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ANALYSIS OF GROUND PENETRATING RADAR SIGNALS FOR PAVEMENT CONDITION EVALUATION

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ABSTRACT
Ground penetrating radar (GPR) technology has been used over the last two decades for a variety of applications including the assessment of pavement condition by obtaining pavement layer thickness and material properties. This paper describes the application of a system identification and analysis of radar signal (SIDARS) methodology to rapidly analyze and compute layer thickness and changes in layer properties of a pavement, using digitized images of reflected radar signals obtained from a conventional GPR. A comparison of the result obtained from a case study analysis using this methodology and that obtained from direct core measurements for the same pavement sections show that the SIDARS measurements provide reasonably accurate results in the form of comprehensive and continuous maps of the quality of compaction and the composition of the asphalt mixture. Upon validation and industry acceptance the SIDARS system can be a valuable tool for quality assurance and quality control of pavement construction. Because it permits the calculation of quantities such as total volume or total weight placed, as well as the quality of placement, it allows for computing incentive and penalty pay as prescribed by performance-based specification. With this kind of detailed information, warranty programs become practical for both the highway agency and the general contractor.

KEYWORDS
Pavement Construction, Quality Control, Quality Assurance, Ground Penetration Radar, SIDARS

1. INTRODUCTION

Conventional ground penetrating radar was used to obtain digitized images of reflected radar signals from a multi-layered subsurface system. Standard mathematical techniques are applied to determine the number of layers, the thickness of each layer, and the dielectric constant for each layer within the multi-layered system using the identification and analysis of radar signal (SIDARS) technique. This methodology takes advantage of the fact that each layer in itself composed of three distinct types of material: solids, fluids, and gases/air. Thus, the dielectric constant obtained for a layer is, in fact, a composite value, namely a combination of the layer's solid, fluid, and gas dielectric constants. SIDARS employs a wave propagation model of the subsurface system to generate a synthetic reflected radar signal. Through an iterative process, initial concentration estimates of each material (solid, liquid, gas) in each layer are adjusted to minimize the mean-squared-error between the measured reflected and calculated synthetic radar signals. This process converges rapidly and yields accurate values for density, water, and gas values of each layer. The technology is based on peer-reviewed science and proven by field-testing in known environments and conditions.

2. DATA COLLECTION

State-of-the-art subsurface radar (GPR) equipment is used to transmit signals through the layers of a pavement, some of it being reflected back toward the surface from each layer interface that it encounters. The radar equipment simultaneously collects and stores the reflected signals from four antenna setups to supply readings across the full lane width where they are analyzed using the SIDARS software (Lyric 2001). The greatest accuracy of the measured results is achieved by using the results of a core that provides the thickness, unit weight, and fluid content of each layer at a spot where the radar signal has been captured. This ground truth information is used to calibrate the analysis software that provides a strip map or a multi-colored plan view contour map of the measured quantities. For example, in an asphalt pavement, the SIDARS output provides, in addition to layer thickness, asphalt content, total density (or unit weight), voids in the mineral aggregate (porosity), percent air and dielectric constant. In the supporting layers, such as base course and subgrade, SIDARS produces not only the layer thickness and dielectric constant but also water content, dry unit weight, porosity, and Percent air. Concrete layers are also analyzed by SIDARS to produce the layer thickness and dielectric constant as well as evaporable water content, and dry unit weight, porosity, percent air and location of reinforcing bars or dowels. This information is extremely useful for bridge and pavement management, providing highway agencies with the means to quickly collect inventory data on all bridges and pavements they maintain.

The accuracy of SIDARS is greatly dependent on following the required specifications. The procedures specified have come from years of experience. Of great importance is the setting of samples per trace. Samples per trace are the number of digitized points that make up a radar scan (sampling density) as illustrated in Figure 1. For accuracy in determining thickness less than 5 inches, it is imperative that at least 512 samples/trace be used. Without the density of sampling that 512 or greater samples/trace gives, a small thickness will be poorly resolved.

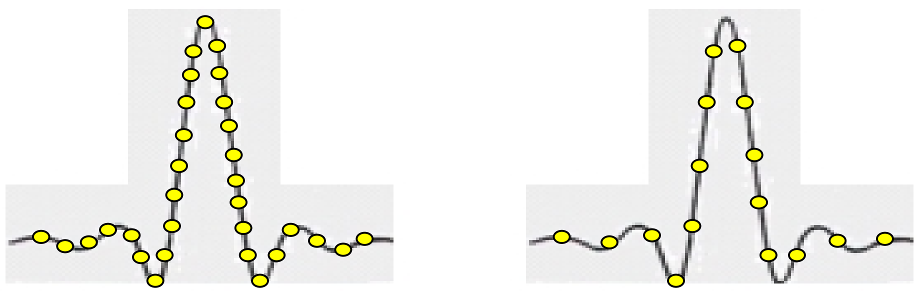


Illustration of (a) High Sampling Density (b) Low Sam Sampling Density

Figure 1: Sample Density

3. CORE ANALYSIS RESULTS

The asphalt content was measured using the ignition method for asphalt determination, an approved alternative to trichloroethane immersion. Ignition oven correction factors were verified by the original asphalt design. The following is a typical result for a four 6-inch diameter cores:

Table 1: 6-Inch Diameter Core Results

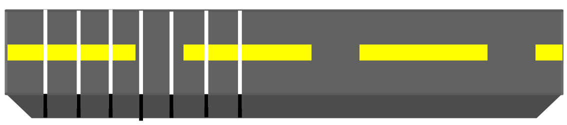
Location	Asphalt Content (W_f/W_t %)	Total Unit Weight (pcf)	Thickness (in)
Marker 1, Core #1	7.78	122.6	1.005
Marker 1, Core #2	8.15	122.4	0.877
Marker 5. Core #3	7.15	123.0	1.250

3.1 SIDARS Calibration

Like any scientific instrument, SIDARS needs to be calibrated. To insure a proper calibration, at least two cores are required, one for calibration, and another to verify that the first is a true representative sample of the layer to be analyzed. Considerable variations in the core values of asphalt content or total unit weight may indicate errors in coring or sample testing and would cause an inaccurate calibration. The SIDARS analysis could begin once both the radar data and core analysis information are submitted. The analysis calculates and numerically quantifies the material properties of layers by utilizing one of a selection of mathematical models and a patented approach to systematically converge upon the reported values based on the calibration values inputted from the cores. Due to the differences that can occur between samples in core drilling and sampling, the information and location for at least two cores are required, one for calibration, and other for verification. In some cases, it is recommended that more cores be taken, especially if the mix design or the aggregates used in the mixture change considerably along the length of the project. Considering the variability of the properties of the core samples, the one representing properties closest to the average could be selected as the calibration core. The properties of thickness and back-calculated volumetric concentrations of solids and fluids are used to calibrate SIDARS at the particular scan corresponding to the location at which the chosen core was taken. Once calibration is complete, dielectric models are selected, and analysis is carried out (Lyric 2001).

3.2 Running Averages

The radar data are configured to be collected at a one-foot spacing, but individual measurements, whether calculated from radar scans or ground truth core samples are subject to error. Averages are subject to less error and therefore report more accurate readings. Because of this, the sample data used for this paper are presented as a running average of seven points, the three preceding the point of interest, the three after the point and the point itself as shown in Figure 2.



x_{-3} x_{-2} x_{-1} **x** x_{+1} x_{+2} x_{+3} ....1-foot increments

Figure 2: Running Averages

(1) $x_{average} = (x_{-3}+x_{-2}+x_{-1}+x+x_{+1}+x_{+2}+x_{+3})/7$

The error of the mean (ε_μ) equals the error of an individual reading (ε) divided by the square root of the number of measurements averaged:

(2) $\varepsilon_\mu = \varepsilon/\sqrt{n} = \varepsilon/\sqrt{7} = 0.378\ \varepsilon$

This shows that by taking the running average, more accurate numbers can be achieved, with reduced local variability of measurement.

3.3 Average of Footprint

Air-launched, ground penetrating radar works by sending and receiving electromagnetic energy at a distance through layered strata. The energy radiates out in an elliptical shape and returns signal reflections based on the properties of the area within the "footprint" of the antenna. Because of this, the information derived from the reflected signals represents an average of the footprint along the path of the antenna. This averaged area is approximately 2 feet wide by 1 foot long. Figure 3 depicts an average Footprint.

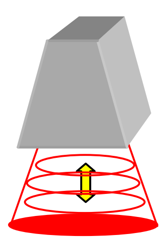


Figure 3: Average of Footprint

4. TYPICAL RESULT OUTPUTS

SIDARS analysis results are presented in a strip-map format showing a running average of the calculated properties in one-foot increments. The data, going from left to right, represents one-mile stretch of resurfaced asphalt along the path of the antenna. The data were measured in the left wheel-path of the outside lane of the test stretch. The average asphalt content shown in Figure 5 represents a measure of the percentage of the weight of asphalt fluid over the total weight along with the ground-truth core data values. The asphalt content varies from approximately 7.12 to 8.36 %. The air void design takes into account the expected level of traffic, along with the risks associated with rutting and texture loss. The designed air void level determines compaction levels. The quantity of air voids affects the rate of rutting, fatigue life, structural strength, and permeability (Cossens et al. 1999). SIDARS found that the air voids varied from 8.26 to 21.97% in this section (Figure 6). Maintaining the proper design quantity of percent air is crucial for achieving the design service life of the pavement. The VMA, also referred to as porosity, is a measure of void volume related to total volume. VMA, along with total unit weight and percent air are all good measures of the quality of compaction. Noticeable patterns of peaks in VMA are seen that correspond with the lows in total unit weight in Figure 7. The variations range from 25.91 to 34.99 %. These regular patterns may indicate a pattern in construction, possibly related to compaction or temperature loss. By taking a closer look at the section from 3000 – 5000 feet, these regular intervals of lower compaction, or higher porosity, occur at from 250-280 foot increments.

The void design takes into account the expected level of traffic, along with the risks associated with rutting and texture loss. The designed air void level determines compaction levels. The quantity of air voids affects the rate of rutting, fatigue life, structural strength, and permeability. SIDARS found also analyzes the variations air voids along each section. Maintaining the proper design quantity of percent air is crucial for achieving the design service life. In Figure 8 it can be seen that if a 1-inch thick course was specified, the 1-mile stretch generally remained within specifications, having a 0.921-inch mean, except for a few sections such as from 551-913, 1237-1500, at 3155 and at 3382 respectively where the minimum was not reached. The overall minimum was calculated at 0.50 inches while the maximum was 1.34 inches. For contractor payment purposes, SIDARS is invaluable in identifying and pinpointing areas of deficiency that cannot be easily achieved using random core selections.

5.1. Statistical Variations

In order to show the actual variability of the asphalt content, total unit weight, VMA, percent air, and asphalt layer thickness on the project, a strip map of each of these quantities is plotted with error bands above and below the local average value as in Figure 4. The bandwidth is two-standard deviations, meaning that 68.26% of all sample data will fall within the plotted error. Figure 9 and Figure 10 shows the average asphalt content and thickness measured by SIDARS with a standard deviation upper and lower bound. The standard deviation was calculated over the full length of the project using over 5000 SIDARS measurements. Similar plots were achieved for average total unit weight, average VMA, average and average Percent air void.

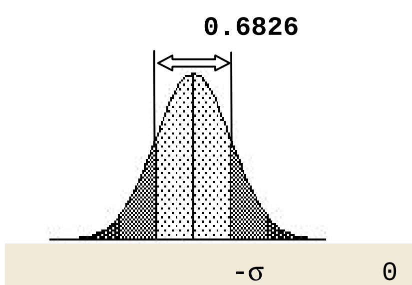


Figure 4: Plotted Error

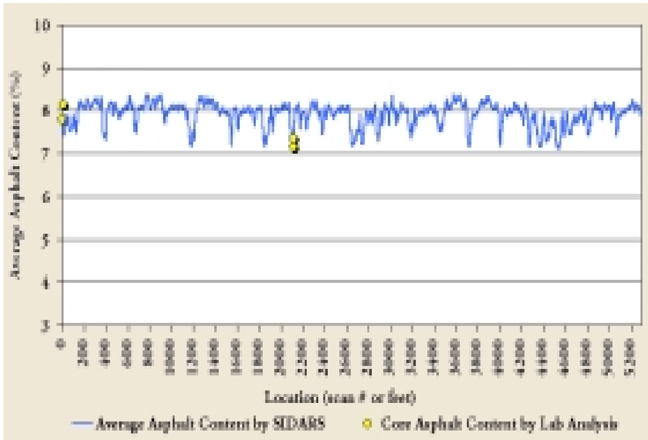


Figure 5: Average Asphalt Content

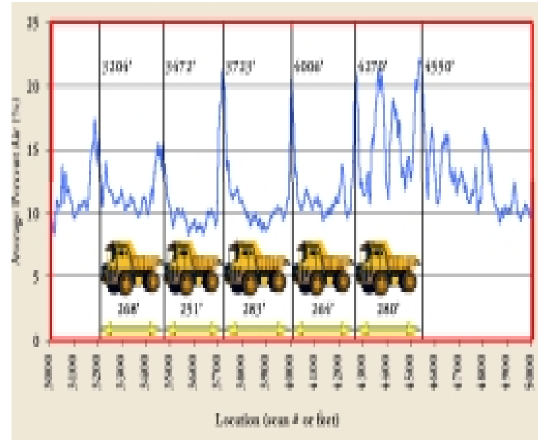


Figure 6: Average Percent Air Void – Detailed Pattern

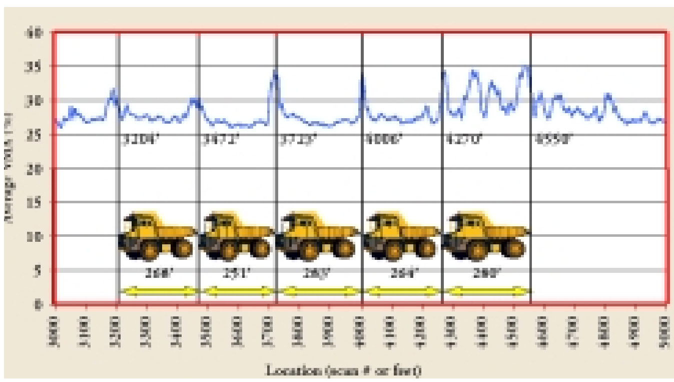


Figure 7: Average Void in Mineral Aggregate – Detailed Pattern

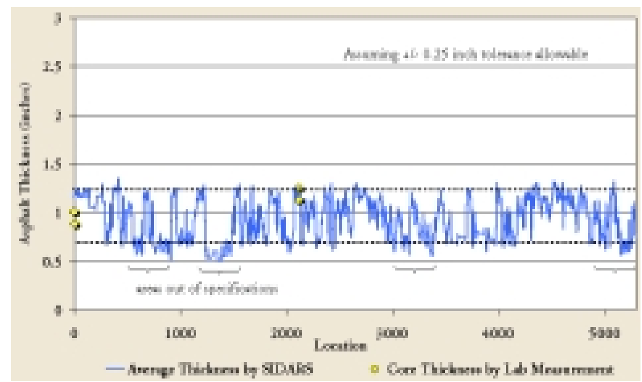


Figure 8: Average Thickness

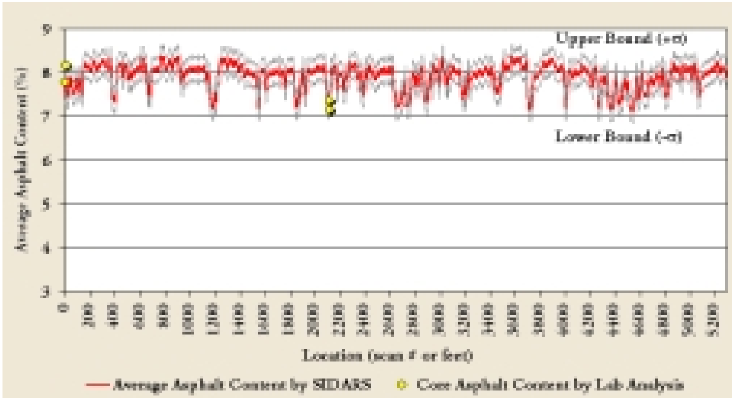


Figure 9: Average Asphalt Content with Standard Deviation (σ) Boundaries

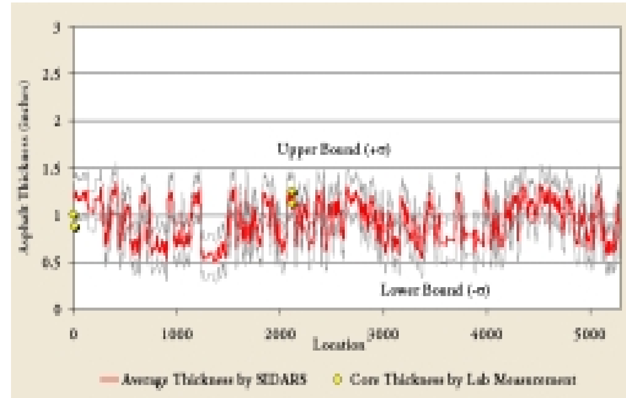


Figure 10: Average Thickness with Standard Deviation (σ) Boundaries

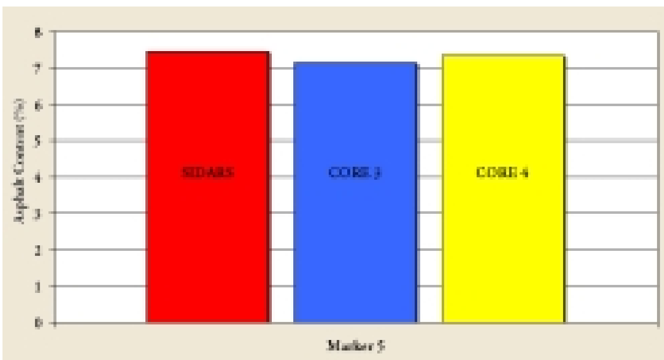


Figure 11: Asphalt Content Comparison – Marker 5

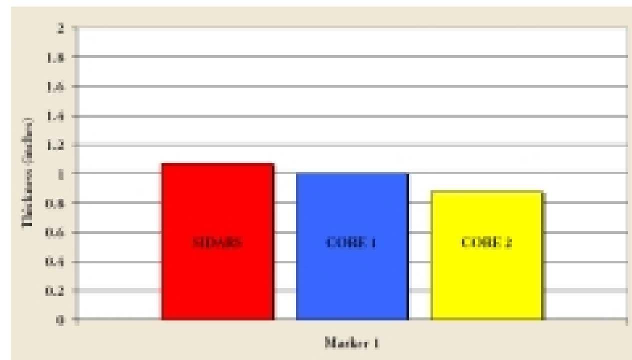


Figure 12: Thickness Comparison – Marker 1

7. COMPARISON BETWEEN CORE AND SIDARS MEASUREMENTS

The comparisons between the core values and those produced by SIDARS are shown first for the Marker 5 location since SIDARS was calibrated to Core #3 at Marker 5. Figure 11 and Figure 12 shows the comparison of the asphalt content and the thickness of the friction as measured with the cores taken at Marker 5 and Marker 1 respectively as measured with SIDARS at the same locations. Both core thicknesses are smaller than that computed with SIDARS at this location, but the difference is less than one standard deviation of the thickness measurement on the project, which is 0.21 inches. This shows how closely the radar matched the thickness at a point after having been calibrated at another point over 2000 feet away. The SIDARS thickness is between the two core thicknesses. Similar computations were carried out for to compare the total unit weight as measured with the cores taken at Marker 5 and as measured with SIDARS at the same location. By applying standard deviations to the asphalt content, total unit weight and thickness results compared to the ground-truth core values, it was shown that the core values are all within one standard deviation of the SIDARS measurements. Figure 13 show the mean and a two-standard deviation range of the asphalt content measured in the four cores. This is compared with the mean and two-standard deviation range of the asphalt content as measured by SIDARS at the sample locations. This figure shows that the mean of the core values fits well within the SIDARS range.

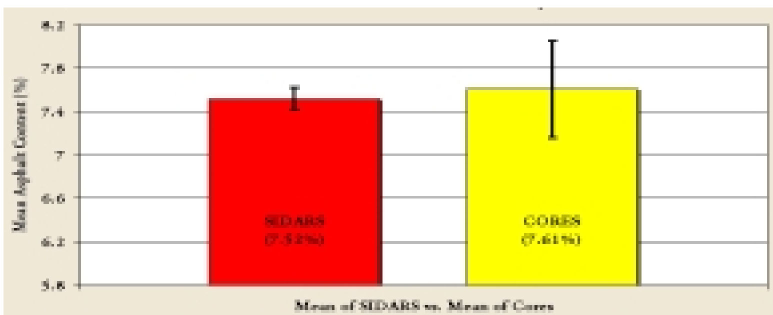


Figure 13: Mean Asphalt Content (SIDARS) – Cores with Local Standard Deviation

Figure 14 shows the mean and a two-standard deviation range of the thickness of the friction course as measured with the four cores. The figure shows the mean and two-standard deviation range of the thickness of the layer from over 5000 measurements made with SIDARS. Once more, the core values fit well within the SIDARS range.

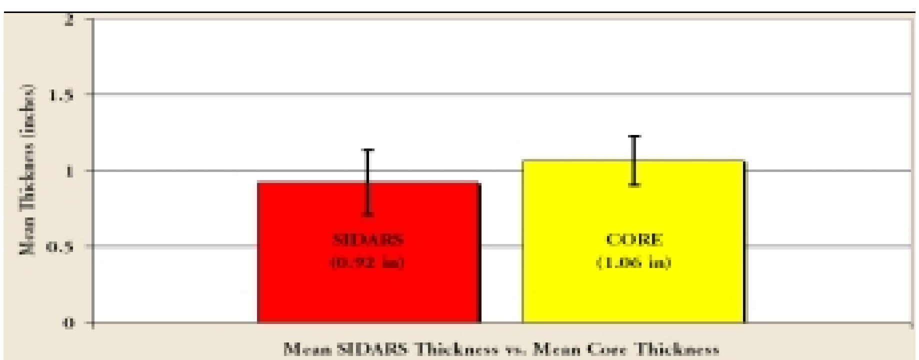


Figure 14: Mean Thickness of SIDARS vs. Cores with Standard Deviations

There is no reason to expect that the means of the core values, made with only four measurements, should equal the means of the SIDARS values when averaged over 5000 separate measurements. The table given below shows the relative size of the error of the mean of the cores and SIDARS measurements, indicating that the SIDARS mean is much more reliably measured than is the mean of the cores. This is because of the well-known principles that measurement repetition and averaging (Maser 1994) reduces random error as depicted in Table 2.

Table 2: Summary of Errors of the Mean

	Standard Deviation For the Project (σ)	Number of Error Measurements	Error of the Mean
Cores			
Asphalt Content	0.447	4	$\sigma/2 = 0.2235$
Total Unit Weight	1.063	4	$\sigma/2 = 0.5315$
Layer Thickness	0.160	4	$\sigma/2 = 0.0800$
SIDARS			
Asphalt Content	0.270	5293	$\sigma/\sqrt{5293} = 0.0037$
Total Unit Weight	3.438	5293	$\sigma/\sqrt{5293} = 0.0473$
Layer Thickness	0.213	5293	$\sigma/\sqrt{5293} = 0.0029$

Measuring the asphalt layer thickness and the composition of the layer every foot of the length of the project provides a strip map of the patterns of random and systematic variations of these quantities. The random variations are the erratic variations of the thickness, asphalt content, total unit weight, VMA, and percent air along the length of the pavement from which the project means, standard deviations, and errors of the means were computed. The systematic variations are the periodic spikes of VMA and percent air on an average of 265 feet apart that were probably caused by the lay-down machine waiting for the next 20-ton asphalt dump truck to maneuver into its discharge position. This permits the uncompacted 1-inch thick friction course material beneath the lay-down machine to cool off and consequently become more difficult to compact.

8. CONCLUSION

A comparison of the result of the SIDARS system and that obtained from direct core measurements show that the SIDARS measurements provide reasonably accurate results in the form of comprehensive and continuous maps of the quality of compaction and the composition of the asphalt mixture. Because it permits the calculation of quantities such as total volume or total weight placed, as well as the quality of placement, it allows for computing incentive and penalty pay as prescribed by performance-based specification. With this kind of detailed information, warranty programs become practical for both the highway agency and the general contractor. It is evident from this presentation that upon proper validation and eventual industry acceptance the SIDARS system can be a valuable tool for quality assurance and quality control of pavement construction.

9. ACKNOWLEGEMENT

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