EVALUATION OF NETWORK LEVEL GROUND PENETRATING RADAR EFFECTIVENESS

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ABSTRACT

As part of the Oklahoma Department of Transportation (ODOT) network level pavement evaluation of the National Highway System (NHS), ODOT sought to establish the structural capacity of over 3,300 directional miles of their NHS network (excluding toll roads). Three primary data collection activities were carried out to initiate this structural capacity analysis: Nondestructive Deflection Testing using a Falling Weight Deflectometer (FWD), Ground Penetrating Radar Testing (GPR), and Pavement Materials Sampling. This project provided a unique opportunity to compare over 3,300 miles of GPR thickness information to approximately 1500 cores taken at select locations. FWD deflections and GPR scan traces were reviewed to identify locations where coring data would be helpful for quality control purposes. Each of these sources of data were examined independently and conjointly to determine the optimal core locations. Cores were selected with the intent of taking one core per every identifiable pavement structure change that was apparent in the review of the FWD deflections and GPR scan data. The cores selected covered nearly all of the pavement sections that were evident from this review process. This paper will examine the correlation of the GPR and coring results obtained for the ODOT network as well as the effectiveness of GPR for different pavement types.

INTRODUCTION

As part of its ongoing efforts in pavement management, the Oklahoma Department of Transportation (ODOT) sought to improve its decision making process through enhanced knowledge of its pavements' structural capacities. Previously, ODOT's pavement management system (PMS) utilized only surface distress data to identify deficiencies at the network level and recommend appropriate treatments. ODOT desired to acquire information characterizing the pavement structural condition using non-destructive testing (NDT) techniques. The agency decided to pursue a network-level falling weight deflectometer (FWD) testing program for the non-toll portion of its National Highway System (NHS) that would provide the needed structural information.

The non-toll NHS in Oklahoma is comprised of 2,765 centerline miles (4,450 km) of highways that are critical to the state's economy, mobility, and defense. These are typically high-volume routes with a higher percentage of heavy trucks than other highways in the state. The FWD testing protocol stipulated that testing would be performed in the outside wheel path of the outside lane in the primary direction for undivided routes and in both directions for divided. Sections that were under construction, recently completed, or had current FWD data available were not tested. This resulted in a total of 3,300 (5,300 km) directional miles to be tested. Three primary data collection activities were carried out during this structural capacity analysis:

1) Nondestructive Deflection Testing
2) Ground Penetrating Radar Testing
3) Pavement Materials Sampling

GPR and materials sampling provided two sources of information for material thickness and material type. This paper is a case study that will examine the correlation of the GPR and coring results obtained for the ODOT network. Additionally, the effectiveness of GPR for the different pavement types encountered for the ODOT network is examined.

Nondestructive Deflection Testing

Nondestructive deflection testing was performed every tenth mile (0.16 km) in the outside lane in each direction over the entire project length (approximately 3,300 directional miles or 33,000 test points). The purpose of the deflection test program was to determine the structural response characteristics of the pavement structure and underlying subgrade materials to wheel loads as well as variability of the structural properties along the pavement facilities. The deflection testing was performed in accordance with ASTM Test Standard D4694 (Standard Test Method for Deflections With a Falling Weight-Type Impulse Load Device) and D4695 (Standard Guide for General Pavement Deflection Measurements). The type of testing conducted was a Level 1 program, for a network level evaluation of pavement condition, with fully calibrated FWDs. ODOT specified the number of test drops and the corresponding target load as two drops at 9,000 pounds (40.1 kN), one at 12,000 pounds (53.4 kN), and one at 15,000 pounds (66.8 kN). This deflection testing setup was conducted consistently at each of the 33,000 drop locations. A geophone spacing of 0, 8, 12, 18, 24, 36, and 60 inches (0, 20.32, 30.48, 45.72, 60.96, 91.44, and 150 cm) from the load was used for all test points.

Global Positioning System (GPS) data was collected concurrently with the FWD data collection. The same Distance Measuring Instrument (DMI) and GPS receiver controlling the ground penetrating radar (GPR) data collection controlled the FWD data collection. This correspondence provided coordination between FWD test locations and GPR data, and enabled the location of data features on the pavement.

Prior to the start of the survey, the vehicle DMIs were calibrated to a known distance. These calibrations were checked routinely (monthly maximum). During the testing, event markers were placed in the FWD data at specific features (as noted in the protocols) to provide additional ground truth for location coordination with the GPR data collection for the production of profile plots of deflection data and scan traces. The event markers were useful in paring the FWD and GPR data, especially at bridge decks and milepost markers. Three SHRP-Calibrated Falling Weight Deflectometer (FWD) units were used for the completion of this data collection effort.

Ground Penetration Radar Testing

The GPR equipment consisted of a GSSI SIR-20 radar control and data acquisition unit, a Model 4108, 1-GHz horn antenna, mounting equipment, and an electronic distance-measuring device (DMI) attached to the vehicle wheel. Although this equipment is capable of collecting at least two GPR scans per foot of linear travel at 60 mph (96 kph), generally no more than 1 scan per foot is required. Other data collection parameters included 16 bit data with 256 data points per scan. The 16 bit data provides better resolution and enables higher levels of data processing and filtering. The number of points per scan used has shown, from experience, to be appropriate for pavement thickness applications.

A Trimble AgGPS 114 Global Positioning System (GPS) receiver serviced by Omnistar was operated concurrently with the GPR data collection. The GPS coordinates were transmitted every second, and recorded along with the GPR DMI by the GPR data collection system. The recorded file provided a direct correspondence between GPR data and GPS coordinate measurement. This correspondence provided coordination between FWD test locations and GPR data, providing thickness information specific to each FWD test location.

One pass was made in each direction (for divided highways) or the primary direction as defined by the control section maps for undivided highways. The vehicle and antenna were positioned to capture a GPR profile of the center of the surveyed lane.

Preliminary Analysis

Using the non-destructive deflection testing data and GPR profiles, the roadway was analyzed to identify those areas responding differently to loads. Deflection profile plots were produced for all sensors, as a quick preliminary analysis, to identify variability of the pavement and subgrade response. Using the profile plots, quick and efficient identification of areas where material sampling was warranted were selected. All corresponding deflection profile plots and GPR traces were plotted out on the same page (one on top of the page the other at the bottom) to facilitate review by all parties concerned. Boring locations were selected from evaluations of the FWD and GPR profile plots. Preliminary selections were provided to ODOT staff for review and comment. Use of the FWD and GPR results in this selection process assured that variations of the pavement structure were sampled for confirmation and characterization. This selection process also optimized the amount and location of destructive sampling and testing. Through this process 1,515 locations were identified for coring and material sampling.

Pavement Materials Sampling

During the material sampling, logs were produced to identify descriptions and thickness measurements of the pavement surface, base and sub-base courses sampled. These core logs also documented characteristics of each layer, and included the degree of stripping in asphalt pavements and any separation noticed, honeycomb, and "D" cracking in concrete pavements. Digital photographs with scale of each core were included with all core logs. In addition any seepage of water in the underlying pavement and soil layers during the materials sampling program was also documented. All unbound layers were augured down to the original subgrade, except where there was substantial fill material.

Structural Evaluation

Backcalculation of the deflection data was performed to obtain layer moduli for each test point. The pavement was analyzed to identify the load response at each test location using the network level non-destructive deflection testing data. Material properties and layer structure information was used to backcalculate layer moduli from the deflection data. Once these preliminary analyses were completed work could begin on the development of suitable summary statistics for consideration as additional parameters in ODOT's Pavement Management Data Base.

EVALUATION OF SENSITIVITY AND RELIABILITY OF GPR DATA

One of the most attractive features of using GPR in addition to core information is that while the core may get you an exact description of the pavement at one point, the GPR can pickup variation and differences in pavement structure that may occur between cores. Ideally, the GPR should match the core at the core location and then show variation of thickness throughout the section. Ground penetrating radar was analyzed at each FWD station (approximately every tenth mile). Core locations did not always match up exactly with an FWD test location. For example FWD data was collected at 5.45 and 5.55 mileposts and the core was taken at milepost 5.5. For such points, the core thickness would be expected to have a thickness value between the GPR thickness values at each FWD point.

Both the core thickness values and material types and the GPR thickness values and material types were uploaded into the analysis database for comparison. All 33,513 data points were manually reviewed. The GPR and core material types and thickness values were compared at each location. Additional information, which included FWD field comments, GPR analysis comments, core field comments, and structural history information was consulted to resolve any apparent differences in the core and GPR layer thickness and material type information. Data where a difference was obvious (i.e. surface type different or large thickness discrepancies) were flagged for required investigation. More subtle differences in thickness or subsurface layer types were performed by manual review of available data sources. Issues that did arise ranged from differences in surface type to base layers not being detected, as well as layer thickness. Items encountered are discussed in greater detail in the next section.

Pavement Structures Encountered

The Oklahoma NHS routes exhibited a broad range of pavement structures. All pavement layers were identified by the coring and boring down to subgrade. Pavement structures encountered were AC, PCC, and various composite pavements. Composite pavements were considered any pavement composed of both AC and PCC, which included AC over PCC, PCC over AC, AC over PCC over AC, and PCC over AC over PCC. Other structures that were encountered were very thick AC (over 16 inches), AC over multiple bituminous layers (total thickness often over 16 inches), and infrequent occurrences of brick. Bituminous base (BB) layers were encountered quite regularly throughout the ODOT network. Bituminous base, BB, generally refers to soil asphalt, hot sand, as well as fine and course aggregate bituminous bases as well as other asphalt stabilized base courses. Asphalt concrete, AC, refers to actual asphalt concrete including Type A, B, C, and D mixes. Base materials included aggregate base as well as several forms of stabilized base including but not limited to bituminous, cement treated, and asphalt stabilized bases. The lowest boundary that the GPR would be expected to detect would be at the surface of the subgrade.

AC Pavements

The response of GPR to AC pavements was very interesting coupled with the pavement materials used in the state of Oklahoma. A large proportion of ODOT's roads have some kind of bituminous base and in addition, several lifts of asphalt are quite common. The AC pavements over subgrade alone tended to be adequately evaluated by the GPR. The layers compared were a combination of AC and BB layers. GPR was not always able to distinguish the exact material type beneath the surface, i.e. sometimes AC was labeled as BB and vice versa.

Thick AC Where the AC had multiple layers (which were determined through coring), the GPR would sometimes not be able to penetrate all the layers to sufficient depth. This variation could be from county to county or even point-to-point depending on the pavement properties specific to any given road. Reviewing a set of data would sometimes show two total depths that would constantly fluctuate throughout a road section. It would be evident that a lower layer was fading in and out of the detection capability of the GPR equipment. The fading of this interface could be due to a loss of cohesion in the lower bituminous layer, giving it dielectric properties more similar to the base, or due to the larger depth not always having layer interfaces detectable.

AC/Multiple Bituminous Layers This scenario is essentially the same as the previous one with the thick AC pavements with multiple layers only this time there are several bituminous base layers. These layers would tend to fade in and out of the detection capability of the GPR for some control sections. This was especially evident where multiple BB layers were very thick (where the total AC and BB combined thicknesses exceeded 16 inches). The bottom layer was often times considered part of the subgrade. Occurrences involving non-bituminous subgrade and base issues will be further addressed in a later section.

PCC Pavements

Where the GPR was able to detect the bottom of the PCC layers, which was the vast majority of the time. GPR adequately evaluated such PCC pavements. The scattered locations where GPR could not detect the layer bottom the GPR results were in agreement with the core data on either side of the gaps in the GPR data. Where the boundary information is clear for PCC pavements, the GPR information was highly reliable and was utilized for the structural evaluation analyses performed (i.e. backcalculation).

AC/PCC Pavements

In general the thicknesses obtained for such pavement structures were very close to the core thicknesses. It was evident where very thin (thickness less than 1.5 inches) AC layers were present that the GPR AC thickness and occasionally the PCC thickness did deviate more from the core data than when the AC was greater than 1.5 inches. The AC thicknesses reported by the GPR were up to an inch greater than the core thickness for such pavements. This occurrence was for less than 1% of the entire network.

PCC/AC Pavements

Thickness information from GPR was generally in agreement with coring information where the GPR was able to detect the AC layer beneath the PCC layer. There were four situations that arose for PCC/AC pavements: 1) GPR could not determine bottom of PCC layer but it was evident that the structure was PCC/AC, thus the total thickness was reported (PCC + AC or PCC + BB); 2) the GPR failed to detect the underlying AC or BB layer and only the PCC thickness was reported; 3) the GPR misinterpreted AC as BB and vice-versa, or 4) the GPR correctly identified material types and thicknesses. The GPR often correctly identified that the underlying layers were bituminous bound in cases such as these and provided a thickness consistent with the coring. In such cases the GPR served the role of confirming the coring and the limits of roadway for which the core was representative.

Identification of Base/Bituminous Base Layers

GPR could not always determine whether a layer was bituminous or not. The thickness information would often match the coring, but the material types were incorrectly identified. This was not considered too serious since the layer thickness agreed with the core data and the core provided proper identification of the layer type. It was not entirely uncommon for the lowest base and sometimes BB layer to be grouped with the subgrade by the GPR. If the materials had similar dielectrics, they could be seen as one layer. The other scenario observed was the GPR misidentifying additional layers. This extra layer was usually between 4 and 6 inches thick. The best assessment of what this could be is a dielectric change within the first few inches of the subgrade probably due to differences in moisture. The GPR would incorrectly identify a base layer at such locations.

Other Composite Pavements – AC/PCC/AC and PCC/AC/PCC

In each of these pavement structures, the GPR was unable to detect the material types of the unconventional layering. For the AC/PCC/AC sections, the GPR most frequently recognized the pavement as only containing AC or BB layers, often with the correct thickness, but incorrect material classification. The GPR would also not detect the bottom AC layer, but the top two layers would coincide with the coring. As for PCC/AC/PCC pavements, the GPR would generally only detect the top PCC layer or the top PCC layer and the AC layer as either AC or BB (and sometimes base). Also, the GPR was unable to detect the bottom of the lower PCC layer.

Brick

Brick was not identified with the GPR, especially in the subsurface. Thickness information regarding pavement structures with brick relied entirely upon coring information. There was less than one mile of brick surface roads tested.

Comparison of Core and GPR Layer Thicknesses

Core and GPR thickness information was compared where the GPS coordinates of the core location and GPR thickness at the FWD location were matched. An absolute error tolerance of the GPS coordinates of 0.001 was used and was calculated using the following equation.

$$\Delta GPS = \sqrt{\left(Latitude_{GPR} - Latitude_{Core}\right)^2 + \left(Longitude_{GPR} - Longitude_{Core}\right)^2} < 0.001$$

A tolerance of 0.001 on the GPS coordinates corresponds to a length approximately just under a tenth of a mile on either side of the core location. Once the database was filtered for the GPS match, a comparison of the core layer thicknesses was performed. The data was further subdivided into two populations. One population considered where GPR was considered representative and the other where it was not representative. This means that the GPR was considered to be acceptable after the quality control process of comparing ground truth core information. Figure 1 shows the error distribution for total samples, GPR, and core. The y-axis shows the percentage of samples and the x-axis shows the percent error.

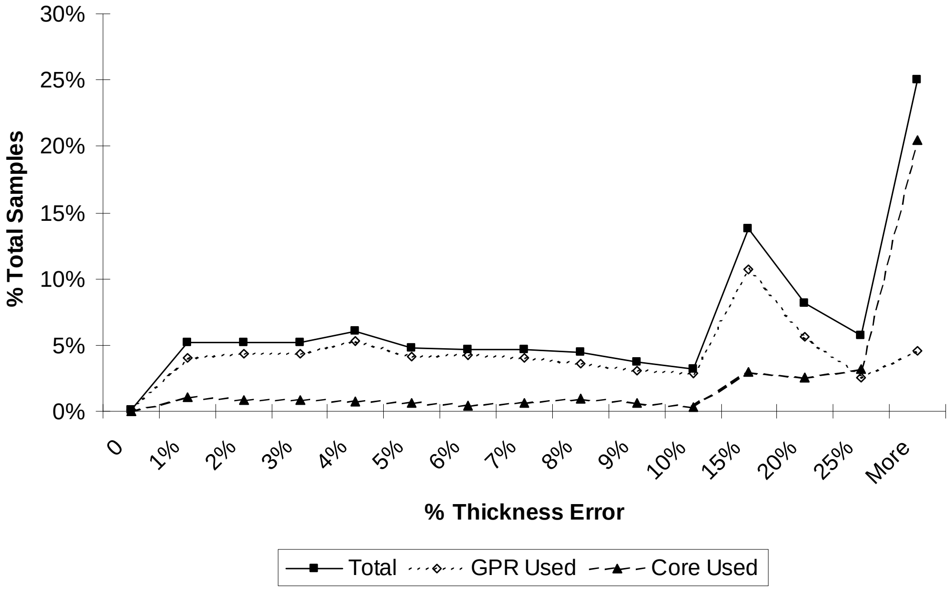

FIGURE 1 Error distribution of as a percentage of total pavement structure thickness

From observing Figure 1, it is evident that the core information was utilized with a higher frequency when the thickness difference of the GPR to core thickness was very large. The GPR information was used as much as it passed the QC process as it provide information on the variability of the layer thicknesses which were not obtained from coring.

UTILIZATION OF GPR BASED ON PAVEMENT STRUCTURE

Different pavement structures are better identified with GPR analysis than others. Table 1 below summarizes the percentage of GPR versus coring that was used based on the major pavement structure types encountered as well as for the entire data set. The statistics shown include data from all 33,513 data points. For AC/PCC pavements a higher percentage of points could be characterized by GPR. However, statistically, approximately two-thirds of the GPR data was used for AC, PCC, and the overall dataset. There were fewer sections and less miles of roadway with AC/PCC than either AC or PCC evaluated for the ODOT network in this project.

TABLE 1 GPR and Core Percentages by Pavement Type

Structure	GPR	Coring
AC	63%	37%
AC/PCC	78%	22%
PCC	64%	36%
All	66%	34%

SENSITIVITY OF GPR TO TOTAL PAVEMENT THICKNESS

Another evaluation of the effectiveness of the GPR is to determine the depth at which the GPR can obtain reliable information. The practical limits of the GPR vary by pavement structure in addition to pavement thickness and frequency of the antenna. Some of the routes evaluated in the analysis are represented solely by coring, others solely by GPR, and many as a combination of the two. The QC procedure where each data point was manually reviewed was where this determination was made. In most locations where GPR thicknesses were used, coring information could have sufficed.

Figure 2 shows a comparison of the frequency at each thickness interval for the number of points where GPR was considered representative compared to the number of points that GPR was not considered representative for the entire data set. The thickness values indicated are for the entire pavement structure. Pavement structures greater than 16 inches above subgrade did not lend themselves well to the 1 GHz GPR antenna. Only about 50% of data was characterize by GPR above this point.

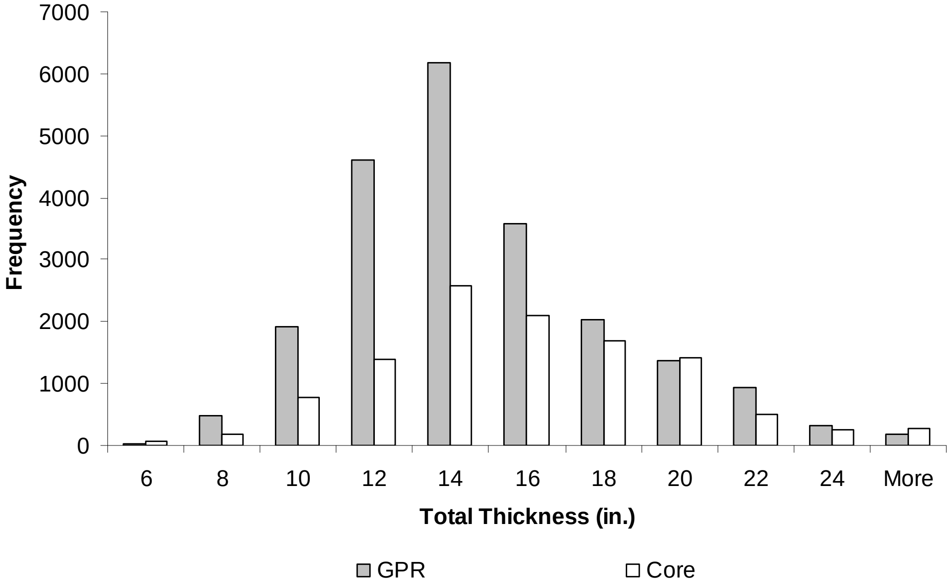

FIGURE 2 Frequency distribution of thickness for all pavement types.

Figures 3, 4, and 5 divide the quantities shown in Figure 3 by the three primary pavement structures that were defined, AC, composite (AC/PCC), and PCC, respectively. Thickness information for AC pavements from GPR was usually found to be acceptable for the analyses performed. For locations where AC thicknesses are beyond 16 inches, the effective us of GPR does diminish and appears to be most effective for AC pavement structures less than 14 to 16 inches thick.

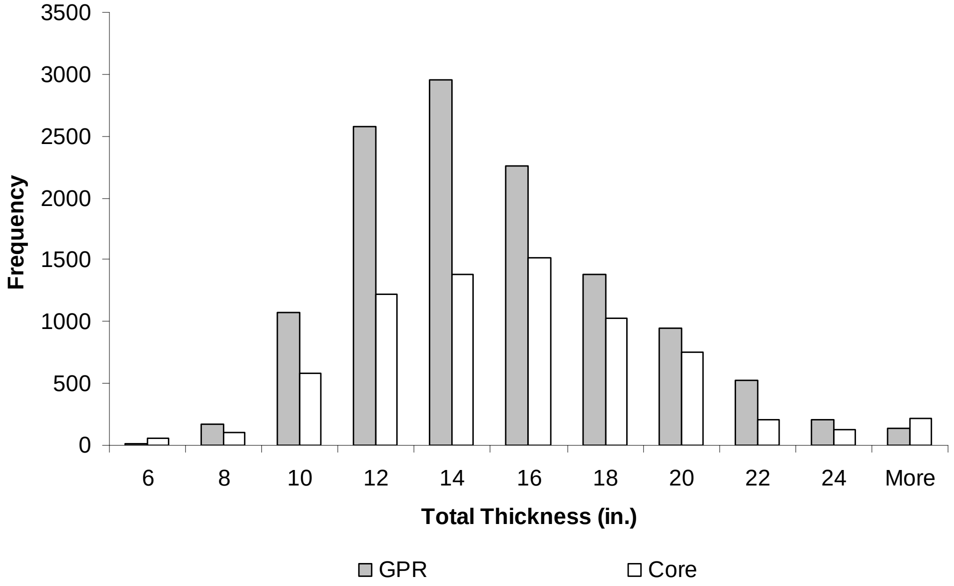

FIGURE 3 Frequency distribution of thicknesses for AC pavements.

For composite pavements, GPR can be utilized quite effectively. Although the pavement structures were above 18 inches in several instances, GPR was effective most of the time in identifying pavement thicknesses.

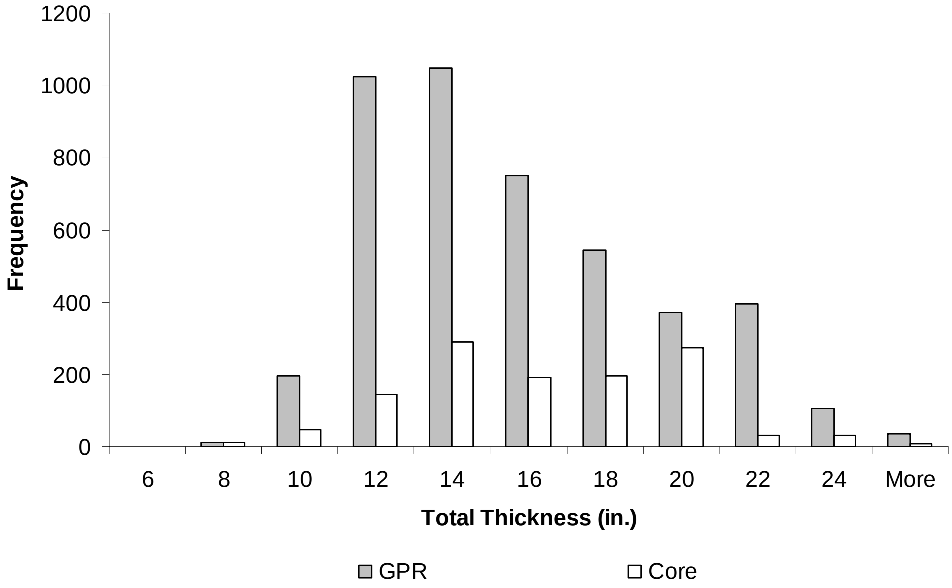

FIGURE 4 Frequency distribution of thicknesses for composite AC/PCC pavements.

For pavements with PCC as a surface layer, the effectiveness of the GPR drops off significantly beyond the 14 to 16 inch range. Pavement structures beyond 16 inches were not practical to identify with GPR. For areas where the known pavement structure may be beyond 18 inches, a 1 GHZ GPR antenna should be considered very carefully before being employed. For thinner (below 14 inches) PCC sections, GPR was very effective.

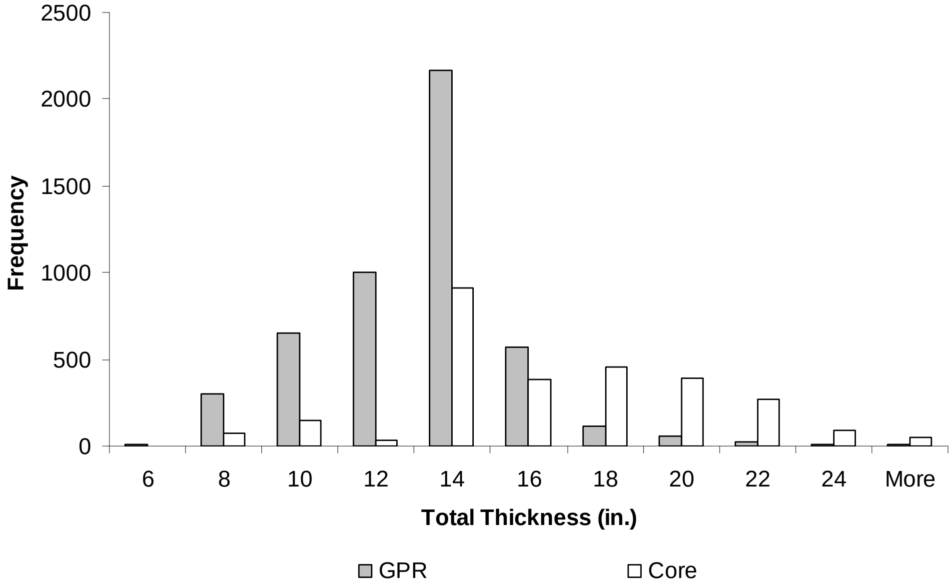

FIGURE 5 Frequency distribution of thicknesses for PCC pavements.

SUMMARY AND CONCLUSIONS

The use of GPR for a network level analysis enables the collection of large quantities of thickness and layer type information that would be a daunting task for thousands of miles of roadways. The GPR data played two roles in this project (1) it served, in conjunction with FWD data, to identify homogeneous sections so that cores could be taken in representative locations; and (2) it provided useful layer thickness data for 66% of the network. For the remaining 34%, the core data was used to represent the layer structure within the defined homogeneous sections. To improve the results of the GPR for sections where the error was unacceptable it is recommended to reprocess the thickness information using dielectrics that match the core thickness at GPR data matched to within a foot of the core location.

The volume of data collected for the ODOT network evaluation provided a unique opportunity to evaluate the effectiveness of utilizing GPR on a network level. The limitations as well as the strengths of GPR were encountered. GPR tended to be more effective for given pavement types and thicknesses than others while at the same time providing much information about the variability of layer thicknesses along a given roadway.