Pavescan Evaluation of In-Place Asphalt Mixture Density

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ABSTRACT

Dielectric profiling systems developed under the US Federal Highways Administration Strategic Highway Research Program 2 (SHRP2) Solutions program provide a means to estimate the in-place compaction of asphalt concrete by correlation to the relative dielectric constant of the near-surface materials. The Pavescan™ system, a ground penetrating radar-based surface dielectric profiling system produced by Geophysical Survey Systems Inc., was used to continuously scan segments of an asphalt concrete pavement placed during two paving projects in 2019 that were constructed in Nova Scotia. The first project involved a paving trial of a C-HF asphalt mixture placed on 25 mm thick steel plates to simulate an orthotropic steel bridge deck. Pavescan™ data was recorded over various sections which received different levels of compaction effort to create a wide range of in-place density. Excellent correlation was observed between the surface dielectric measured from the pavement surface reflection and the bulk density of core samples, yielding a coefficient of determination equal to 92.2%. The trial also indicated that the minimum mat thickness that could be tested without interference from the underlying steel plate was approximately 45 mm. The correlation developed for test data obtained on the steel plates did not accurately predict the bulk density of the same asphalt mixture compacted on granular base, indicating an interaction between compaction and the underlying base stiffness. Pavescan™ surveys were also completed on five segments of asphalt mixture placed on a rural roadway. The most accurate predictions of bulk density resulted when using daily calibrations of bulk density from cores and the measured surface dielectric constant with a 94.7% rate of correctly predicting air void contents above and below 7.5%. A comparison of the Pavescan™ results and quality assurance sampling within the same locations of the mat provided consistent measures of quality. However, contour plots of the surface dielectric or interpreted compaction were effective in mapping lower levels of compaction associated with transverse and longitudinal cold joints in the mat.

Introduction

Wood Resilient Infrastructure, a division of Wood Canada Limited (Wood) conducted a review for Nova Scotia Transportation and Infrastructure Renewal and Halifax Harbour Bridges of the Pavescan RDM dielectric profiling system produced by Geophysical Survey Systems Inc. (GSSI) to evaluate asphalt compaction. The purpose of the trial was to evaluate the correlation between surface dielectric values and compaction levels determined from asphalt concrete core samples obtained from paving projects, and observe the consistency in compaction over typical paving projects in Nova Scotia.

Wood used a Pavescan RDM dielectric profiling system produced by Geophysical Survey Systems Inc. (GSSI) to evaluate compaction in two different projects in Nova Scotia. The first project involved monitoring compaction of an asphalt concrete mixture with Rosphalt-50 on the A. Murray MacKay Bridge in Halifax, Nova Scotia for Halifax Harbour Bridges. Surface dielectric profiling is of interest for evaluating asphalt compaction on bridge decks since current methods have not be shown to provide accurate results. The second project involved paving of a rural highway for the Nova Scotia Transportation and Active Transit (NSTAT) using a typical C-HF asphalt concrete mixture. The objective of the study was to evaluate the correlation between surface dielectric values and compaction levels determined from core samples

Literature Review

Dielectric profiling systems were developed under the US Federal Highways Administration SHRP2 Solutions program, R06C for non-destructive techniques for detecting defect areas and evaluating uniformity in asphalt pavements during construction. This program involved two technologies, which included a paver mounted thermal profiler for measuring thermal segregation and a Ground Penetrating Radar (GPR) rolling density meter (RDM) system, which measures density or compaction. The equipment and analysis software used for dielectric profiling systems has been standardized in AASHTO PP 98-19 “Standard Specification for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar”. The standard is based on equipment developments recommended through studies, including Khazanovich et al. (2017), who noted:

> *“While the RDM surveying can be used without core collection to provide relative compaction assessment, calibration cores are required to convert the dielectric values into air void estimates. The quality of the calibration model is highly influenced by the uncertainty associated with air void estimates. The proposed core data collection protocol involves taking hundreds of measurements directly over the core and the immediate location of the core. It has been shown to produce accurate measurements of the dielectric at the core location and has resulted in good calibration models capable of making air void estimates with low uncertainty. Calibration models produced using this method typically have R^2 values ranging from 0.80 to 0.95.”*

A dielectric profiling system uses a GPR antenna mounted in air above the pavement surface to measure the amplitude of the reflected signal from the surface of the asphalt concrete, consistent with GPR based pavement thickness surveys except that the focus of dielectric profiling surveys is to record very high resolution surface reflections to estimate the surface dielectric properties. Earlier attempts to monitor asphalt concrete density, such as those described by Scullion et al. (1999), Al Qadi et al. (2001) and Popik et al. (2010), involved air-launched antennas often used in pavement thickness surveys, which helped support the development of current surface dielectric profiler systems conforming with AASHTO PP98-19.

Surface dielectric profiling systems use higher frequency antennas for higher sensitivity of the surface dielectric properties. Asphalt concrete is a dielectric material which partially transmits and partially reflects the incident GPR energy. The amplitude of the reflected and transmitted components depends on the differences in the relative dielectric properties of the air and asphalt "layers" which meet at the surface interface. Air has a relative dielectric constant equal to 1, so the amplitude of the pavement surface reflection depends on its relative dielectric constant. For a newly placed, well controlled asphalt mixture, the moisture content is essentially zero and the aggregate and binder content should not vary considerably, so the relative dielectric constant is therefore assumed to vary with the air-void content. A less compact asphalt layer with higher void content results in a lower relative dielectric constant for asphalt concrete while a more compact asphalt layer with lower void content results in a higher relative dielectric constant. The amount of incident energy arriving at the pavement surface, A_i, is commonly measured from a calibration file using a thin metal plate which is placed at the same operating height as the pavement surface and is assumed to reflect 100% of the incident energy. The relative dielectric constant of the asphalt concrete is calculated based on Equation 1.

$$e_r = \left(\frac{1 + (A_0/A_i)}{1 - (A_0/A_i)}\right)^2 \qquad \text{Equation 1}$$

Where:

e_r is the dielectric constant of the asphalt concrete surface materials;
A_0 is the amplitude of the GPR reflection measured from the asphalt concrete surface; and,
A_i is the amplitude of the GPR reflection measured from a flat metal plate.

Dielectric profile surveys are conducted after allowing the test system to warm up for 10 minutes to maintain a consistent transmission power to ensure repeatable consistent data. The GPR data is recorded at pre-set intervals over a distance that is measured using a calibrated distance measurement encoder.

Most asphalt concrete is placed in mats that are compacted to thicknesses exceeding 30 to 40 mm, so it becomes necessary to calibrate the surface dielectric measurement to either bulk relative densities measured per AASHTO T166 from core specimens or either void content or percent compaction determined from the bulk relative density values and the maximum theoretical specific gravity of the mix according to AASHTO T209 in order to provide an estimate of these compacted physical properties in the mat. At the time of this study, GSSI was developing a calibration procedure that was based on testing the surface reflection and bulk relative density of laboratory specimens produced using a gyratory compactor to a range of void contents.

Dielectric profiling surveys should be completed as soon as possible after final compaction of the new asphalt layer to avoid the effects of construction traffic and debris on the surface amplitude measurements. Conway et al. (2017) noted that site conditions which add uncertainty or affect the operation of the RDM system should be avoided which include hot mix asphalt overlays less than one inch (25 mm) or greater than 3.5 inches (87.5 mm) in thickness, stone mastic asphalt, permeable friction courses, temperatures less than 40 F (4.4 °C), and rainfall or other conditions that lead to wet pavement.

Construction traffic may further knead and close the pavement surface layer which influences the reflection amplitude. The GSSI Pavescan RDM surface dielectric profiling system uses a 2.0 GHz antenna for recording the surface reflection data. Wave velocity is equal to the product of frequency and wavelength, and the speed of the GPR signal through a dielectric material is often simplified for low-loss materials as the speed of light in a vacuum = 300 mm/ns divided by the square root of the relative dielectric constant. If the thickness of asphalt concrete that influences the surface reflection is assumed to be one half of pulse wavelength, then this represents approximately 30 to 40 mm for relative dielectric constants ranging from 6.0 to 3.5. Water and debris accumulation on the surface will influence the measured dielectric, shifting it to a higher value that is more indicative of a lower void content. Water has a dielectric constant of approximately 81, so subtle changes in moisture content will have a significant impact on the surface reflection amplitude. As a result, dielectric profile surveys should be completed after any residual moisture from rolling operations has evaporated from the mat. Metallic tape for marking paint striping and clayey soil materials are both conductive and can also significantly influence the surface reflection amplitude.

Surface dielectric profiling technology has been implemented successfully by several State agencies, including Maine, Minnesota, Nebraska and Alaska. Alaska Department of Transportation has been using intelligent compaction and paver mounted infra-red scanners as contractor pay factors as part of project acceptance since 2016, and has been one of the first states to propose using surface dielectric profiling for evaluating a compaction bonus on overbanded longitudinal joints (Sommerfeldt, 2019). The Alaskan joint compaction bonus is based on the compaction level and percent conformance to specified compaction levels per 100 foot station of distance along the project.

A. Murray MacKay Bridge Paving Trial

The A. Murray MacKay suspension bridge is approximately 1,200 m in length and spans over Halifax Harbour connecting the cities of Halifax and Dartmouth. This was the first suspension bridge built in North America using an orthotropic steel deck over the approximately 740 m length of the suspended span. The orthotropic deck span is constructed of individual plate segments that are inter-connected using steel splice plates placed above the main deck plate.

A 12.5 mm C-HF hot mix asphalt concrete with Rosphalt-50 additive was selected for paving the deck, based on enhanced waterproofing and improved resistance to fatigue cracking and rutting of the mixture as indicated by the manufacturer. The specified thickness of the wearing surface for this deck was originally 50 mm which was to be placed as a single lift. Monitoring compaction using conventional nuclear density gauges was considered unreliable for this project due to the influence of the orthotropic steel deck. The Pavescan RDM system appeared to be a feasible solution for monitoring hot mix asphalt compaction on bridge decks due to the relatively thin depth of asphalt concrete surface that affects the dielectric value measurement. If the steel plate remained outside of this depth of influence, it would have no impact on the compaction measurements developed using the Pavescan RDM system, unlike a nuclear density gauge.

The project specifications required that a paving trial be conducted to evaluate the proposed mix design and the roller pattern required to develop the low void content required for waterproofing. A trial was conducted using the proposed mixture placed on a granular surfaced lot at the paving contractor's asphalt cement terminal. The mixture was placed at the proposed spread rate over a section that was approximately 70 m in length. A portion of the trial section was placed on two 25 mm thick steel plates totalling approximately 10 m in length to simulate paving on the orthotropic steel deck. The granular surface was roughly levelled to support the steel plates. The steel plate test section was divided and marked into six zones which received different levels of roller passes to provide a wide range of void contents in the materials as shown in Figure 1.

Five lines of surface dielectric data were recorded along the length of the trial section, at transverse offsets of 0.5, 1.0, 1.5, 2.0 and 2.5 m from the edge of the mat. Each survey line and core location were marked on the asphalt concrete surface, adjacent to each survey line to avoid unintended effects on the surface reflection amplitude. High-definition core calibration files were recorded at exact pre-marked locations where cores samples would be obtained from the mat. An additional line of surface dielectric data was recorded at several other marked locations of the mat that was placed directly on the granular surface of the lot.

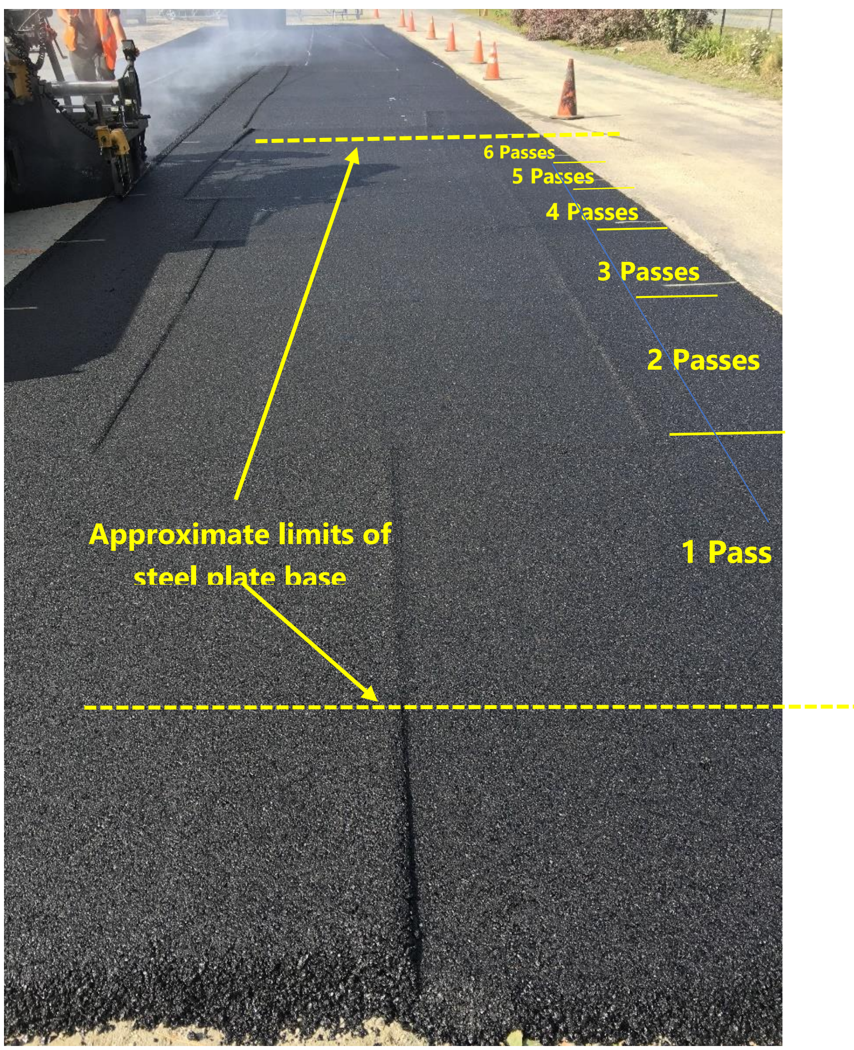

Figure 1 – Roller marks indicating various compaction levels in trial section placed over steel plates.

The variation in the calculated surface dielectric over the surface of the trial placement on the steel plates is shown via a plan view contour plot in Figure 2. It is evident from the roller marks observed in Figure 1 and the contour plot in Figure 2 that the rolling operations were not exactly aligned within the six zones, but a variation in the surface dielectric can be observed from left to right across the plot which shows a decrease in the dielectric value with a lower number of roller passes applied to the mat.

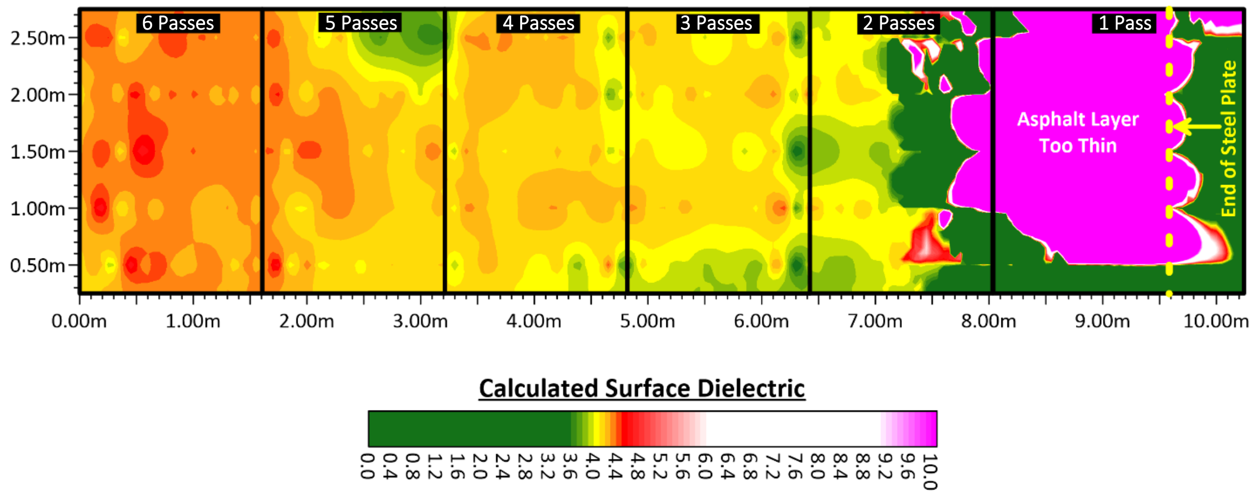

Figure 2 - Variation in surface dielectric at trial section for MacKay Bridge paving trial.

An area of very large dielectric values ranging up to a value of 22,000 was observed between distances of 7.2 to approximately 9.7 m where the steel plates terminated. Later analysis of cores and the GPR data files recorded by the Pavescan RDM system near this area of anomalous high amplitude reflections indicated that the asphalt concrete thickness decreased to approximately 37 mm or less. Dielectric values leading up to this zone were in the range of 3.7 to 3.9, which would represent depth of influence equal to 39 mm that would impact the surface reflection amplitude. Steel essentially provides complete reflection of the GPR signal versus the relatively low dielectric value of the asphalt concrete. As the mat thickness decreases, the high amplitude steel reflection superimposes with the asphalt reflection, causing dramatic increases in the surface reflection amplitude and the resulting calculated dielectric value. Asphalt mixtures which may have high levels of air voids and corresponding dielectric values approaching 3.0 would be limited to a minimum thickness of approximately 43 mm for results that would not be influenced by underlying materials.

Core samples from survey lines 2, 3, 4, and 5 were obtained at the exact marked locations where the Pavescan calibration files were obtained. The bulk density was tested for each core according to AASHTO T166, from which the air void content was determined based on the maximum theoretical density determined for the mix according to AASHTO T209. Table 1 lists the core ID, density, air void content, and average surface dielectric value measured each specific core location. The laboratory data for cores from survey lines 2, 3, and 5 were analyzed to develop a correlation between the surface dielectric value and the air void content. Core data from survey line 4 was provided to the analyst after the correlation was developed to objectively check the accuracy of the model.

Table 1 - Asphalt concrete core density, air void content, and mean surface dielectric values used to develop predictive models.

Test Location	Average Surface Dielectric	Bulk Density (kg/m^3)	Void Content (%)
L2-2	4.064	2205	8.2
L2-3	4.172	2222	7.5
L2-4	4.204	2234	7.0
L2-5	4.299	2284	5.0
L2-6	4.332	2308	4.0
L3-1	3.812	2007	16.5
L3-2	3.911	2133	11.2
L3-3	4.109	2190	8.9
L3-4	4.148	2232	7.1
L3-5	4.281	2268	5.6
L3-6	4.409	2310	3.9
L5-1	3.766	2086	13.2
L5-2	4.046	2151	10.5
L5-3	4.063	2211	8.0
L5-4	4.260	2251	6.3
L5-5	4.233	2272	5.5
L5-6	4.378	2319	3.5

Linear and exponential regression models were developed to predict the air-void content as a function of the surface dielectric value, as shown in Figure 3. Both models provided similar coefficients of determination with R^2 = 91.7% for the linear model and R^2 = 92.2% for the exponential model. However, based on a Sum of the Squared Errors (SSE) equal to 16.1% for the linear model versus SSE = 21.7% for the exponential model, the linear model appeared to provide the most accurate prediction of the in-place void content. The average absolute residual error for the exponential model was 0.82% air voids with a standard deviation of 0.80% air voids, while the linear model yielded an average absolute residual error of 0.74% air voids with a standard deviation of 0.65% air voids. It is observed that the linear model appears to result in slightly lower residuals at lower air void content values.

Table 2 lists the bulk density, air void content, average surface dielectric, and predicted air-void content for cores obtained from GPR survey line 4 (L-Series) and three cores obtained from a section of the trial placed directly on the granular surfaced lot (G-Series). The predicted air-void content is based on the linear model developed from the data provided in Table 1 from asphalt concrete specimens compacted on the steel plates. The residual errors between the predicted and actual air-void contents for core samples obtained from GPR survey line 4 ranged from 2.5% air voids for specimen L4-1 with an actual air void content of 9.8% to 0.1% air voids for specimen L4-6 which had an actual air void content of 3.7%.

The average absolute value of the residual errors for the GPR line 4 cores was 0.8% air voids, while the median value was 0.5% air voids.

It is interesting to observe that the average absolute residual of the predictions made for the section of the mat placed without a supporting steel plate placed on the granular lot was 1.4% air voids with a median value of 1.3% voids. This appears to indicate that the model does not exhibit the same level of accuracy between these sections of the trial pavement having different support conditions. Despite similar surface dielectric values, differences in the bulk relative density seem to exist over the depth of the mat. It is commonly accepted that the effectiveness of granular material compaction depends on part in the stiffness of the support conditions upon which it is placed, and it is likely that different correlation functions between surface dielectric and air void content may be required for different base support conditions due to variations in the development of a bulk density "gradient" over the thickness of the mat.

Table 2 – Comparison between predicted air void content and validation core results.

Test Location	Average Surface Dielectric Value	Bulk Density (kg/m^3)	Void Content (%)	Predicted Void Content (%)
L4-1	4.170	2310	9.8	7.3
L4-2	4.328	2274	5.1	4.5
L4-3	4.095	2193	8.5	8.7
L4-4	4.235	2234	6.7	6.2
L4-5	4.367	2308	3.7	3.8
G1-1	4.173	2339	5.5	7.3
G1-2	4.350	2336	2.8	4.1
G1-3	4.368	2272	2.7	3.8

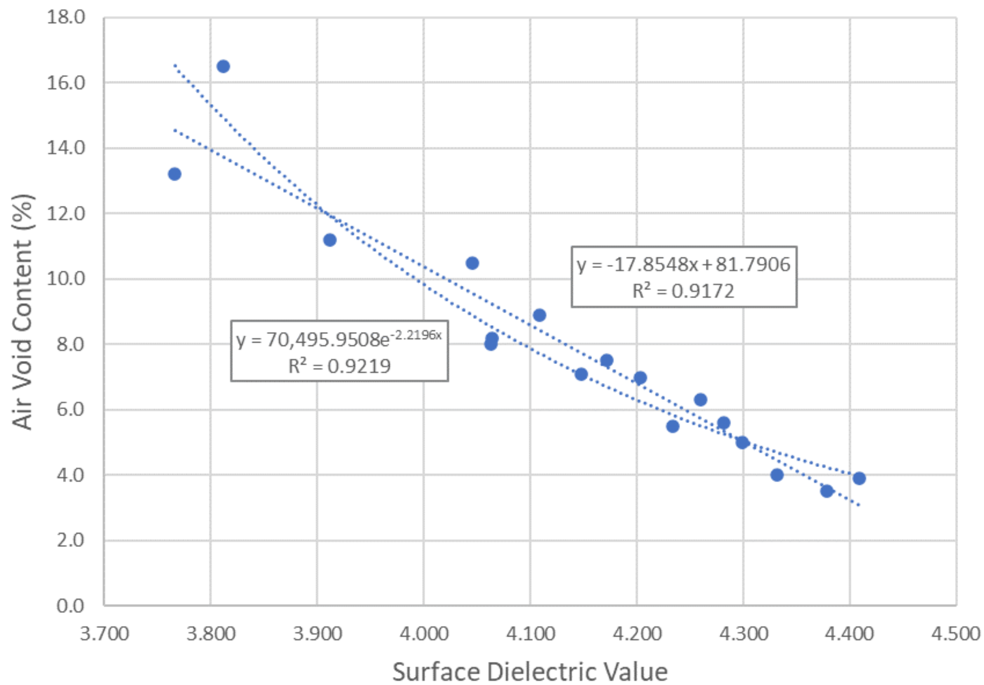

Figure 3 – Relationship between surface dielectric value and air void content.

Based on these results which confirmed the accuracy of the linear model, the Pavescan RDM was expected to provide a high degree of accuracy for monitoring the in-place compaction on the bridge during paving operations. This would be the first time that the surface dielectric profiling would be applied to paving on an orthotropic steel deck, providing an accurate method for non-destructively monitoring in-place compaction for quality control and quality assurance purposes.

Unfortunately, a change occurred which prevented the use of the Pavescan RDM for quality control during paving operations on the bridge and further evaluation of its capacity for mapping density variations throughout the project. The construction plan for paving the orthotropic steel deck was adjusted to provide the required smoothness on the deck because it was expected that the placement of a single 50-mm lift would result in significant bumps at the deck splice plate locations. After Wood verified via a calibrated GPR survey that the existing pavement thickness on the deck exceeded 60 mm, the design changed from a single 50-mm lift to the placement of one 38-mm thick base course, followed by localized grinding of high spots at the splice place locations, and the placement of a final 22-mm thick surface course using a nominal 6.3 mm maximum aggregate size to be paved in echelon over both northbound lanes. The Pavescan correlation developed using a 12.5-mm aggregate was not expected to be representative of the more finely graded 6.3 mm surface course mixture. Attempts to monitor the base course compaction on the bridge deck confirmed distortion of the surface reflection by the orthotropic steel deck plate reflection below the 38-mm thick asphalt concrete layer.

This project identified minimum lift thickness requirements to avoid interference from underlying materials and confirmed the effectiveness and accuracy of the method for predicting compaction levels in asphalt concrete.

Rural Highway Paving Project

A second case study involved using the Pavescan RDM system for asphalt concrete compaction along segments of a 2-lane rural highway that was being reconstructed. The original asphalt concrete pavement structure was pulverized and recompacted in-place in 2018, with asphalt paving deferred until 2019. Surface dielectric profiling was completed on several sections of the 17.5 km paving project over the course of five days.

Daily paving operations were generally completed one lane at a time within a lane closure to accommodate traffic on the open lane. The initial segment generally consisted of several hundred metres of hot mix asphalt concrete placed in the closed lane before switching lanes and placing a longer segment in the opposite traffic direction. Generally, the third and final placement of the day would involve paving the first lane up to the termination of the second placement in the opposite lane. Local traffic was being escorted by traffic accommodations vehicles operating in the open lane while paving operations were underway in the closed lane. This paving approach somewhat limited access for the Pavescan RDM data collection because the surface dielectric profiling could not interfere with either paving operations or traffic being carried in the open lane. The length of the test sections needed to be long enough to highlight any possible variations in the mat and to be representative of the project, while allowing enough time to complete the survey, select and scan core locations, and to remove the core specimens before paving operations changed from one lane to the other.

Wood attempted to survey a portion of the daily paving completed in each lane, with a short section of overlap between the scanned areas, where possible. Data collection began after paving operations had progressed several hundred meters along the route to avoid any disruption to construction and to allow moisture from the rolling operations to evaporate. The Pavescan RDM system was started and calibrated after the required 10-minute warm-up period each morning. Surface dielectric values were monitored during data collection to note unusually high, low, and typical values to direct the location of core samples which were re-surveyed using “core calibration” scans. After surveying the test segment along the first portion of the daily placement, a second survey area was established in the opposite lane with some length of overlap where possible, enabling a full scan of the paved surface effectively from shoulder to shoulder.

Surface dielectric profile surveys were completed on five different segments of the highway as listed in Table 3. The Pavescan RDM data was recorded at eleven offsets from the shoulder of the first daily test segment, including the longitudinal construction joint along the centreline where possible.

Table 3 – Variation in maximum theoretical density over Pavescan RDM testing days.

Pavescan RDM Testing Date	Chainage (m)	Maximum Theoretical Density (kg/m^3)
Oct 25	15+400 m to 15+800 m	2482
Oct 28	10+900 m to 11+463 m	2484
Oct 29	9+100 m to 9+940 m	2483
Oct 30	7+700 m to 8+370 m	2482
Nov 4	5+540 m to 6+000 m	2484

Core locations were selected to sample the daily range of dielectric values for surveys conducted on October 28, 29, 30 and November 4. Core samples were tested at Wood's materials laboratory in Dartmouth NS to determine the bulk relative density. The void content was determined based on the Maximum Theoretical Density (MTD) determined from loose samples of the mixture sampled each day as listed in Table 3. The average MTD was 2483 kg/m^3 with a standard deviation of 3.7 kg/m^3, resulting in a coefficient of variation of 0.15%. These results indicate that mixture production was consistent in quality. The highest impact of such small variations in the MTD of the mixture placed at any given core location on the calculated void content would be ± 0.23% void content for the range of bulk densities observed from the core samples. The average MTD for a given test day was used in calculating the void content of core specimens to ensure an even lower potential error.

Survey Results

Surface dielectric profile data across each test section were tabulated and analyzed to develop contour maps shown in Figure 4. Significant variations in surface dielectric values were observed by transverse position across the lanes. Sporadic occurrences of lower dielectric values less than 4.3 with elevated air void contents were observed near the shoulders and the centreline construction joint between the two lanes. This appears to be the result of mixture segregation and either confinement of the mix preventing adequate particle movement and kneading and/ or base layer movement which reduced the effectiveness of compaction effort. These issues appeared to be especially prevalent at transverse joints within the first few metres of each placement and along both confined and unconfined longitudinal mat edges.

Recognizing the likelihood of segregation and compaction issues at these locations, the Nova Scotia Standard Specification for Highway Construction and Maintenance includes guidance regarding the location of core samples for quality control and quality assurance purposes. Section 6.2.4 in Division 4, Section 19 "Superpave End Product Specification (EPS)", states that cores shall not be taken within 0.15 m of the pavement edge or longitudinal joint, nor closer than 6 m to a transverse joint. While this avoids localized segregation/ compaction issues from influencing the statistics representing the bulk of the pavement quality, defects at these locations are overlooked within the current QA/QC methodology yet have significant impact on the maintenance requirement and service life of the pavement. Identification of these defects has been made by visual inspection by the Department or their designated representatives. The Pavescan RDM results appear to provide an objective and quantifiable means by which areas of segregation exhibiting excessive void content can be identified and located within a compacted mat. Further development of this technology for mounting on roller compaction equipment could provide a valuable tool to contractors for quality control purposes.

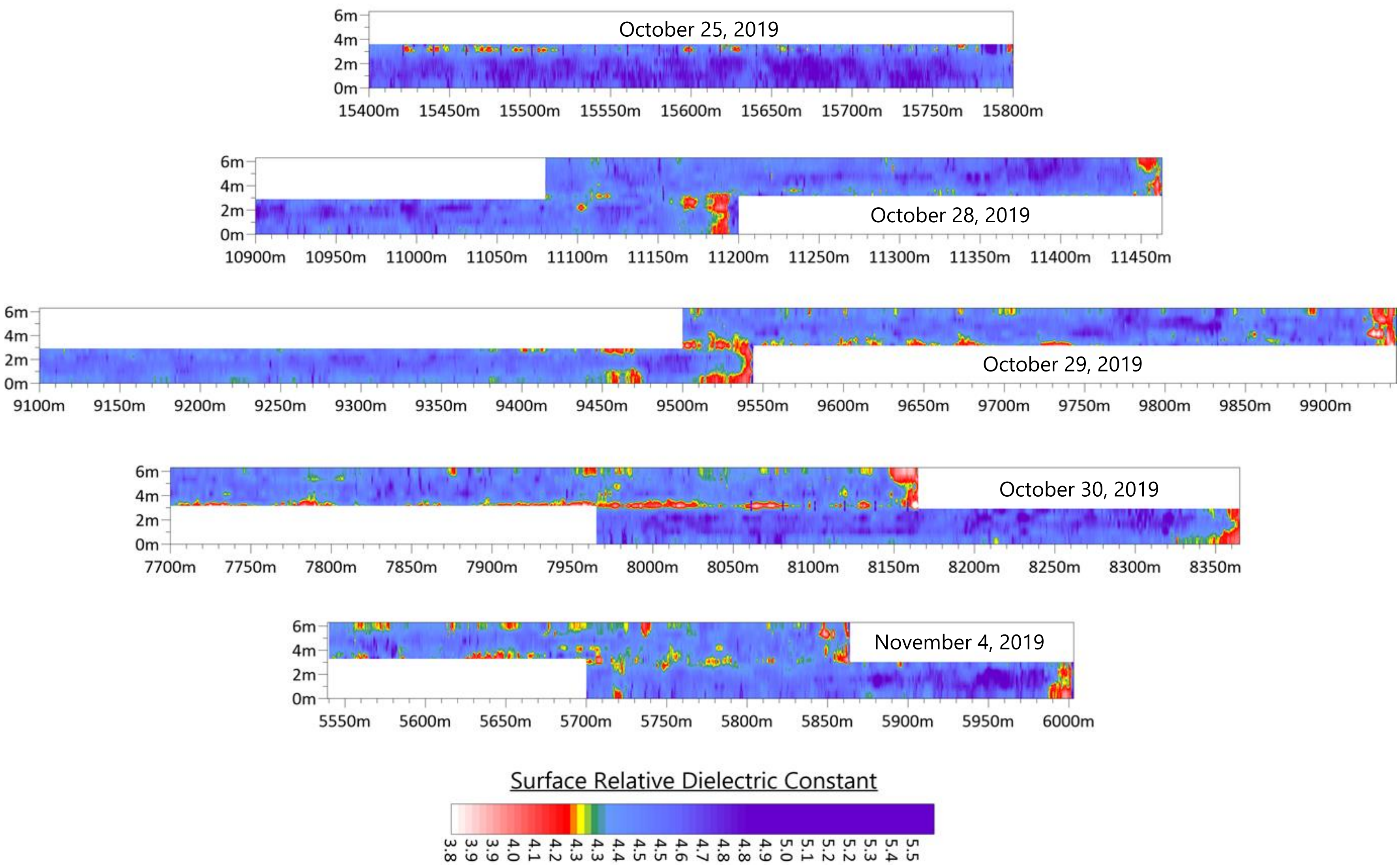

Figure 4 - Variation in surface dielectric value over test sections.

Model Calibration

Four to five core locations were sampled on the October 28, 29, 30 and November 4 Pavescan survey days based on relatively high, low, and average surface dielectric values observed during testing. The bulk relative density of each core was tested to determine the air void content based on the average MTD for the lot corresponding to the location of each core sample, as shown in Table 3. Table 4 lists the sampling date, range of chainage describing the corresponding Pavescan RDM test section, surface dielectric value at the exact core location, and the bulk density and air void content of each core specimen. These values were used to develop calibration models for predicting air void contents at each Pavescan measurement.

Table 4 – Bulk density and Air Void Content of Calibration Core Samples

Sampling Date	Chainage (m)	Surface Dielectric	Bulk Density (kg/m^3)	Air Void Content (%)
Oct 28	10+900 m to 11+463 m	4.02	2153	13.3
		4.37	2230	10.3
		4.86	2422	2.6
		4.11	2154	13.4
		4.51	2347	5.6
Oct 29	9+100 m to 9+940 m	4.50	2349	5.5
		4.85	2385	4.1
		4.96	2421	2.7
		4.46	2321	6.7
		4.31	2124	14.6
Oct 30	7+700 m to 8+370 m	4.32	2277	8.4
		4.82	2408	3.2
		4.51	2317	6.8
		3.97	2072	16.7
Nov 4	5+540 m to 6+000 m	4.49	2222	10.7
		5.10	2183	4.6
		4.03	2267	15.3
		4.56	2106	8.8
		4.28	2372	12.2

Daily predictive models of core sample air void contents were developed based on the surface dielectric value of the pavement at the core sample locations. Wilson et al. (2019) observed a significant interaction between a given production day and the dielectric value on the corresponding air void content, causing a shift in the calibration function. It was speculated that "When the calibration shifts, it could be a result of changes in the produced mix (change in asphalt content, aggregate substitution, etc.). Though researchers sampled plant mix each day and tested the asphalt content and theoretical maximum specific gravity, the variability inherent with each laboratory test makes it difficult to ascribe changes in the calibration to the mixture alone." Exponential models relating void content to surface dielectric exhibited the highest coefficients of determination for this study, compared to the linear model. Table 5 lists the model coefficients developed for each day of asphalt concrete production. The exponential models are shown in Figure 5.

Table 5 – Daily Exponential Model Coefficients.

Air Void Content = a ▪ e $^{(c \cdot \text{Surface dielectric value})}$			
Production Date	**a**	**c**	**R^2**
Oct 28	53,299.3435	-2.0215	93.81%
Oct 29	106,645.2183	-2.1320	86.38%
Oct 30	33,137.7482	-1.9074	98.67%
Nov 4	1,560.9279	-1.1334	98.15%

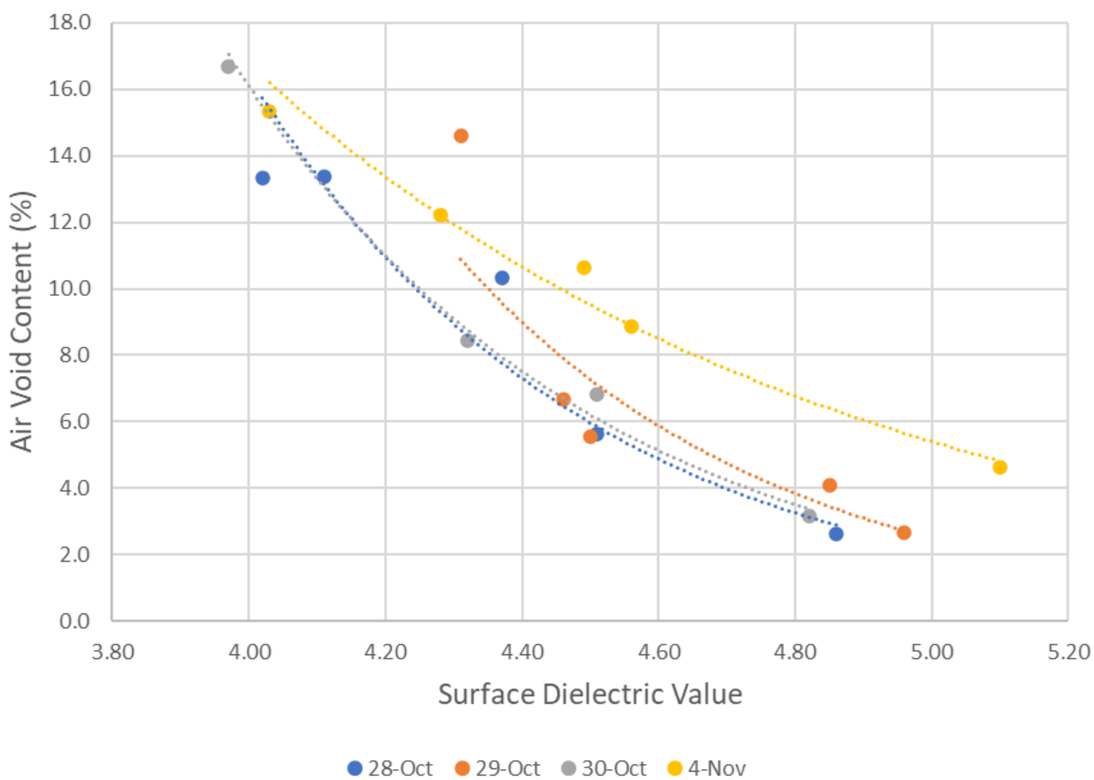

Figure 5 – Daily exponential air void prediction models.

Figure 6 shows plan view contour plots of the interpreted void content within each test segment. Areas of high void content are evident at the lower dielectric values observed along the longitudinal joint, at transverse joints, and at various locations along the shoulders. The void content exhibited for the November 4 test segment appears to generally higher than in the other segments, but the model still provides an accurate prediction of the compaction levels for that day. No cause for the change in the model was determined, but the change in the model behaviour could indicate a change in the material characteristics of the asphalt concrete or compaction characteristics. However, given the consistency in the maximum theoretical density amongst all test days, it seems unlikely that changes in the material occurred. It was observed from the MacKay Bridge trial that large differences in base stiffness conditions cause different relationships between surface dielectric and void content. It is unknown if the base stiffness conditions were significantly different within the test section that was paved on November 4 compared to the other sections.

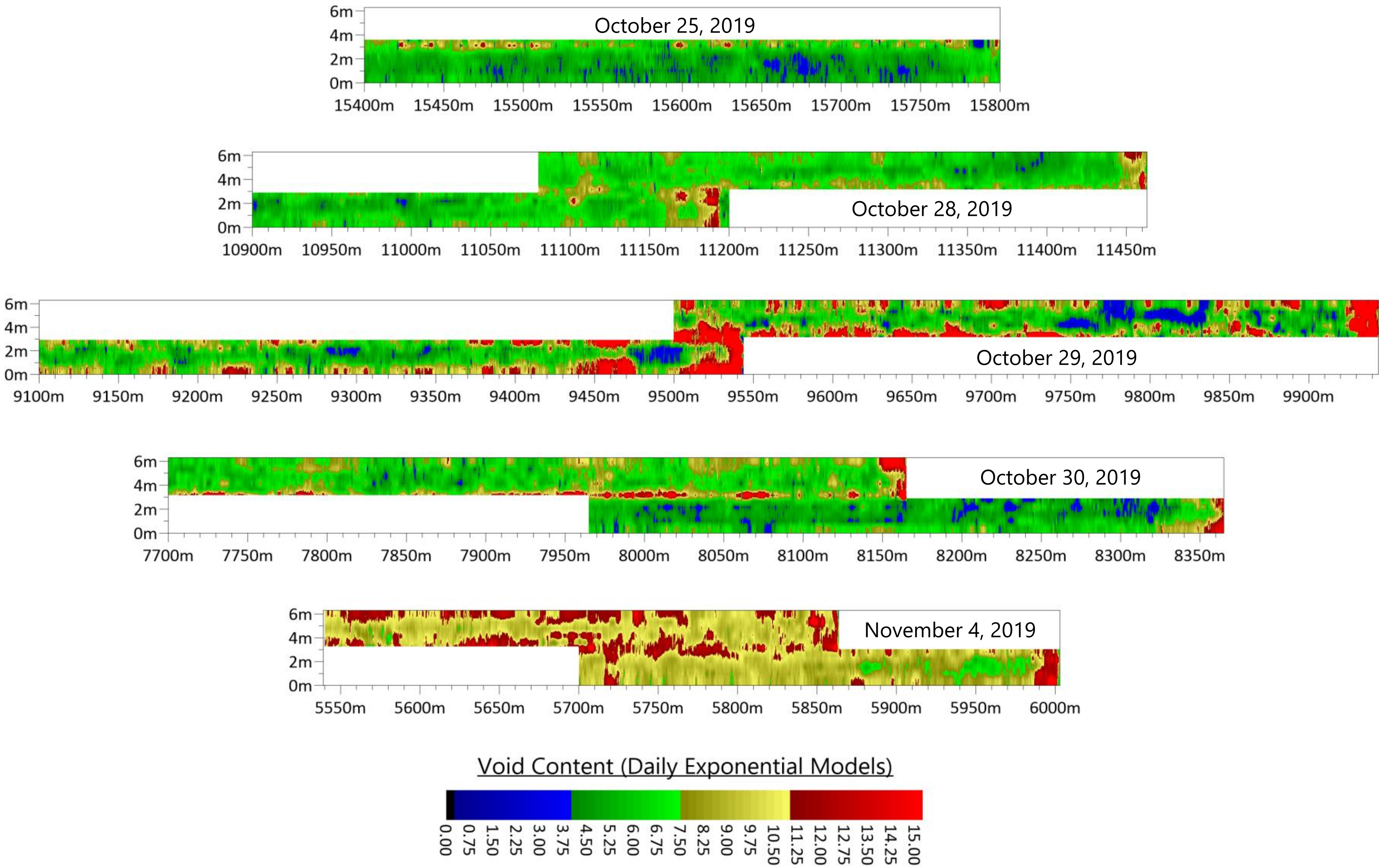

Figure 6 - Variation in interpreted void content over test sections.

Table 6 compares the predicted air void content and error versus the actual measured air void content for each test segment.

Table 6 – Predicted Air-Void Content at Core Sample Locations.

Sampling Date	Chainage (m)	Surface Dielectric	Actual Air Void Content (%)	Predicted Air Void Content (%)	Difference
Oct 28	10+900 m to 11+463 m	4.02	13.3	14.5	1.2
		4.37	10.3	8.3	-2.1
		4.86	2.6	3.8	1.2
		4.11	13.4	12.5	-0.8
		4.51	5.6	6.6	1.0
Oct 29	9+100 m to 9+940 m	4.50	5.5	6.9	1.4
		4.85	4.1	2.0	-2.1
		4.96	2.7	1.4	-1.3
		4.46	6.7	8.0	1.3
		4.31	14.6	13.5	-1.0
Oct 30	7+700 m to 8+370 m	4.32	8.4	8.8	0.3
		4.82	3.2	3.5	0.3
		4.51	6.8	6.2	-0.6
		3.97	16.7	16.7	0.0
Nov 4	5+540 m to 6+000 m	4.49	10.7	9.8	-0.9
		5.10	4.6	5.2	0.6
		4.03	15.3	15.6	0.3
		4.56	8.8	9.1	0.2
		4.28	12.2	12.1	-0.1

Accuracy in Predicting Compliant and Non-compliant Compaction

The daily exponential models predicted air void contents above 7.5% in 11 of 19 core samples. Ten of these predictions were correct, resulting in a true positive prediction rate of 90.9% and a false positive prediction rate of 9.1%. Eight of the cores were predicted to have void contents less than or equal to 7.5% voids and 100% of the predictions were true with 0% false predictions. The overall correct prediction rate of the daily exponential models was 94.7% for predicting air void content above and below 11.0%, which is the maximum allowable compaction level beyond which rejection occurs. The daily exponential models predicted air void contents above 11.0% in 6 out of 19 core samples with no false predictions. 13 of the cores were predicted to have void contents less than or equal to 11.0% voids with no false predictions. The overall correct prediction rate of the daily exponential models was 100.0% for air void contents above and below 11.0%. A summary of the prediction rate analysis is provided in Table 7.

Table 7 – Rate of Correct Predictions for Air Void Above or Below 7.5% and 11.0%.

Rate of Predictions Above and Below 7.5% Air Void Content			Rate of Predictions Above and Below 11.0% Air Void Content		
≤ 7.5%	> 7.5%	Overall	≤ 11.0%	> 11.0%	Overall
90.9%	100.0%	94.7%	100.0%	100.0%	100.0%

Comparison to Quality Assurance Core Sample Results

Thirty-four cores were obtained by the contractor from seven lots of asphalt concrete placed over the length the project for both quality control and quality assurance testing at predetermined random locations selected by NSTAT. Five cores were tested from each 2,400 tonne lot of asphalt concrete, except for a total of four cores obtained from Lot 7 which required less material to complete the project. Table 8 lists the air void contents measured from each core sample and provides the mean and standard deviation for each lot. The date when the Pavescan RDM survey was completed on a portion of the lot is also listed. The groups of five air void contents measured from Lots 1, 3, 5 and 7 varied over a range of 1.7% to 2.7% between the minimum and maximum values. The air void contents from Lots 2, 4, and 6 varied over larger ranges from 5.2% to 6.9% up to a single maximum value of 10.2%. The transverse locations of the core samples were mostly located within the mid-lane area of each mat, from 0.9 m to 2.0 m and from 4.0 to 5.6 m across the full road width. These core locations provide little indication of the suspect areas along the longitudinal joint and shoulders that were observed within the Pavescan RDM results.

Table 8 – Air Void Content Observed in Quality Assurance Core Samples.

Lot	Survey Date	Core 1	Core 2	Core 3	Core 4	Core 5	Average	Standard Deviation
1	Oct 25	6.2%	4.1%	5.5%	5.5%	4.8%	5.2%	0.8%
2	Oct 28	8.8%	5.4%	4.4%	3.6%	6.1%	5.7%	2.0%
3	Oct 29	4.4%	5.9%	6.1%	5.5%	5.0%	5.4%	0.7%
4	Oct 30	3.0%	7.2%	4.4%	4.4%	9.9%	5.8%	2.8%
5	Nov 4	8.3%	7.0%	5.8%	7.0%	6.9%	7.0%	0.9%
6	N/A	6.2%	10.2%	7.4%	6.7%	3.9%	6.9%	2.3%
7	N/A	7.2%	8.6%	7.9%	5.9%	N/A	7.4%	1.2%

Review of the air void contents predicted by the Pavescan RDM survey using the daily exponential calibration models exhibited significantly larger mean and standard deviations compared to the quality assurance core samples listed in Table 8. These larger values are expected since the surface dielectric survey provides a more complete inspection of the total road surface, including areas that are avoided by the core sampling protocol per the current NSTAT Standard Specifications. Most of the core samples were obtained at offsets which place them within the central portion of the lane. Table 9 also lists the mean and standard deviation of the Pavescan results obtained near the middle for each lane, excluding the shoulders and centerline areas of the roadway where core samples are not obtained. These statistics are similar to those developed from the quality assurance core samples but are slightly higher in air void content and variability since they also include the effects associated with transverse joints which are excluded from the core samples. The difference in mean values between Lots 1, 2, and 4 versus the corresponding October 25, October 28, and October 30 test sections were 0.4%, 0.4% and 0.0% air void content, respectively. The difference in these means for Lot 3 and the October 29 test section was higher at 0.9% air void content, but the Pavescan RDM results also exhibited more significant areas of lower dielectric/ higher void content adjacent to two transverse joints compared to the October 25, October 28, and October 30 sections. The Pavescan results appear to overestimate the air void content within the mat for Lot 5 as expected due to the apparent difference in the calibration model compared to the others, but the relatively higher air contents within this lot are reflected in both the surface dielectric and core sample results.

Table 9 – Comparison Statistics for Predicted Air Void Content to Core Samples.

Lot	Survey Date	Pavescan – All Data		Pavescan – Midlane Data		Core Samples	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
1	Oct 25	5.9%	2.5%	4.8%	1.0%	5.2%	0.8%
2	Oct 28	6.7%	1.7%	6.1%	1.4%	5.7%	2.0%
3	Oct 29	8.8%	7.1%	6.3%	3.4%	5.4%	0.7%
4	Oct 30	6.8%	3.1%	5.8%	1.7%	5.8%	2.8%
5	Nov 4	10.0%	1.8%	9.4%	1.6%	7.0%	0.9%

A total of 648,000 surface dielectric measurements were obtained from the 10,860 m^2 of paved surface within the five test sections that were scanned for the project. Conversely, a total of 34 quality assurance core samples were tested to represent the approximate 110,250 m^2 total surface area of the project. Given that the net total of normally distributed random errors over a large number of samples tends to zero and provided that accurate daily calibration models are developed, it follows that the Pavescan RDM results likely provide a more accurate and extremely robust statistical measure of the compaction throughout the test sections than what is provided by the relatively sparse number of core samples which by design are not representative of the entire roadway surface. This requires careful selection and precise superposition of the Pavescan RDM data and core samples, ensuring that the full range of measured dielectric values are evenly represented throughout the calibration model.

The ability of the Pavescan RDM to inspect the compaction quality of the full width roadway and identify areas of high air void content provides Provincial transportation agencies with the capacity to visualize and map areas where poor pavement performance is expected to result, including longitudinal and transverse joint areas which are precluded from conventional quality control/ quality assurance core sampling. Mapping these areas provides the opportunity to require repair of these areas and/ or update the current pay adjustment process to reflect the overall quality of the roadway construction. In either circumstance, the inspection methodology also provides a means by which new placement and compaction processes can be evaluated to minimize joint compaction issues.

Conclusions and Recommendations

This study has determined that the Pavescan RDM surface dielectric profiling system can provide a robust evaluation of pavement compaction when accurate daily calibration models have been developed for a specific mixture placed on uniform base support conditions. The exponential function calibration model should be developed based on selecting core samples which are evenly distributed across the full spectrum of surface dielectric constants measured over a given production day. Intact, undamaged core samples must be taken at exact locations marked in the Pavescan data. While calibration models developed in this study utilized up to five cores per production day, a larger number of daily samples is expected to provide more accurate models for predicting the air void content at other locations.

Surface dielectric surveys of the mid-lane portions of the roadway provided similar results to quality assurance core testing results while identifying poor compaction adjacent to transverse joints. Comprehensive full-width surveys were able to image areas of lower compaction along longitudinal and associated transverse joints, where conventional quality assurance core sampling tends to avoid these problematic areas.

Based on review of the Pavescan technology, the following recommendations are provided:

- Use a surveying grade GPS unit during Pavescan RDM surveys to provide horizontal positioning accuracy in the range of 20 mm or less. This will provide sufficient accuracy to develop contour plots directly from the Pavescan analysis software data output and enable precise re-location of areas of interest in the field.
- The Pavescan RDM system could be used to monitor compaction over the entire paved surface for quality assurance purposes and could provide the basis for a weighted payment adjustment based on the measured distribution of void content. Current quality control/ quality assurance coring protocols exclude these problematic areas, leaving significant areas of potential low compaction and future underperformance unaccounted. Randomly selected test areas could be surveyed as quality measures for each different lot of asphalt concrete.
- Consider collaborative review and trials of current best practices for longitudinal and transverse joint compaction with local industry, such as the notch-wedge method used by Alaska Department of Transportation. Implementation of a longitudinal joint and shoulder compaction bonuses based on surface dielectric profile testing can provide incentive to improve compaction quality in these locations.
- Evaluate the Pavescan RDM for monitoring bridge deck pavement compaction and as the basis of measurement for an updated bridge pavement specification. Along with a waterproofing membrane, densely compacted asphalt forms a crucial component of the deck waterproofing protection system that contributes to the longevity of both the protection system and the deck. Conventional nuclear density gauges are influenced by the density of the concrete deck and reinforcing steel, while surface dielectric profiling of lifts greater than 40 mm should be feasible.

References

AASHTO PP98-19 Standard Specification for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar, American Association of State Highway and Transportation Officials, 2019.

Al-Qadi, I. L., S. Lahouar, and A. Loulizi. 2001. "In situ measurements of hot-mix asphalt dielectric properties." NDT & e International 34.6: 427-434.

Conway R., Hoegh, K., and Khazanovich, L. (2017). "Test Protocol for the Rolling Density Meter", http://shrp2.transportation.org/documents/SHRP2_R06C_Test_Protocol_Appendix_r6.pdf.

Hoegh, K., Dai, S., and Khazanovich, L. (2017). "Asphalt Pavement Compaction Assessment using Ground Penetrating Radar-Arrays", http://shrp2.transportation.org/SiteAssets/Pages/R06C_RapidTechnologiestoEnhanceQualityControl/RDMpaperForCongressProceedings.pdf.

Khazanovich, L., Hoegh, K., Conway, R., and Dai, S. (2017). "Nondestructive Evaluation of Bituminous Compaction Uniformity Using Rolling Density", http://shrp2.transportation.org/documents/SHRP2_RO6C_NonDestructiveEval_v6.pdf.

Pavescan RDM Manual, Geophysical Survey Systems Inc., MN36-540 Rev E, 2019.

Popik, M., K. Maser, and C. Holzschuher. (2010). "Using high-speed ground penetrating radar for evaluation of asphalt density measurements." Annual conference & exhibition of the Transportation Association of Canada.

Scullion, T. and Y. Chen. (1999). Using Ground-Penetrating Radar for Real-Time Quality Control Measurements on New HMA Surfaces, Report 1702-5, Texas Transportation Institute.