes and arrival times are converted to layer thicknesses."[4]

"All data for this study for the project and network level surveys were collected by setting the horn antenna 18 inches above the pavement surface at normal driving speeds which ranged from 25 mph on urban roads to 55 mph on the interstate highways. No lane closures or traffic control was required. Data collection for the project level survey included one for each wheel path and one at the center of the lane. The results of data analysis were presented as plots, maps and American Standard Code Information Interchange (ASCII) data files."[3]

"The pavement analysis was carried out by dividing each pavement into homogeneous sub-sections and identifying the layer boundaries and layer material types for each subsection. The data from this sub-sectioning is exported to an analysis program which automatically computes the layer thicknesses at a prescribed interval. Two output files are produced from this analysis – one for plotting and one for database reporting. For each file, the user can specify the output data interval in feet, meters, or miles, and an averaging interval around each output. For this project, the following intervals were used:

Analysis Type	Basic Analysis Interval (ft.)	Plotting Interval (ft.)	Reporting Interval (ft.)
Project	1	5	50
Network	5	50	250

Pavement thickness was analyzed for all the network surveys and for the right wheelpath data for the project level surveys. The right wheel path was used since it is where the cores were taken."[3]

3.2 Air-Ground-Coupled (A-G-C) GPR System:

"The system employed is patent pending ROAD RADAR™ which employs a hybrid antenna system consisting of a "ground-coupled" antenna system operating at a center frequency of 1 GHz and an "air-coupled" antenna operating at a nominal 3 GHz. The 'air-coupled' antenna is mounted on an adjustable boom above the pavement and measures thin pavement layers. The ground-coupled" antenna is mounted on a runner connected to the rear of the vehicle and measures deeper layers and determines signal velocity. This combination of antenna configurations makes the system versatile, self-calibrating and reliable under a wide range of situations. All electronics are rack mounted inside the vehicle. The rack mounts include control and timing electronics for each sub-system, digitizing computer and monitor, and video sub-system. A comprehensive radar signal processing hardware and software provides the means to effectively combine the large volumes of raw data and allow automated interpretation to provide continuous multiple pavement layer thickness and velocity profiles. The data processing represents a synergism of many programming domains, effectively combining artificial intelligence, time domain digital signal processing, neural networks and pattern recognition. The patent pending approach determines signal velocity at each measurement point. The system measures the signal

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velocity to determine the thickness at each location by varying the geometry between the transmitter and the receiver. Measuring the different signal travel times to a reflector at different known transducer geometries permits the signal velocity to be determined. The output of the data interpretation operation includes graphical radar profiles showing the data acquired during the survey. These profiles present the opportunity to examine the road for qualitative features as well. Such features include base course/subgrade constituent variations and anomalous areas. The Road Radar™ also uses a distance measuring instrument (DMI), connected to the transmission of the vehicle to trigger the radar so that the system is not speed dependent and the location of each measurement is known."[6]

"All network level surveys were conducted at approximately 40-45 mph. The right wheel path is surveyed since it is the track where the GTD cores were taken. The spatial sampling interval for all network level surveys was approximately 24 in., producing about 2640 samples per mile. Project level surveys were conducted at approximately 15 mph with a spatial sample interval of approximately 8 inches. This increased spatial resolution provided more details and extended automated radar data interpretation capabilities. Each wheel path and center of lane were surveyed for all project level lanes on a continuous basis."[7]

4. SUMMARY OF FINDINGS

The accuracy of the GPR systems can be assessed by a correlation comparison with available GTD. The comparisons included in this research study utilized linear regression analysis. All core measurements, forming the basis for the comparisons for both project and network level surveys, are presented with the corresponding GPR measurements. Graphical GPR versus core measurement comparisons have been segregated into project and network level surveys for individual statistical comparisons of surface and base course layer measurements.

Figures 1, 2, and 3 represent project level surveys of the thickness of the AC and PCC pavement surface course for all project sites. Figures 4, 5, and 6 represent network level surveys of the thickness of the AC and PCC pavement surface course for all project sites. Figures 7, 8, and 9 represent project level surveys of the thickness of the AC and PCC pavement base course for all project sites. Figures 10, 11, and 12 represent network level surveys of the thickness of the AC and PCC pavement base course for all project sites. Figures 1, 4, 7, and 10 represent comparisons of the GTD with A-C GPR data. Figures 2, 5, 8, and 11 represent comparisons of GTD with A-G-C GPR data. Figures 3, 6, 9, and 12 represent comparisons of the A-C GPR data with the A-G-C GPR data. The data plotted in each figure was subjected to a best-fit linear regression analysis and calculation of a coefficient of correlation.

Figures 1, 2, and 5, with average deviations of 2.5, 4.7, and 9.8 percent respectively, were found to have large correlation coefficients indicating statistical reliability of the best-fit regression. The level of accuracy achieved by using GPR for surface course pavement thickness measurements is consistent with that reportedly achieved in previous studies.[3] Figure 3 was also found to have a large correlation coefficient. Analysis of the raw data used to derive the figures resulted in the following average deviations between the compared pairs of GTD and GPR measurements.

Figure No.	Measured Thickness	Survey Level	Compared Relations ( ) minus ( )	Average Deviation	
				Percent	Inch
1	SC	P	(A-C) - (ITD/GTD)	2.5	0.13
2	SC	P	(A-G-C) - (ITD/GTD)	4.7	0.31
3	SC	P	(A-C) - (A-G-C)	--	-0.11
4	SC	N	(A-C) - (ITD/GTD)	4.5	0.06
5	SC	N	(A-G-C) - (ITD/GTD)	9.8	0.53
6	SC	N	(A-C) - (A-G-C)	--	-0.44
7	BC	P	(A-C) - (ITD/GTD)	-6.7	-0.92
8	BC	P	(A-G-C) - (ITD/GTD)	13.2	0.19
9	BC	P	(A-C) - (A-G-C)	--	-1.08
10	BC	N	(A-C) - (ITD/GTD)	45.9	0.88
11	BC	N	(A-G-C) - (ITD/GTD)	0.02	-0.29
12	BC	N	(A-C) - (A-G-C)	--	0.50

LEGENDS: SC = Surface Course BC = Base Course
P = Project Level N = Network Level

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Figures 1, 2, 3, and 5 have line slope values close to 1.0, indicating an almost direct proportional relationship between the compared relations, *i.e.*, the GPR-based results match very closely to the GTD data obtained by coring. The remaining figures indicated large data scatter with low coefficients of correlation, suggesting minimal statistical relationships between the compared values.

The comparison of results from Figures 1 and 2 indicates that both A-C and A-G-C GPR systems are equally capable of predicting GTD obtained from project level surface course thickness measurements. Figure 3 also suggests almost equal capability between A-C and A-G-C GPR systems in estimating the thickness of the surface course obtained during project level GPR survey. However, results from both GPR systems at the network level surveys, as shown in Figures 4 and 5, appear to indicate an overestimatation (between 4.5 and 9.8 percent) of the thickness of surface course pavement. Figure 6 shows that the A-G-C GPR system slightly overestimates the thickness of network level surface course compared to the A-C GPR system-based surface course results. The evaluations of Figures 7, 8, and 9, for project level, and Figures 10, 11, and 12, for network level, base-course thickness measurements indicate that both GPR systems appear not to be accurately predicting the GTD within the expected ranges. The results are not very comparable to reported values in previous studies (Reference 3).

Additional statistical analyses of the data was done using Pearson's Correlation Coefficient. The results are summarized in Table 2. The interpretation of the Table 2 results is presented in Table 3. The evaluation of the data suggests good, dependable relationships between GPR and GTD for measurement of the thickness of the surface course. Base course thickness measurements appears to have only a minimal to moderate relationship between GPR and GTD.

5. CONCLUSIONS AND RECOMMENDATIONS

The research objective of this project was to evaluate the effectiveness of GPR as a NDT method component of a highway-pavement, structural evaluation system in Idaho. The knowledge of pavement layer thickness is needed for highway network analysis to establish load carrying capacities and develop rehabilitation and maintenance priorities. Previously, the acceptable methods for pavement-thickness measurements included test pits and borings to obtain core samples. These methods are time consuming, intrusive to traffic and destructive to the pavement system. The GPR systems provide a relatively low-cost, and reasonable reliable alternative to coring.

The study has shown that reasonably accurate, dependable determination of pavement surface course (AC/PCC) layer thickness can be achieved using a normal driving speed data collection method by either A-C or A-G-C based GPR NDT systems. The results indicate that, for both systems, project level surveys provide higher quality and more accurate data in comparisons to the network level GPR surveys. Base course thickness measurement results of both the project and the network level surveys indicate that both GPR technologies are capable of providing the similar results. The reported base course thickness values appear to deviate significantly from the GTD, suggesting that the proper estimation between surface and unbounded base course layers will require occasional cores for conditions encountered in Idaho.

6. ACKNOWLEDGEMENT

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Table 1: ITD Roadway Test Sections for Network and Project Level GPR Surveys

Roadway	Description/Location	Mile Posts (Beginning-Ending) (miles and feet)	Survey Type	Total Length Surveyed	Miscellaneous Information	Mile Posts for ITD Core Data (Boring location) (miles and feet)
SH-16	State Highway-16, minor arterial, asphalt concrete surface, two lane rural highway, Ada County Line to Sand Hollow Road	8.359 – 11.960	N	3.601 miles	Ascending direction	9.1 + 0; 9.1 + 500; 10.0 + 0; 10.0 +250; 10.0 +500; 11.0 +0; 11.0 +250; 11.0 +500
		9.1 – 9.1 + 500 ft.	P #1	500 ft.		
		10.0 – 10.0 + 500 ft.	P #2	500 ft.		
		11.0 – 11.0 + 500 ft.	P #3	500 ft.		
US-20	US Highway-20, principal arterial, asphalt concrete surface, two lane rural highway, Canyon County Line to Junction SH-55 (State Highway-55)	32.283 – 40.229	N	7.946 miles	Ascending direction, 0.3 ft. overlay in June 1995	34.0 + 0; 34.0 + 105; 34.0 + 500; 36.0 + 0; 36.0 + 500; 38.0 + 500
		34.0 – 34.0 + 500 ft.	P #1	500 ft.		
		36.0 – 36.0 + 500 ft.	P #2	500 ft.		
		38.0 – 38.0 + 500 ft.	P #3	500 ft.		
SH-44	State Highway-44, principal arterial asphalt concrete surface, two lane rural highway, Intersection State and Knox Street to Junction SH-16.	10.771 – 12.298	N	1.527 miles	Ascending direction	11.0 + 0; 11.0 +500
		11.0 – 11.0 + 500 ft.	P #1	500 ft.		
I-84/WB	Interstate-84, six lane divided highway, west bound inside lane, Portland cement concrete surface Meridian City Limit to Ridenbaugh Canal	44.960 – 46.770	N	1.810 miles	Asphalt treated permeable base	46.0 + 0; 46.0 +500
		46.0 – 46.0 + 500 ft.	P #1	500 ft.		
I-84/EB	Interstate-84, four lane divided highway, east bound lane, asphalt concrete surface, A-Line Canal to Maintenance Cross-Over	5.968 – 12.610	N	6.642 miles	0.4 ft. overlay in 1985	8.0 + 0; 8.0 + 500; 10.0 + 0; 10.0 + 500
		8.0 – 8.0 + 500 ft.	P #1	500 ft.		
		10.0 – 10.0 + 500 ft.	P #2	500 ft.		
I-84/EB	Interstate-84, four lane divided highway east bound lane, Portland cement concrete surface, Interchange #95 to Interchange #99	96.153 – 99.570	N	3.417 miles	Open graded base	97.0 + 0; 97.0 + 500; 98.0 + 0; 98.0 + 500
		97.0 – 97.0 + 500 ft.	P #1	500 ft.		
		98.0 – 98.0 + 500 ft.	P #2	500 ft.		
I-84B/EB	Business route of Interstate, four lane divided highway, principal arterial, asphalt concrete surface, east bound outside lane, Caldwell Blvd., N. Midway to Homedale Road	53.842 – 54.468	N	0.626 miles	--	54.0 + 0; 54.0 + 130; 54.0 + 500
		54.0 – 54.0 + 500 ft.	P #1	500 ft.		
US-95	US Highway-95, principal arterial, asphalt concrete surface, two lane rural highway, Milepost Equator Marker to N. End Devils Elbow	86.600 – 90.300	N	3.700 miles	Open graded base	88 + 0; 88 + 500; 89 + 0; 89 + 500; 90 + 0; 90 + 500;
		88.0 - 88.0 + 500 ft.	P #1	500 ft.		
		89.0 – 89.0 + 500 ft.	P #2	500 ft.		
		90.0 – 90.0 + 500 ft.	P #3	500 ft.		

LEGEND:
WB – West Bound
EB – East Bound
SH – State Highway
US – United States Highway
I – Interstate
N – Network Level
P – Project Level

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Table 2: Pearson's Correlation Coefficient (r) and Coefficient of Determination (r^2) for GPR and ITD's Groud-Truth Data

Type of Pavement Thickness Measurement	Suvey Type	(A-C) GPR versus ITD Data				(A-G-C) GPR versus ITD Data				(A-C) GPR versus (A-G-C) GPR Data				Data used in Figure Numbers
		Sample Size	r^2	r	Interpretation*	Sample Size	r^2	r	Interpretation*	Sample Size	r^2	r	Interpretation*	
Surface Course (Asphalt or Concrete)	Project	32	0.9627	0.9812	Very high correlation, very dependable relationship	35	0.9778	0.9888	Very high correlation, very dependable relationship	32	0.9290	0.9638	Very high correlation, very dependable relationship	1, 2, 3
	Network	32	0.6546	0.8091	High correlation, marked relationship	35	0.9498	0.9746	Very high correlation, very dependable relationship	32	0.6006	0.7750	High correlation, marked relationship	4, 5, 6
Base Course	Project	30	0.004	0.0211	Slight negligible relationship	35	0.1854	0.4306	Moderate correlation, substantial relationship	30	0.2449	0.4948	Moderate correlation, substantial relationship	7, 8, 9
	Network	12	0.0879	-0.2965	Negligible Relationship	35	0.2416	0.4915	Moderate correlation, substantial relationship	12	0.0346	-0.1859	Negligible Relationship	10, 11, 12

* Reference 8, pp. 216, Table 10.3 (Guilford's suggested interpretations for values of r).

Note: (R^2) values indicated on Figures 1 through 12 are correlation coefficients used in regression analysis.

Table 3: Statistical Analyses Results of GPR and ITD's Ground-Truth Data

Type of Pavement Thickness Measurement	Survey Type	Variations (Differences) Between:																	
		(A-C) GPR and ITD Data						(A-G-C) GPR and ITD Data						(A-C) GPR and (A-G-C) GPR Data					
		Sample Size	Mean (in.)	Std. Deviation	Student's (t)	Probability Associated with Student's (t)	Interpretation*	Sample Size	Mean (in.)	Std. Deviation	Student's (t)	Probability Associated with Student's (t)	Interpretation*	Sample Size	Mean (in.)	Std. Devia -tion	Student's (t)	Probability Associated with Student's (t)	Interpretation*
Surface Course (Asphalt or Concrete)	Project	32	0.13	0.586	1.2067	0.2367	Difference between is not significant	35	0.31	0.568	3.2409	0.0027	Difference between is significant	32	-0.11	0.831	-0.7660	0.4489	Difference between is not significant
	Network	32	0.06	2.068	0.1710	0.86525	Difference between is not significant	35	0.53	0.762	4.1048	0.00024	Difference between is highly significant	32	-0.44	2.264	-1.0929	0.28210	Difference between is not significant
Base Course	Project	30	-0.92	2.572	-1.9531	0.0591	Difference between is probably significant	35	0.19	1.710	0.6720	0.5061	Difference between is not significant	30	-1.08	1.690	-3.5117	0.0013	Difference between is significant
	Network	12	0.88	3.362	0.9015	0.3866	Difference between is not significant	35	-0.29	1.784	-0.9568	0.3592	Difference between is not significant	12	0.50	3.313	0.5228	0.6115	Difference between is not significant

* Reference 5, pp. 227-233, Fig. 81 and Reference 8, pp. 370-383.

Figure 1: ITD Core Data (Ground Truth) versus Air-coupled (A-C) Data for Surface Course Thickness (Project Survey, All Sites)

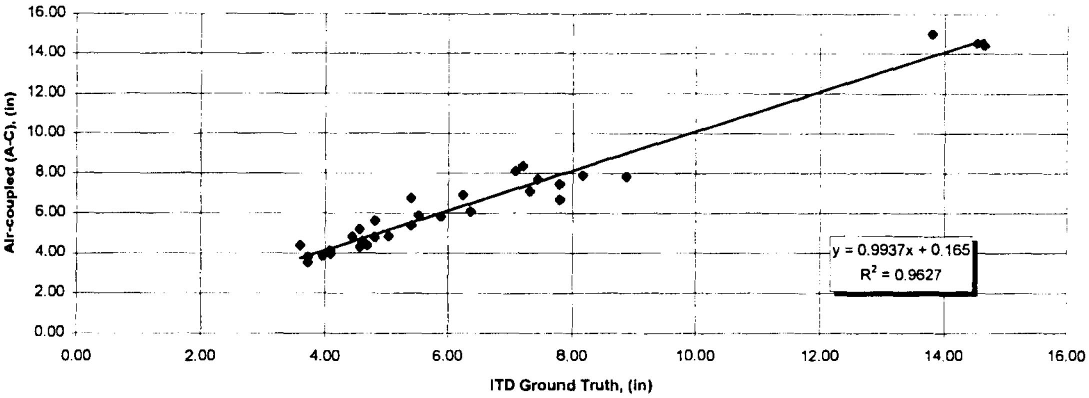

Figure 2: ITD Core Data (Ground Truth) versus Air-ground-coupled (A-G-C) Data for Surface Course Thickness (Project Survey, All Sites)

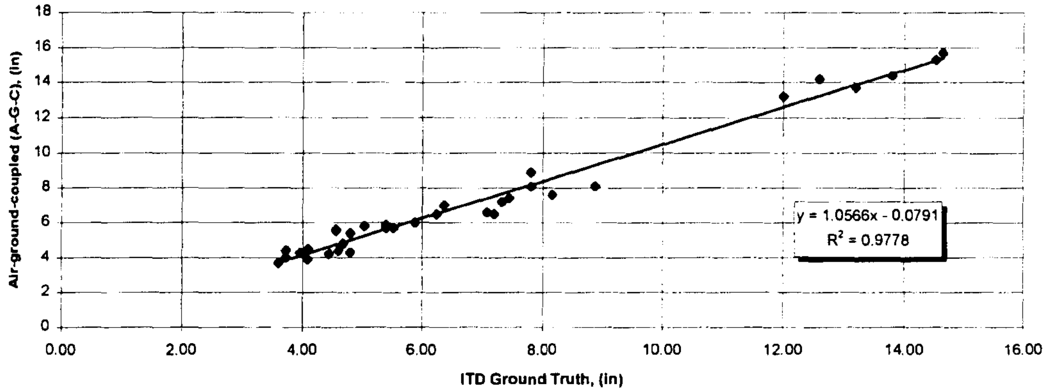

Figure 3: Air-coupled (A-C) Data versus Air-ground-coupled (A-G-C) Data for Surface Course Thickness (Project Survey, All Sites)

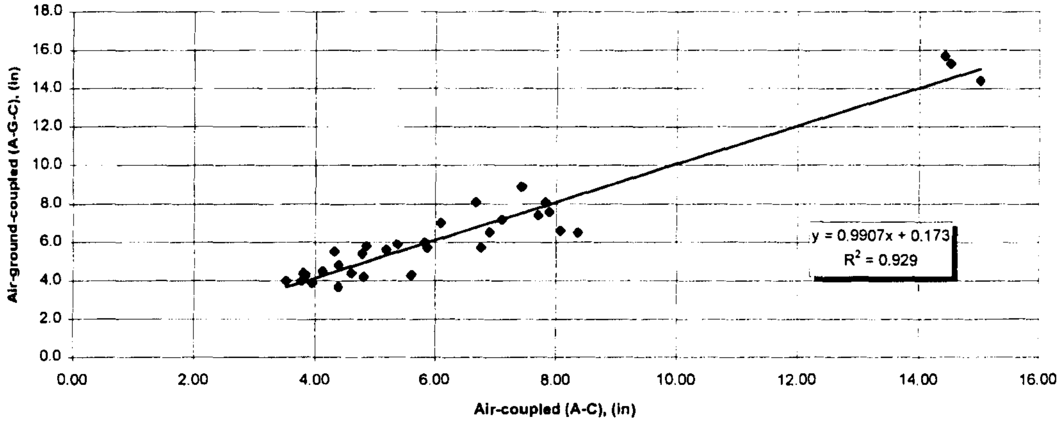

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Figure 4: ITD Core Data (Ground Truth) versus Air-coupled (A-C) Data for Surface Course Thickness (Network Survey, All Sites)

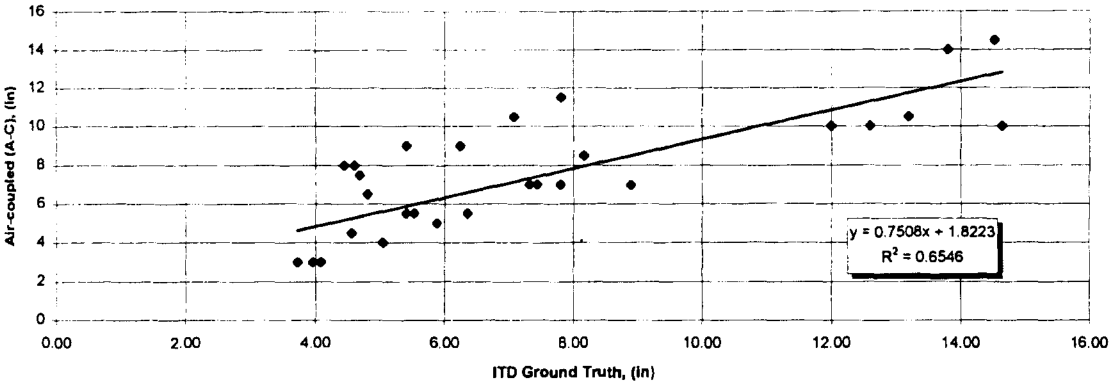

Figure 5: ITD Core Data (Ground Truth) versus Air-ground-coupled (A-G-C) Data for Surface Course Thickness (Network Survey, All Sites)

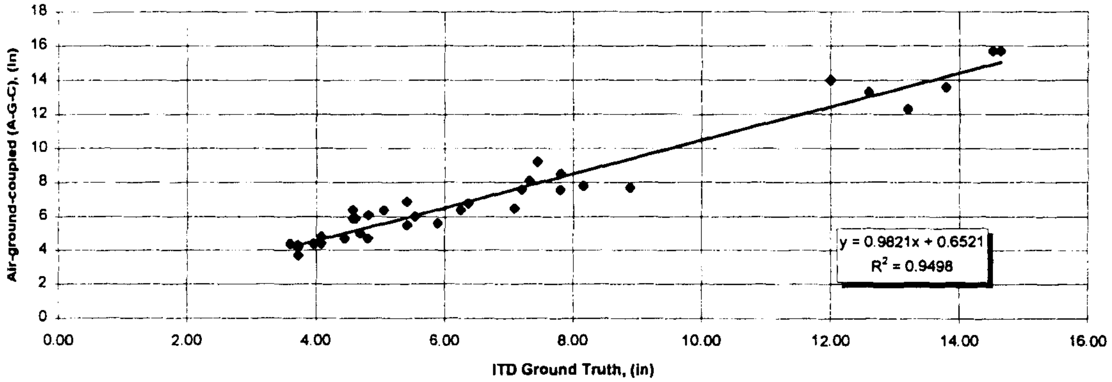

Figure 6: Air-coupled (A-C) Data versus Air-ground-coupled (A-G-C) Data for Surface Course Thickness (Network Survey, All Sites)

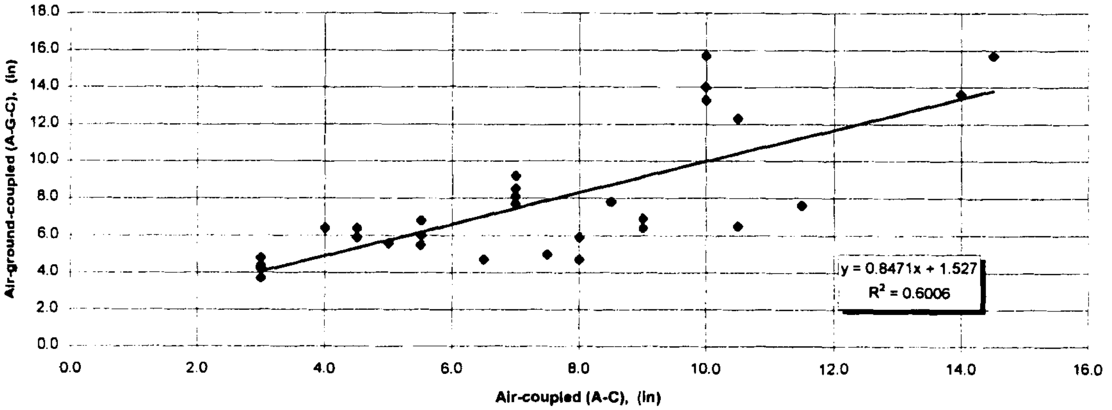

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Figure 7: ITD Core Data (Ground Truth) versus Air-coupled (A-C) Data for Base Course Thickness (Project Survey, All Sites)

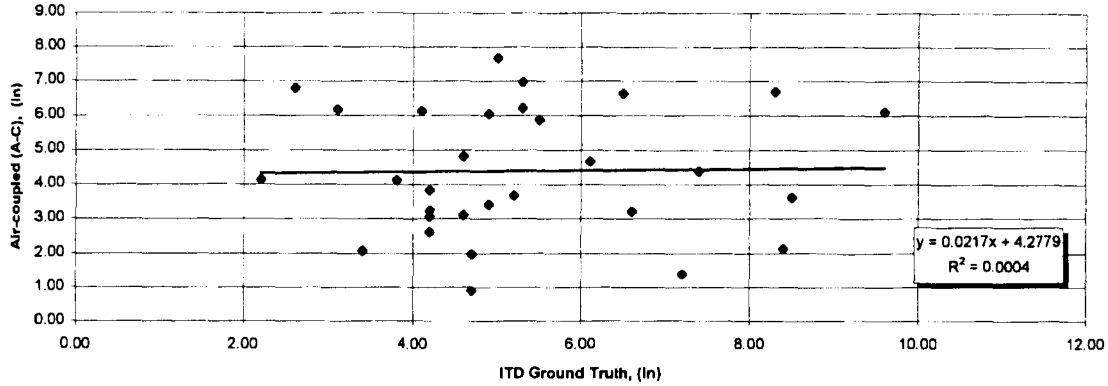

Figure 8: ITD Core Data (Ground Truth) versus Air-ground-coupled (A-G-C) Data for Base Course Thickness (Project Survey, All Sites)

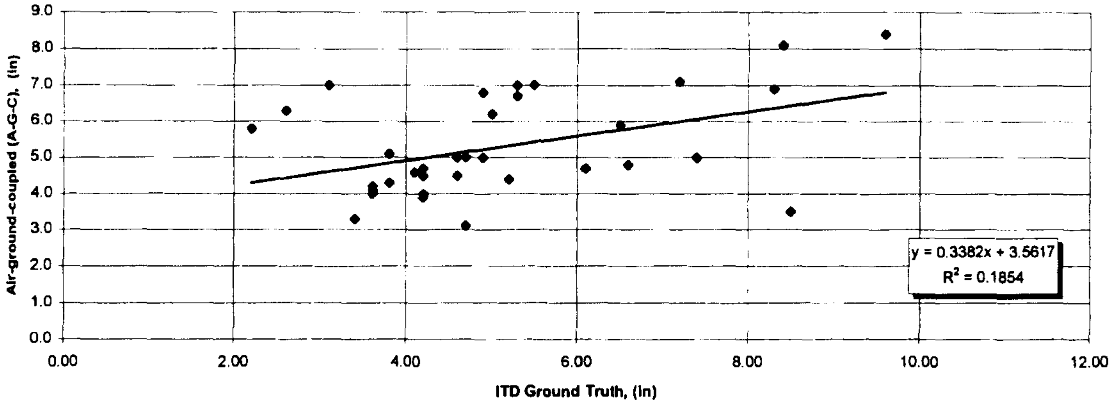

Figure 9: Air-coupled (A-C) Data versus Air-ground-coupled (A-G-C) Data for Base Course Thickness (Project Survey, All Sites)

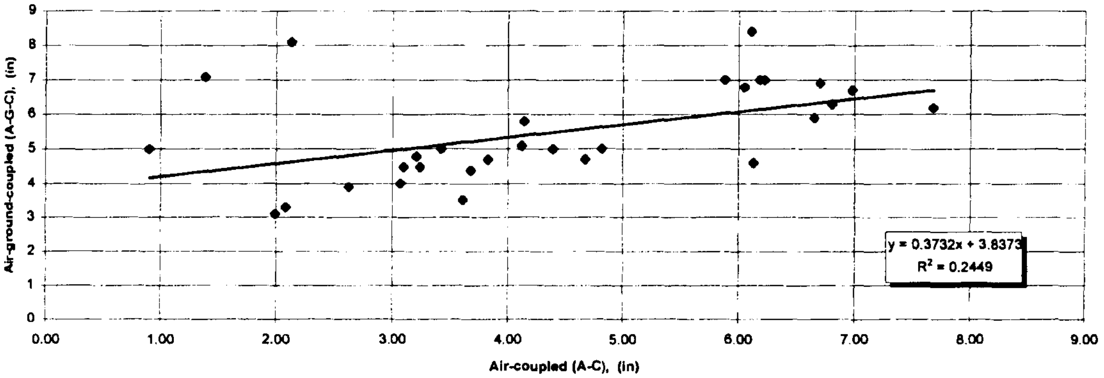

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Figure 10: ITD Core Data (Ground Truth) versus Air-coupled (A-C) Data for Base Course Thickness (Network Survey, All Sites)

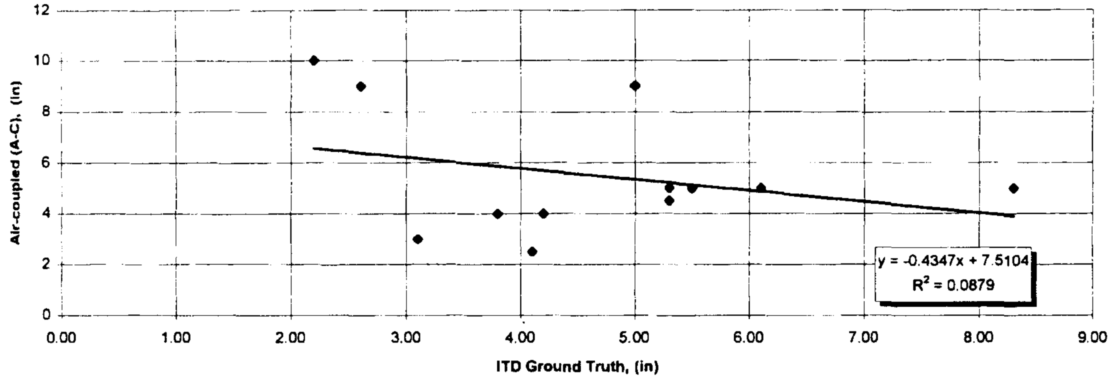


Figure 11: ITD Core Data (Ground Truth) versus Air-ground-coupled (A-G-C) Data for Base Course Thickness (Network Survey, All Sites)

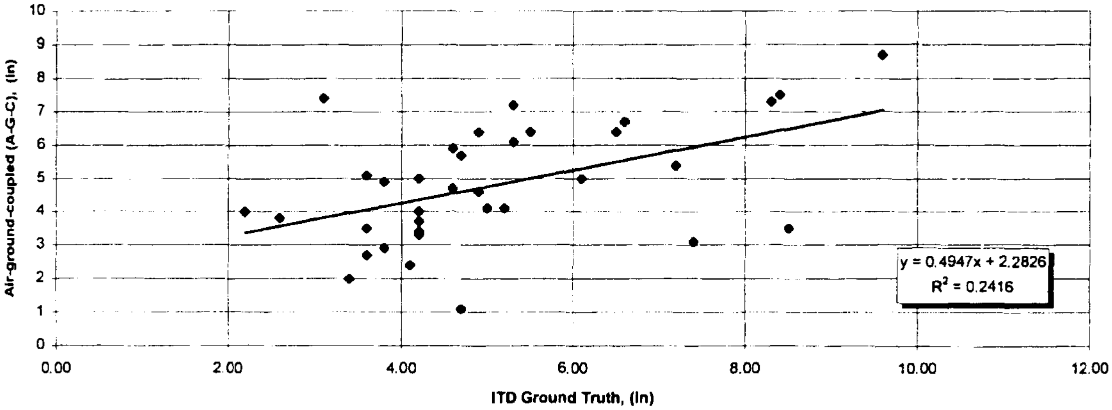
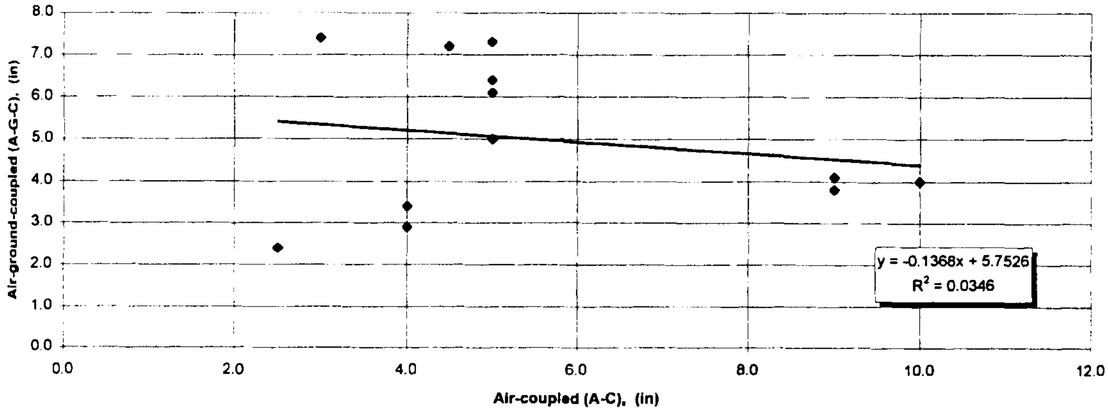


Figure 12: Air-coupled (A-C) Data versus Air-ground-coupled (A-G-C) Data for Base Course Thickness (Network Survey, All Sites)



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