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# Minnesota Department of Transportation Case Studies for Coreless Asphalt Pavement Compaction Assessment

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**Abstract**

Available methods for assessing hot-mix-asphalt pavements are typically restricted to destructive methods such as coring that damage the pavement and are limited in coverage. Recently, density profiling systems (DPS) have become available with the capability of measuring asphalt compaction continuously, giving instantaneous measurements a few hundred feet behind the final roller of the freshly placed pavement. Further developments of the methods involved with DPS processing have allowed for coreless calibration by correlating dielectric measurements with asphalt specimens fabricated at variable air void contents using superpave gyratory compaction. These developments make DPS technology an attractive potential tool for quality control because of the real-time nature of the results, and quality assurance because of the ability to measure a more statistically significant amount of data as compared with current quality assurance methods such as coring. To test the viability of these recently developed methods for implementation, multiple projects were selected for field trials. Each field trial was used to assess the coreless calibration prediction by comparing with field cores where dielectric measurements were made. Ground truth core validation on each project showed the reasonableness of the coreless calibration method. The validated dielectric to air void prediction curves allowed for assessment of the tested pavements in relation to as-built characteristics, with the DPS providing the equivalent of approximately 100,000 cores per mile. Statistical measures were used to demonstrate how DPS can provide a comprehensive asphalt compaction evaluation that can be used to inform construction-related decisions and has potential as a future quality assurance tool.

The mechanical behavior and thus performance of asphalt pavement has been shown to be highly dependent on the air void content of the compacted mixture. Kassem et al. showed that higher air void content in pavement corresponds to increased occurences of pavement distress that negatively affect long-term performance (*1*). This behavior is best summarized by Linden et al., who estimate that every 1% increase in air void content above 7% leads to approximately 10% reduction in pavement life (*2*). Accurate and complete assessment of pavement compaction is therefore an essential step in quality assurance and quality control (QA/QC) of paving projects. Current pavement QA/QC tools to test asphalt compaction are destructive, expensive, and limited in coverage. The state-of-the-practice is to complete random coring to determine incentive-based payouts for the contractor. Random coring assesses less than 1% of the placed pavement, so its coverage is limited and can often misrepresent the true compaction of the placed pavement. There is a strong need for a non-destructive, continuous, and efficient method to complete the QA analysis of a paving project. In addition, traditionally available methods such as nuclear density gage are also spot measurements that do not timely and comprehensively provide feedback to the contractor to make real-time decisions affecting the compaction of the placed pavement.

In an effort to address the limitations of state-of-the-practice QA/QC measurement technology, ground penetrating radar (GPR) has been trialed for decades to measure the surface dielectric of asphalt pavement using non-contact horn antennas (*3*), or other innovative methods including step-frequency and array-based systems (*4–7*). The measured dielectric constant of the pavement is

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inversely proportional to the air void content of the pavement, so an efficient, accurate dielectric measurement using a GPR could be used to determine the relative compaction of the pavement. More recently, smaller-size dipole-type antennas have been used to more accurately measure the dielectric of the asphalt mixture successfully (*8*). As the asphalt thickness across a paving operation is unknown, traditional dielectric calculation based on the travel time to reflection at the depth of the asphalt concrete (AC) layer cannot be used reliably. Instead, the AC surface reflection method, which uses the ratio of the amplitude of the GPR signal reflection from air to the asphalt surface to the incident amplitude, is used to determine the bulk dielectric constant (*9*). GPR systems with the new, smaller antennas can be used on a cart to continuously measure the bulk dielectric constant of the placed pavement.

As the dielectric constant of asphalt is a function of all the individual mixture components, a generalized conversion from measured dielectric constant to air void content is not possible for all pavement types. Instead, unique conversion factors must be determined for a specific asphalt mix. The conventional method for accomplishing the mix-specific conversion requires multiple field cores, which are destructive, and the process is not accommodating to projects in which mix components are changing. To complete this task without requiring field cores from the placed pavement, a method has been proposed using pucks manufactured using a Superpave Gyratory Compactor (SGC) (*10*). Asphalt specimens compacted across a range of observable air void contents are created from the production mix. The specimens are then tested using the GPR antennas to determine the dielectric constants of each gyratory puck, and the Corelok testing procedure is used to determine the corresponding air void content of each specimen. Hoegh et al. show that by using a known dielectric spacer material, the wave from the GPR antenna can be slowed down enough to increase the time gap between the direct coupling and the asphalt specimen response that an accurate measurement of the dielectric constant of the 6 in. specimens created from the SGC can be completed (*10*).

With the proposal of a coreless calibration method, it is important that the method is tested on numerous projects with varying mix designs and paving operations before acceptance as a reliable QA/QC tool. Comparisons between different laboratories, different density profiling system (DPS) equipment types, and different operators would also be useful in determining the reliability of the method. This paper focuses on evaluating the accuracy of the method for various mix designs. To accomplish this, four projects are summarized in which the coreless calibration procedure was completed along with field cores to verify the ability to create a calibration curve that matches the pavement characteristics. The four projects include three from Minnesota and one from North Dakota and a variety of mix types and paving conditions. This selection allows for an in-depth assessment of whether the proposed method can function as a method to convert measured DPS dielectric constant values to air void content. Each of the projects allowed for greater than 1 mi of DPS data collection and selection of at least two field cores at locations in the pavement with a determined air void content. The field cores were used to validate the calibration curve created from the gyratory puck specimens. The calibration curve was confirmed by determining whether the model fell within the random uncertainty range of the measured field core properties. The acceptable dielectric precision range given in the analysis of this paper corresponds to the air-launched dielectric measurement of 0.08 as determined by the AASHTO specification (*11*). Similarly, the acceptable air void content range of the core validation measurements corresponds to the Minnesota Department of Transportation companion core tolerance for bulk specific gravity (Gmb) of 0.03 (*12*). The tolerance based on the Gmb is presented in relation to the effect on air void content, for the maximum specific gravity (Gmm) value, which is typically around 1 percent air void content.

As the proposed method for coreless calibration of a DPS utilizes the in-place QA/QC procedures with only the additional step of creating two more gyratory specimens with corresponding 60 s dielectric tests, the proposed methodology does not complicate the QA/QC process. Excluding the DPS equipment, the contractors and testing agencies do not need to purchase any additional tools to complete the tasks for calibration. The creation of this new procedure will improve the assessment that can be made on a pavement.

Similar to other intelligent construction technologies such as paver-mounted thermal profiling and intelligent compaction, the continuous data collection of the DPS allows for analysis by small sublots while still maintaining statistically significant datasets. In this case of DPS this results in characterizing compaction variation. Although the amount of data provided by the continuous DPS measurements opens up opportunities for many effective statistical assessment strategies, in this paper, the percent above limits by 100 ft sublots across the entire project and a daily summary are chosen to illustrate the value of the continuous data. Along with improving the sampling of the placed pavement, the ability to analyze by sublot will allow contractors to identify changes to the paving process that improve the achieved compaction, especially considering the data are continuously displayed in real time as they are collected.

However, also similar to other intelligent construction technologies, the measured value—dielectric in the case of DPS technology—is not a direct measurement of the pavement performance-related parameter of interest—air void content in the case of DPS technology. As such, the DPS air void content measurements must be validated using the accepted air void content technique (field cores) to be considered for evaluation of as-built asphalt pavements. Each of the case studies presented in this paper includes field core validation.

## Methods

### Field Data Collection and Reporting

Data collection generally includes two passes on the pavement following the final roller of the paving operation. The first pass is a random mat sampling, also referred to as a swerve pass. This arrangement is designed with the goal of ensuring full mat width coverage with the added benefit of validating sensor dielectric calibration throughout the day of testing. The sensors are aligned such that the left and right sensors always remain within 2 and 10 ft from the centerline joint and the middle sensor remains within 4 and 8 ft from the centerline joint. A full cycle is complete when the swerve pattern touches each 2 ft and 10 ft location, and any swerve pattern that completes at least two full cycles is sufficient for random sampling of the mat. The swerve pass is completed by swerving one lot and then turning around to ensure that the outside sensors have the same offset coverage, accounting for cases where there may be a discrepancy in lateral compaction. The pass always starts and ends at the same position. Figure 1*a* shows the pattern that should be followed by the swerve pass.

The second pass is the joint pass, which is designed to have 100% coverage of the centerline longitudinal joint as this is a critical location for potential water infiltration and early density-related pavement failure. For this pass, the outside sensor nearest to the joint is aligned 0.5 ft from the centerline joint, and the operator follows the paving operation. It is most convenient for this pass to occur in lengths that match the stationing stake intervals, but it is sometimes necessary to have long passes for traffic control considerations. Figure 1*b* shows an example of the alignment that is desired during the joint pass.

This paper includes analysis of data collected from North Dakota Highway 18 (ND18), Minnesota Trunk Highway 55 (TH55), Trunk Highway 15 (TH15), and Trunk Highway 371 (TH371). All four of these projects included continuous field testing, gyratory-compacted specimen conversion from dielectric to air voids, field core validation of the coreless conversion, and reporting of the continuously collected field data in relation to the converted dielectric to air void content results. The volumetric properties of the mix are given in Table 1.

DPS testing was conducted on ND18 on Wednesday, June 26th, 2019 in Casselton, ND, Project Number SS-8-018(094)075. The testing was conducted on the top lift with a PG 58-28 type of AC. The testing was conducted following the paving operation from reference point 86.7 to reference point 85.7 with paving moving west to east. The centerline joint edge of the mainline was unconfined throughout the testing. The production mix used for puck testing was collected the same afternoon of paving, corresponding to MDR: 3A-2019—11.

The TH55 project in Annandale, Minnesota on State Project 8606-060 was tested using the DPS on Monday May 20, 2019. The project spanned from Kimball, Minnesota to Buffalo, Minnesota, and testing was

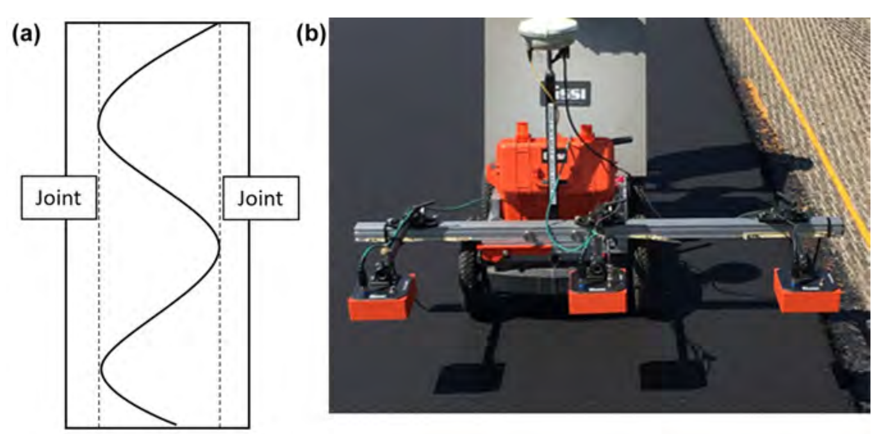


**Figure 1.** Two basic types of field density profiling system collection with (*a*) swerve collection designed to gather random sampling of the mat and (*b*) joint passes designed to obtain 100% coverage at 6 inches from the centerline joint.

**Table 1.** Volumetric Properties of the Mix for the Evaluated Projects

| Route | Designed air voids, % | Designed binder, % | Designed max aggregate, in. |
|---|---|---|---|
| North Dakota 18 | 4.0 | 5.3 | 5/8 |
| Trunk Highway 55 | 4.0 | 5.3 | 1/2 |
| Trunk Highway 15 | 4.0 | 5.3 | 1/2 |
| Trunk Highway 371 | 4.0 | 5.1 | 1/2 |

conducted on the second lift (first of two wear lifts) with mix design SPWEA340. The testing was conducted following the paving operation moving west to east on the mainline eastbound lane with increasing stationing ranging from 74 + 00 to 170 + 00 with paving moving west to east. The centerline joint edge of the mainline was unconfined throughout the testing with no joint edge on the 6.5 ft variable width shoulder side.

In addition, Th15 in Kimball, Minnesota on State Project 7303-50 was tested on Wednesday July 17, 2019. The testing was conducted on the second lift with mix design SPWEA440F. The testing was conducted following the paving operation moving south to north on the mainline northbound lane in the increasing stationing direction with DPS testing ranging from 274 + 00 to 338 + 00. The centerline longitudinal joint was unconfined throughout the reported testing.

The final project assessed in this report is TH371 on State Project 1118-21, which was tested between October 1 and October 6, 2019. The project spanned from stationing 210 + 00 to 570 + 00, and testing was conducted on the second (final) lift with mix design SPWEB230. The testing was conducted following the paving operation moving north to south in both lanes. Testing was conducted on both confined and unconfined sides of the centerline joint throughout the project, but the data reported in this study included only the unconfined joint.

Once the collected DPS data are converted from dielectric to air void content using the laboratory calibration procedure described in the next section, the analysis can be completed in relation to the achieved pavement density at each measured location. The 6 in. sampling rate, with three sensors, using the data collection procedure described above, gives the equivalent of approximately 100,000 cores per mile. This level of data collection allows for the use of statistical methods such as percent within limits (PWL) or percent above limits (PAL) when evaluating the pavment compaction performance. The use of PAL analysis is effective in determining if the pavement compaction meets a required level of quality. Local variations are expected and 100% compliance is difficult to achieve, so the use of these assessments are valuable. In fact, it has been determined that the existence of a small percentage of tests outside of the specification limits is normal and not necessarily detrimental to performance (*13*). The practice of using PWL is common in many QA analyses and is even used in systems such as the SGC to encourage satisfactory performance (*14*). In order for the PWL/PAL assessment to be valuable, there is a trade-off between the cost of additional sampling and the cost of erroneous tests (*15*). The assessment becomes more accurate if more samples are taken, so the DPS, with an extremely high sampling rate, should provide valuable results from PWL/PAL assessments. Also, with this testing coverage, the analysis can be done in smaller sublots than the current MnDOT quality assurance procedure of two cores per 600 tons of placed asphalt. For the purposes of this study the PAL strategy is employed as both NDDOT and MnDOT are primarily concerned with achieving at least a minimum level of compaction. MnDOT limits are differentiated for the joint versus mat with acceptable levels of 91% and 93%, respectively. NDDOT has a 92% acceptable level applied to both joint and mat compaction. In this paper the percentage of pavement at or above these acceptable limits is given for the whole day of DPS collection as well as example 100 ft sublot PAL analysis to illustrate the advantage of continuous coverage data.

### *Coreless Conversion from DPS Data to Actual Pavement Air Void Content*

Until recently, conversion of dielectric to air void content has required calibration to field cores cut in the newlyl placed asphalt pavement. To establish a conversion from dielectric constant of the pavement to air void content without field cores, a procedure as detailed in Hoegh et al. is completed (*10*). Gyratory pucks are created from mix collected from the asphalt plant on the project. Three cylinders (approximately 60 lbs of asphalt) are heated in accordance with MnDOT Lab Manual Section 1806, and the mixture is blended in a tray to minimize segregation (*16*). Two specimens are compacted following the QA/QC procedure to hit the target air voids, and the grams used are recorded. The rice test and extraction gradation are run following the typical QA/QC procedures. The puck heights are recorded after compaction, and the Gyratory Compactor is set to stop at this value instead of number of gyrations. Next, a medium and high air void puck are compacted following the same procedure, but the medium puck uses 250 g less asphalt than that required for the QA/QC pucks, and the high puck uses 500 g less than the QA/QC pucks. All pucks are placed in front of a fan to cool to room temperature before testing. The pucks are then tested using the DPS to determine the dielectric constant before completing the Corelok procedure outlined in the MnDOT Lab

**Figure 2.** Experimental dielectric testing of gyratory specimens. The four setups shown in the figure are performed sequentially for 15 seconds each while operating the density profiling system to calculate the dielectric constant of the puck.

Manual Section 1816 to avoid moisture in the pucks (*17*). Corelok is desired for high air void content pucks because of issues with the saturated surface dry method (SSD) with interconnected voids, but SSD was used on some early projects because of availability. In this case it is critical to measure the dielectric of the puck prior to air void content measurements.

To determine the dielectric constant of the gyratory specimens, the procedure, as detailed in Hoegh et al., is completed using the DPS (*10*). The procedure allows for calculation of the dielectric constant of the asphalt material two ways including the surface reflection and time-of-flight method. The surface reflection method calculates the reflection coefficient between the Delrin and asphalt surface as the basis of the dielectric measurement. As detailed in Hoegh et al. (*10*), although this method is more analagous to the field measurements, it exhibits too much variability, presumably as a result of the effect of asphalt heterogeneity when the signal origin is so close to the asphalt surface. The time-of-flight method is based on a velocity measurement of the signal through the asphalt specimen, which can be calculated using the time of flight as the specimen dimensions are known, and Fermat's principle is an appropriate assumption to estimate the signal path. The time-of-flight-based dielectric measurement is used for the purposes of this study as the precision is better, as described by Hoegh et al. (*10*). To obtain the necessary measurements, two Delrin spacers are first placed on the DPS antenna for 15 s, followed by removal of one of the spacers and placement of a metal plate on the remaining spacer for 15 s. Next, the metal plate is removed and the desired puck is placed on top of the spacer for 15 s. Last, the metal plate is placed back on top of the puck for 15 s, and the test data are saved. This procedure is followed for all of the remaining pucks, and the data are exported. Figure 2 shows the four steps required in the testing procedure.

With the saved scans from the dielectric testing procedure detailed above, the dielectric constant can be determined for each puck. In conjunction with the determined air void content from the Corelok testing procedure, a calibration curve can be created for the conversion from dielectric constant to air void content for a specific mix.

It has been shown that one of the best empirical fits detailing the expected reduction in air void content with an increase in dielectric is the Hoegh–Dai (HD) model (*18*). This model has been shown to effectively predict core behavior between approximately 4% and 15% air voids. An improved, logistic model is currently being used by MnDOT, referred to in this paper as the MnDOT model, to expand the range of the fit outside of these bounds. The HD model fails as a result of over-predicting the slope at the extremes, so the MnDOT model with a logistic form better meets the experimental behavior at the extremes. Adapting from a basic five-parameter logistic function (*19*), the MnDOT model also accounts for the physical bounds on air void content and dielectric. As the physical bound on air void content is zero, the lower bound of the function was set to zero. In addition, as the function approaches a dielectric constant of 1, the fit has to approach 100% air voids, as air has a dielectric constant of approximately 1.0006 at normal pressure and temperature (*20*). To bound this behavior while also allowing the inflection point of the function to occur around a dielectric of 3–7, a second, asymptotic term was added to the fit. The MnDOT model is of the form, Equation 1:

$$AV = \frac{a}{\left(1 + \left(\frac{e}{c}\right)^b\right)^g} + \frac{\delta}{(e-1)} \quad (1)$$

where $AV$ is the air void content, $e$ is the measured dielectric constant, and the other variables are simply parameters fit to the data. The parameter $\delta$ scales the asymptotic behavior to force the fit to include the point corresponding to a dielectric of 1.001 at 100% air voids. The second term prevents any non-physical behavior in the fit, as the dielectric constant cannot go below 1, and the initial logistic term prevents the air void content from going below 0%.

The parameters are optimized using GRG nonlinear regression with Excel's Solver Add-in. The function is constrained to have the upper asymptote of the logistic function, a, at a value of 0.2, corresponding to the approximate physical limit of the possible air void content measured in a hot-mix asphalt field core. With a constant value of a, the value of $\delta$ that forces the fit to be 1.001 at 100% air void was determined to be 0.0008. The model can therefore be rewritten as,

$$AV = \frac{0.20}{\left(1 + \left(\frac{e}{c}\right)^b\right)^g} + \frac{0.0008}{(e-1)} \quad (2)$$

The remaining three parameters are optimized using Solver by minimizing the sum of the square differences between gyratory puck data and the modeled data. Solver is run with the multi-start option enabled to find the global solution, independent of the initial guesses for the parameters.

## Results

Results of DPS testing include calibration and validation of the conversion from DPS-measured dielectric to actual pavement air void content. Once the laboratory-produced prediction curve is validated with field cores, each of the DPS measurements can be treated as the equivalent of individual cores taken at 6 in. spacing continuously behind the final roller compactor. The project level and sublot breakdown of this continuous analysis is then given to assess the pavement performance of the tested pavements. The 2019 projects include data that were tested and corelessly converted to air void content the same day of testing to show the feasibility of this method in handling changes in mix that required recalibration throughout a project. It is anticipated that it will be feasible to use curves from previous production days to complete this conversion if no significant changes to the mix occur. However, for the case studies presented, data were chosen from the first production day to simulate the most challenging scenario for implementation, in which the testing occurs on the first day of production of the new mix type, or a change in mix.

### *Lab Calibration Results on Each Project Including Field Validation*

To accommodate the coreless conversion from dielectric to air void content, the mix from each of the four projects with continuous field DPS data collection was collected following the procedure prescribed by Hoegh et al. (*10*). An additional project on Minnesota Trunk Highway 60 (TH 60) allowed for production mix collection for coreless calibration and static field dielectric measurement and core validation. All of the coreless conversion results from these five projects are given in Figure 3*a* through *e*. An additional comparison of contractor-compacted specimen conversion curve versus agency-compacted specimen produced conversion curves from the same mix on TH 15 is given in Figure 3*f*. In each of these figures the ground truth core verifications are given by the blue triangles. In Figure 3*a* through *e*, the laboratory asphalt samples are given by the red diamonds, and laboratory-produced dielectric to air void conversion is given by the green line. In Figure 3*f* the agency-compacted specimen prediction is given by the green line, the contractor-compacted specimen curve is given by the purple line, and all specimens produced curve is given in blue.

The field cores represent the ground truth dielectric versus air void content relationship with a box surrounding them indicating the respective uncertainty of the core and dielectric measurements (1.2% and 0.08, respectively). If the coreless conversion is accurately assessing the field pavement conditions, the production mix-produced curve should fall within the blue boxes. It can be observed that the validation cores fell within the prediction curve in five of the six validation cores from 371, two of the two validation cores from TH 60, three of the three validation cores from TH 55, four of the four validation cores from ND 18, and two of the two validation cores from TH 15. It should be noted that, although the ND 18 predictions are within the uncertainty of the core validation measurements indicating the reasonableness of the fit, the similar magnitude of overprediction of the model as compared with all four cores indicates a potential bias in the coreless prediction on that project. This bias was not observed in the other four projects evaluated in this study. The only other discrepancy of note was one of the six cores from TH 371. In that case, the high air void content of the core was most likely underpredicted by the SSD method, suggesting that the prediction is not as far off from that core as the reported results indicate. The major takeaway from the validation cores is that the coreless prediction procedure is reasonable for the various types of mixes five different projects encompass (16 of the 17 validation cores were within the uncertainty of

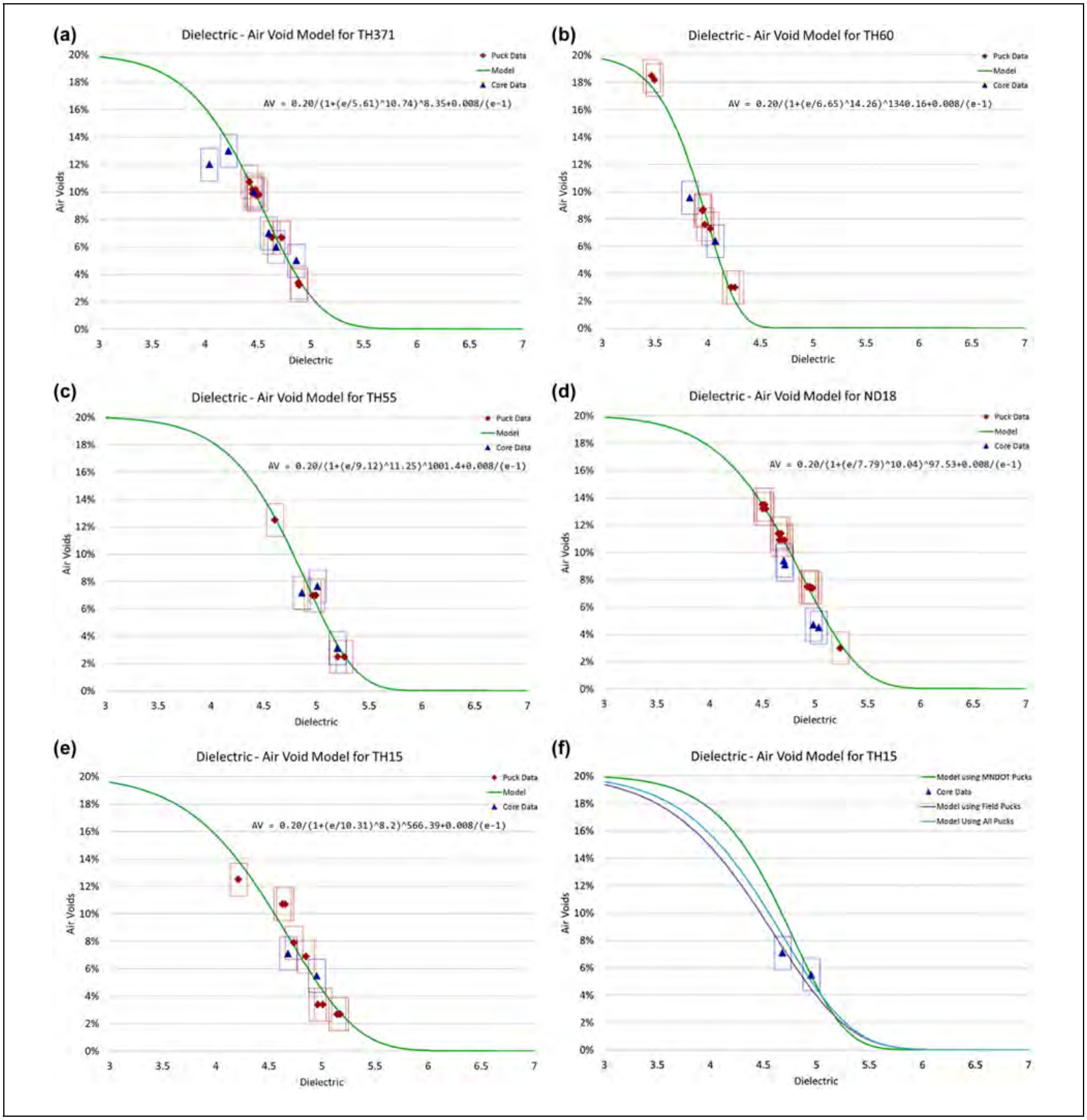


**Figure 3.** Results of coreless calibration for (*a*) TH 371, (*b*) TH 60, (*c*) TH 55, (*d*) ND 18, (*e*) TH 15, and (*f*) TH 15 including break down of agency and contractor pucks.

the methods). With the core validation complete, the DPS data can then be confidently used to assess pavement performance in relation to actual air void content of the placed asphalt pavement.

If this technique is going to be considered for QA, there will need to be a procedure to assure the quality of the collected dielectric and air void relationship. As a step in this direction, an additional analysis was conducted on TH 15, in which both agency and contractor puck data were collected. Predictions curves based on contractor only (purple), agency only (green), and combined (blue), are given along with the validation core (blue triangles) in Figure 3*f*. It can be observed that both agency and contractor predictions are similar, with all of

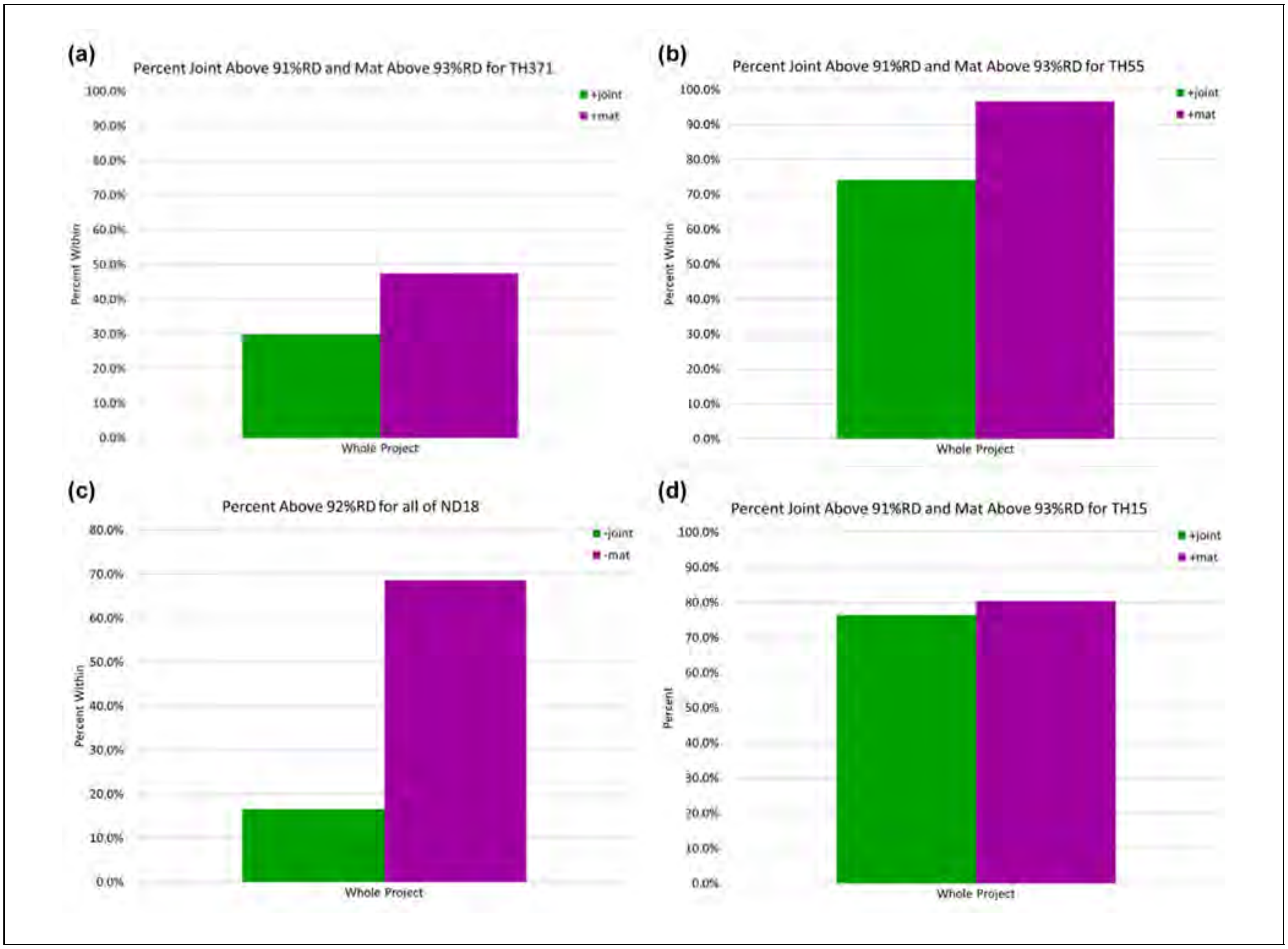


**Figure 4.** Results of project-level percent within limits for (*a*) TH 371, (*b*) TH 55, (*c*) ND 18, and (*d*) TH 15.

the curves predicting air voids within the uncertainty of the core and dielectric measurements (indicated by the boxes encompassing the cores). The prediction when combining both contractor and agency data was most similar to the validation cores.

### *Project Assessment of Asphalt Compaction*

All of the projects tested and reported in this paper consisted of 1 day of testing ranging from 1 to 4 mi of continuous asphalt compaction assessment using the DPS field data collection procedure described above. With each DPS coreless conversion validated, each of the projects could then be evaluated based on the equivalent of 100,000 cores per mile tested by the DPS. As discussed in the methods section, this allows for presentation of the results using PAL analysis using MnDOT acceptable limits set at 91% and 93% relative max-gravity for joint and mat, respectively. ND DOT preferred the PAL acceptable limit to be set at 92% for both joint and mat.

### *Project Level*

All of the data collected in each of the project routes TH 371, TH 55, ND18, and TH 15 are summarized by the PAL analysis given in Figure 4. As the criteria of acceptable compaction were different for ND DOT as compared with the MnDOT, they are discussed separately in this section. It can be observed that, as expected, the mat greatly outperformed the joint compaction with over 50% more data than the joint evaluated above the acceptable level. In the MnDOT projects, there was a wide variety of performance with TH 371 showing the worst joint and mat performance of the group, with both joint and mat under 50% meeting the acceptable limits. It should be noted that this project was paved in October when the temparatures were approaching freezing at the time of paving. TH 55 and TH 15 were consistant with over 75% at the acceptable level in each category, including over 95% acceptable for mat compaction on TH 55.

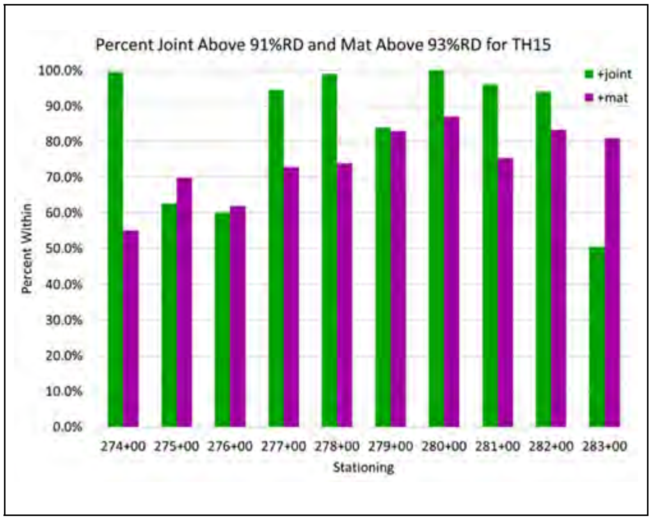


**Figure 5.** Example lot-by-lot percent above limits for TH 55.

## *Sublot Assessment Utilizing Continuous Data*

The PAL analysis method for the entire project is useful in displaying the overall performance of the contractor, but it fails to display the entire quality of the paving operation. Local regions of low compaction can be problematic for the lifetime of the pavement in the specific sections, so an overall assessment may misconstrue the pavement compaction. For example, TH 15 has a very good overall performance, with approximately 80% of the mat being above 93% relative density and 75% of the joint being above 91% relative density; however, when the project is assessed on a lot-by-lot basis, it becomes apparent that some of the regions were insufficiently compacted. Figure 5 shows a relatively small section of sublot PAL analysis sections (showing only 1000 ft of the over 6000 ft reported in Figure 4). It can be observed that, relative to the Minnesota acceptance values, the joint outperformed the mat compaction for several of the selected 100 ft lots. In addition, some of the sublots had PAL pass rates of only about 50%. The analysis on a lot-by-lot basis allows for a better assessment of the pavement quality and can indicate regions that were insufficiently compacted. Doing this type of analysis requires a statistically significant amount of data over relatively small (100 ft) sections, which is not possible without continuous measurements that the DPS provides.

In addition, a sublot analysis allows for the distinction between sections of the pavement. For example, Figure 6 shows selected 700 ft sections of the poorest and best performing pavements, TH 371 and TH 55, respectively. Although TH 371 significantly underperformed compared with TH 55 overall, there are still some sections where TH 371 has better compaction on the joint. Looking at the summaries of the whole project would not suggest this behavior. A few implications can be observed by this: (1) limited random coring could conceivably occur at the good spots of TH 371 and lower spots of TH 55 to give better payment for worse pavement overall. In addition, this highlights the potential in relation to QC, where even on projects that perform well overall there are some sections that can be evaluated for correction of construction operations to consistently get high density in every sublot. Conversely, even projects that do not show good overall performance show some locations with relatively good performance, where construction operations on those sections can be replicated to attemplt to improve the poorly performing pavement for the remainder of the project. Again, the comprehensive amount of data provided by DPS with PAL analysis on a sublot-by-sublot basis provides additional useful

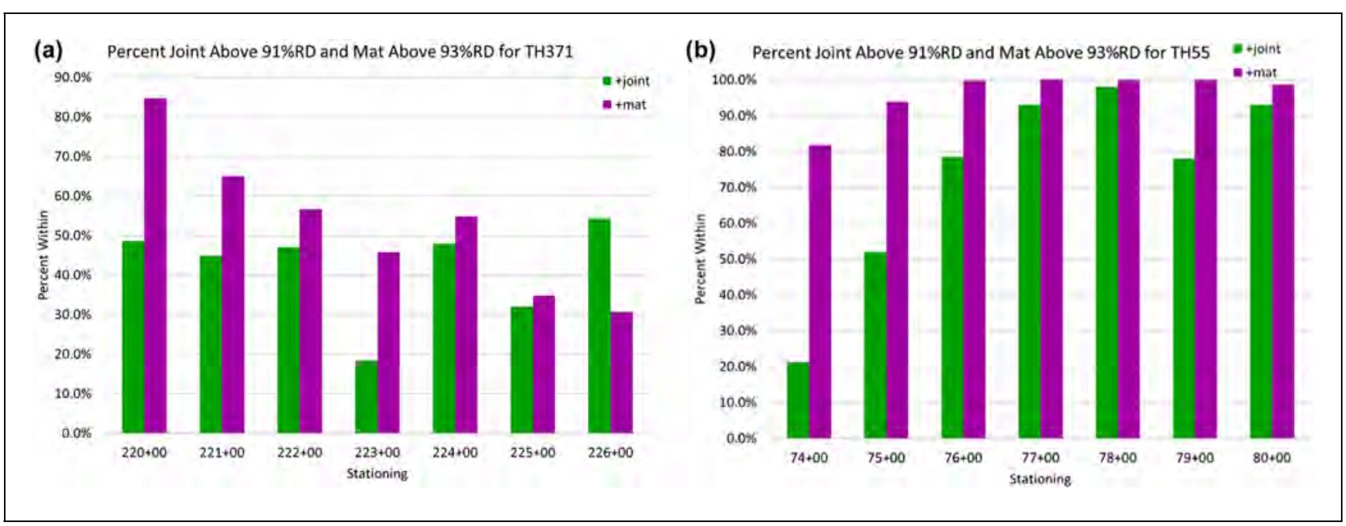


**Figure 6.** Example lot-by-lot percent above limits for (*a*) TH 371 and (*b*) TH 55.

information that an overall analysis may have missed, and that traditional QA methods do not provide enough data for.

## Conclusions

Although a coreless and continuous assessment of freshly placed asphalt pavement is a very attractive concept in relation to addressing destructiveness and limited data problems with current QA/QC procedures, it is important that the method is tested on numerous projects with varying mix designs and paving operations before acceptance as a reliable QA/QC tool. In this study, the accuracy of the DPS coreless calibration method was evaluated for three Minnesota highway paving projects and a North Dakota project. These case studies were used to assess the viability of the procedure proposed by Hoegh et al. in creating a calibration curve that can be used to convert dielectric constants, as measured by a DPS, to air void contents. Special attention is paid to not overcomplicating the QA/QC process, with cost, timing, and labor intensiveness being considered. The proposed method requires only one additional laboratory step of creating two gyratory specimens above the already required design void pucks and the corresponding 60 s dielectric tests. Excluding the DPS equipment, the contractors and testing agencies do not need to purchase any additional tools to complete the tasks for calibration. This procedure has potential to reduce the required time and unsafe coring procedures used to assess the quality of a placed pavement while also improving the coverage of the data that were collected. It was shown through the four projects that models created based on the air void content and dielectric values of gyratory specimens across a range of expected air void contents can correctly model the expected behavior of field cores taken on the projects. The proposed MnDOT empirical model consistently falls within the validation cores taken on each of the projects. This indicates that the proposed procedure should correctly model the compaction behavior of an entire project within the expected uncertainty of the field core measurements.

Although the success of the coreless calibration on multiple projects shown in this publication is a step forward, additional laboratory, equipment, operator, and testing condition analyses must be considered for full QA/QC implementation. Nonetheless, the ability to use a DPS for continuous data collection introduces the new feature of being able to assess compaction quality on a sublot-by-sublot basis. This analysis was demonstrated to indicate regions where the rollers underperformed and potentially indicate sections that may be problematic in the future. The sublot-by-sublot analysis also allows contractors to actively adjust their compaction techniques and determine whether there was a mistake that needs to be corrected or a decision that resulted in worse compaction for a specific sublot. Overall, the creation of a new coreless calibration mechanism will further improve the DPS and its ability to quantify the quality of the placed pavement. With the case studies being completed across Minnesota and in North Dakota, the DPS was further validated on projects that had unique mix designs and paving operations. As all of the projects display that the coreless calibration is viable, it is expected that the use of gyratory specimens to calibrate DPS can become an effective compaction evaluation technique that has the potential to reduce the required number of field cores on a project and drastically improve the comprehensiveness of asphalt compaction assessment.

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### Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Kyle Hoegh, Trevor Steiner, Eyoab Zegeye Teshale, and Shongtao Dai, data collection: Kyle Hoegh, Trevor Steiner, Eyoab Zegeye Teshale analysis and interpretation of results: Kyle Hoegh, Trevor Steiner, Eyoab Zegeye Teshale, and Shongtao Dai; draft manuscript preparation: Kyle Hoegh and Trevor Steiner. All authors reviewed the results and approved the final version of the manuscript.

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