Method for Assessment of Modeling Quality for Asphalt Dielectric Constant to Density Calibration

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ABSTRACT

Traditional measures of asphalt compaction rely primarily on random cores which only measure a small fraction of the pavement. Recently, it has been shown that the use of ground penetrating radar can be used as a non-destructive means for continuous assessment of asphalt compaction. A proposed HD model has been successful in predicting air void content within typically achieved field compaction levels but has reduced accuracy at the extremes. This paper proposes an enhanced, MnDOT model to address this issue. In order to quantify improvement of the MnDOT model, a method for assessment of modeling quality is proposed. The procedure is based on the accuracy of fits when run through a Monte Carlo simulation. The developed procedure shows that the MnDOT model has improved accuracy-- with 0.74% air void variation at a dielectric of 4 compared to 3.83% for the HD fit. Additionally, the MnDOT model is more stable for replicate days of the same mix design and falls within the uncertainty of more of the field cores across several projects than the HD model.

Keywords: GPR, Asphalt Pavement Compaction, Air Voids, Density, Nondestructive Testing, Nondestructive Evaluation,

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INTRODUCTION

Recent developments in methods for asphalt compaction evaluation suggest that ground penetrating radar (GPR) can be effectively employed to nondestructively test the relative compaction of placed pavement. This technology has advanced from non-contact horn antennas (Saarenketo & Roimela, 1998) or other methods such as step-frequency array-based systems (Hoegh, Khazanovich, Dai, & Yu, 2015; Leng & Al-Qadi, 2014; Scott, Gagarin, Mills, & Oskard, 2006; Shangguan & Al-Qadi, 2015) to smaller, dipole-type antennas that can accurately measure the dielectric constant of a placed asphalt mixture (Wilson & Sebesta, 2015). These antennas can be placed on a push-cart or a vehicle mount to allow for continuous assessment of the placed pavement’s air void content. The procedure for calculating dielectric constant values using GPR antennas uses the surface reflection method. This method is based on measuring the reflection amplitude of the air/asphalt interface. The amplitude of the reflection from air to the asphalt surface, as compared to the incident amplitude (represented by the reflection from a metal plate) is then used to determine the bulk dielectric constant of the asphalt. The ability to continuously measure the density of in-place pavement using GPR technologies would make it easier to provide on-site feedback of the paving operations and techniques, as well as a full picture of the pavement compaction quality. Furthermore, giving that that insufficient asphalt density is the most frequent construction-related performance problem (Killingsworth, 2004), the full coverage testing approach made possible by GPR technology would improve the ability to quickly identify density deficient areas and thus determine the service life of the pavement. It is worthwhile noting that, at the present, most quality acceptance programs rely on random coring that measures less than 1% of the produced total asphalt mixture; it is possible for the cores to misrepresent the true compaction of the full pavement.

Compaction level and air void content of a compacted pavement are two interchangeable characteristics: the higher the compaction, the lower air void content. Because of this relationship, the air void content level of pavements is typically reported by the relative compaction or relative density parameter (Equation 1) which quantifies the fraction of the pavement that is not air voids (in reference to the theoretical density):

$$RD = 1 - AV = \frac{G_{mb}}{G_{mm}} \tag{1}$$

where *RD* is the relative density of the pavement, *AV* is the air void content of the mixture, G_{mb} is the bulk specific gravity of the compacted mixture, and G_{mm} is the theoretical maximum specific gravity of the loose mixture. All three components of asphalt mixture (asphalt binder, aggregate and air void) contribute to the measured dielectric constant, and hence several mix characteristic dependent models have been developed to predict the dielectric constant for a specific combination of components (Al-Qadi, Leng, Lahouar, & Baek, 2010). However, these types of models rely in estimating dielectric constants of the aggregate and binder by back-calculation or from the literature (Al-Qadi et al., 2010). As a result, these models are relatively complex to use on a routine basis. Furthermore, the measured mixture dielectric constant is reliant on the various components used for the specific asphalt mixture, for example, aggregate type and distribution in the mixture have great effect on dielectric constant of the mixture (Zegeye Teshale, Hoegh, Shongtao, Giessel, & Turgeon, 2019), thus conversions between dielectric constant and air void content must be determined for each specific mix design . Recently, empirical models, that are better suited to capture the daily variability of asphalt mixture productions than the existing theoretical models (Al-Qadi I. L. and Riad & M., 1996; Böttcher, van Belle, Bordewijk, Rip, & Yue, 1974; Sihvola, 2008) , have been proposed to facilitate the creation of calibration curves. The most commonly used empirical fits are basic linear and exponential fits (Hoegh et al., 2015; Popik, Lee, Aho, Maser, & Holzschuher, 2010; Saarenketo & Roimela, 1998). The empirical models are calibrated to a specific mix design and require recalibration if significant change in the mix design occurs. Historically, these empirical models have required the collection of field cores from the placed pavement. However, in 2018 GSSI and MnDOT researchers showed that asphalt specimens compacted in a Superpave Gyratory Compactor (SGC) can be efficiently used to create a calibration curve that can convert the measured dielectric constant to the air void content of the pavement (Hoegh, Roberts, Dai, & Zegeye Teshale, 2019; Hoegh, Steiner, Zegeye Teshale, & Dai, 2020). SGC are commonly used by a certified lab technician to fabricate asphalt specimens at specified number of gyrations (based on the expected traffic level for the road) to monitor air void content and density of production mixes. The coreless calibration method described by Hoegh et al. (2019) uses these standard SGC specimens along with additional higher air void content specimens to develop a dielectric to air void content relationship. This new approach provides advantages as it can better represent the overall pavement quality without requiring field cores that are expensive to take and limited in coverage.

The empirical fits can be used to reasonably estimate the air void content of a pavement in the 5-10% range but fail to model the extremes of the data. Recently, a new model, the Hoegh-Dai (HD) model has been proposed to better match the data at the extremes and is the current best empirical fit for the experimental data (Hoegh, Dai, Steiner, & Khazanovich, 2018). The HD model also includes physical bounds on the maximum and minimum values possible with the model, preventing the model from predicting negative air void contents or dielectric constants less than 1. Both the exponential and linear models are unbounded. The HD model addresses these issues by allowing for only positive values of air void percentages and having a dielectric of 1 correspond to 100% air voids. The HD model has the form,

$$AV = exp\left(-B\left(D^{\left|\frac{1}{e-C}-\frac{1}{1-C}\right|}-1\right)\right) \tag{2}$$

where the parameters *B*, *D*, and *C* are fit to minimize the sum of the difference of squares between the model and the experimental data. The variables AV, and *e* represent the modeled air void content and the dielectric constant, respectively.

Deficiency of the HD Model

Although the HD model effectively matches experimental cores with air void contents between 4% and 12%, the HD model fails to match the trends apparent at the farther extremes of the collected field core data. **Figure 1** shows field validation cores and the HD model for trunk highway 371 and trunk highway 15. From the figure, it is clear that the HD model overestimates the slope of the air void vs. dielectric behavior at the extremes of the data. TH 371 was the most convincing data set based on the higher quantity of field validation cores that were taken. In the figure, both of the fits are made using gyratory specimens and then compared to the field validation cores. The HD model is almost within the uncertainty of the validation cores, but the apparent trend at the extremes is not matched, suggesting that the HD model is deficient in its ability to model high air void content data.

OBJECTIVES

An adjusted, logistic model is proposed in this paper to better match field core behavior and allow for improved quality assurance analysis of pavement compaction. This model, thereafter called “MnDOT Model,” expands the range of the fit to cover essentially all reasonable air void contents from a placed pavement. It is currently being used by Minnesota

Department of Transportation to assess the ability of GPR to be used in conjunction with coreless calibration from SGC specimens (Hoegh et al., 2019). With improvements to the HD model, a calibration curve can be developed in laboratory using SGC gyratory pucks without taking field cores which damage the pavement. The method for core-free pavement compaction evaluation will be further improved with the new proposed MnDOT model (Hoegh et al., 2019).

In addition to providing an improved empirical fit, this paper details a testing procedure to verify fit accuracy and assess the quality of new empirical models. The basis of the proposed method is simulation of random fluctuations in the measured dielectric constant and air void content of the SGC specimens and field validation cores. All experimental measurements have some expected random errors which can come from, for example, the precision of the equipment being used and testing procedure, so it is important that random fluctuations in the measured values do not drastically change the conversion drastically. Accuracy based on random uncertainty will ensure that specific operators or equipment will not result in completely different assessments of the same pavement. To complete an accuracy assessment, a Monte Carlo simulation is conducted (Sokolowski & Banks, 2010). A Monte Carlo simulation simulates numerous test scenarios and forecasts the expected outcomes. To explore the accuracy of the empirical models, the measured values of the air void content and dielectric constant for the SGC specimens were randomly varied within the uncertainty range of each measurement. Next, the values were fit with the empirical model, and the percentage of the simulations where the fit was within the uncertainty of the field validation cores was recorded. By running the simulation on the empirical models, the accuracy of a newly proposed model can also be assessed.

Along with Monte Carlo simulations, sensitivity to fluctuations in the mix and parameter sensitivity assessments were conducted. The mix stability was assessed by analyzing two days of paving on the same highway project with an identical target mix design. This is a good scenario to test the stability of the models since there are QA/QC measures in place to ensure that the actual produced mix does not vary significantly from the target properties (ex. target 4% air voids at 60 gyrations). Ideally, the fit would remain constant within these acceptable levels of mix variation. Lastly, the parameter sensitivity was assessed to determine if there were any unnecessary parameters. Additionally, the parameter sensitivity analysis can be used to provide starting values for the parameters. Overall, the combination of these three tests is used to evaluate the proposed MnDOT model. This process is also suggested as a useful process to determine if future models can make further improvement over the existing empirical models. This will be especially useful as density profiling becomes more widespread since the catalogue of available laboratory versus field data that can be used to evaluate the models is increased.

METHODOLOGY

Proposed MnDOT Density Model

Assessment of field core data shows a reduction in slope at the extreme high and low air void content regions suggesting that the exponential, linear and HD models used to convert dielectric values to air void contents do not correctly predict the behavior of the asphalt at the extremes. **Figure 1** shows that, especially in the case of TH 371, the HD model over predicts the slope at the high air void content data. The observed behavior shows an inflection point with flat slopes near the extremes, which suggests that the data may be better represented by a logistic function of the form (Gottschalk & Dunn, 2005):

$$y = d + \frac{a}{\left(1 + \left(\frac{x}{c}\right)^{b}\right)^{g}} \tag{3}$$

where the parameters *b*, *c*, and *g* correspond to adjustments in the slope and inflection point of the logistic function while *d* and *a* correspond to the lower and upper limits of the logistic function, respectively. The logistic function in equation 5 was selected due to the observed trend of decreasing slope at the boundaries of the collected field core data. The parameters in the formula allow for the inflection point and location of these boundaries to be adjusted to the dataset under study. Air void content must be nonnegative, so the lower bound of the function, *d*, was set to zero. Air has a dielectric constant of 1.0006 at normal pressure and temperature (not 1.0 as commonly assumed). For dielectric values close to that of air, the function must approach 100% air voids (Hector & Schultz, 1936). Considering these limitations, a second, asymptotic term, $\frac{\delta}{(e-1)}$, was added to the fit. The proposed MnDOT model is of the form,

$$AV = \frac{a}{\left(1+\left(\frac{e}{c}\right)^{b}\right)^{g}} + \frac{\delta}{(e-1)} \tag{4}$$

where *AV* is the air void content, *e* is the measured dielectric constant, and the other parameters are defined above. The second portion of the model will force *AV*=100% when *e*=1.0006. The remaining parameters are obtained by means of regression (optimization) conducted with the constraints on *e* and *d*.

The parameters can be optimized using Excel's Solver Add-in or another optimization technique such as Matlab's fminsearch function (Mathworks, 2019). Additionally, field hot mix asphalt pavement air void content should not approach 20% in practice. This restriction is valid for Hot Mix Asphalt (HMA) pavements. Any open graded friction courses or porous pavement with extremely high air void content would require modification to the testing method and model. Therefore, the parameter, a in the function is set to have a value of 0.2, corresponding to the approximate physical limit of the possible air void content measured in an HMA field core. With a constant value of a, the value of δ that forces the fit to be 1.0006 at 100% air void consistently had a value of 0.0008 across over 50 fits. Since this parameter remained a constant value, it was decided to fix δ at 0.0008. The model can therefore be rewritten as,

$$AV = \frac{0.20}{\left(1 + \left(\frac{e}{c}\right)^{b}\right)^{g}} + \frac{0.0008}{(e-1)} \tag{5}$$

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

Model Sensitivity Testing

In order to quantitatively assess the quality of improved models, a stability testing routine is proposed. The procedure begins with a Monte Carlo simulation to assess how the random uncertainty in the air void and dielectric constant of the specimens can influence the model stability. The evaluation is made by comparing the 95th percentile confidence windows across the dataset. Next, the variability caused by marginal changes in the mix design is assessed. For this analysis, two or more days of puck data are fit individually, and the fits are compared by calculating the difference between the fits. Again, 95th percent confidence intervals are compared to assess the depth of influence small mix changes have on the model. The final step in the assessment of the model viability is the sensitivity of the fit to changes in the parameters. For this step, each parameter is incremented individually, and the remaining parameters are then refit to the data. This will help to establish cutoff values as well as determine if parameters can be held at a single value to improve the computation time.

Monte Carlo Simulation

Since each of the measurements on the pucks has an associated random uncertainty, a Monte Carlo simulation is suggested to simulate how a model would respond to the innate uncertainty in these measurements. 1000 different simulation sets were conducted based on the collected laboratory puck air void contents and dielectric values. For each simulation, the measured values of dielectric constant and air void content were used as a starting point. The starting dielectric constants and air voids are included in **Table 1**. Each measured value was allowed to vary by ±1.2% for the air void measurements and ±0.08 for the dielectric measurement. Each simulation set chose a random value within these ranges of the experimental value for each of the 21 collected laboratory pucks. The 1000 sets were then fit to the three models and plotted to show how random uncertainties in the puck measurements would influence the spread of fits that the model would provide. This simulation gives an idea as to how stable each model is to variation in the individual puck dielectric and air void values. This process is recommended as a method for all future models to assess the stability of the proposed models by comparing the percentage of simulated fits that fall within the uncertainty of the field validation cores. This assessment is valuable as it simulates the randomness that could be expected from any given dielectric or air void measurement. It is important that the proposed model can correctly match the core data (or at least be within reasonable uncertainty of the core data) in order for the model to provide a useful dielectric to air void conversion.

The Monte Carlo Simulation is intended to simulate variation in air void and dielectric measurements that may be caused by the use of different testing procedures, devices or operators. The simulations are not intended to suggest a function relating air void change due to a change in mix components.

Mix Sensitivity Assessment

It is important that models of laboratory tested pucks do not vary significantly when asphalt mix has typical production mix fluctuations throughout the day. Thus, the proposed coreless calibration model should remain stable with slight mix variations to avoid the requirement of recalibration every time a small fluctuation occurs. A more stable model will reduce the number of recalibrations required for a paving project. Additionally, understanding the influence of mix design changes is useful in suggesting the extent a mix can be altered before recalibration is necessary to assure the fit matches the field data. For a new proposed model, it is suggested that the model be run on several days of test puck data and the fits be compared for how much they vary day-to-day.

Parameter Sensitivity

In order to understand the influence of each of the parameters on the fit quality, a sensitivity study was conducted. The proposed parameter sensitivity analysis fixes the value of one parameter and allows the other parameters to vary while still meeting the constraints for the function (e.g. the dielectric of 100% air must be 1.001). This sensitivity analysis selects one project and fits the specimen data with fixed values of one parameter to determine the parameter’s influence on the quality of the fit. This analysis is only intended to determine the reporting accuracy required for each parameter and if any of the parameters can be removed to simplify the model and reduce computation time.

RESULTS

The MnDOT model is applied on the data collected from a project on trunk highway 371 (TH 371) in Hackensack, MN. Field cores and production mix were collected from the project for the purpose of coreless calibration and validation of the model fit quality. The uncertainty of the field core measurements is within the acceptable precision range of dielectric measurements of 0.08 (AASHTO PP 98-19, 2019) and the Minnesota Department of Transportation core tolerance for bulk specific gravity (G_{mb}) of 0.03 (Minnesota Department of Transportation, 2018). The uncertainty in the G_{mb} is converted to air void content based on the 2.472 maximum specific gravity (G_{mm}) values for the TH371 production days which corresponds to approximately 1.2% air void content. The air void content for the validation field cores was measured using the saturated surface dried method, while the laboratory samples were measured using the AASHTO T331 method (AASHTO T331, 2017). It has been shown that the surface dry method under-predicts the air void contents due to large, interconnecting voids (Cooley, Prowell, Hainin, & Buchanan, 2003). The saturated surface dry bias for large air void contents was shown to be 0.041 in terms of G_{mb} by Cooley et al. This suggests a reduction in air void contents by approximately 1.6% for the high end of the measured field core data. This value is used to correct the high air void content core during the analysis.

Figure 2 shows results from TH 317 project. The traditional exponential model, HD model, and the proposed MnDOT model are used to fit puck test results. Also, five field cores at random locations were taken to verify the calibration models. The cores were brought to MnDOT laboratory for density determination. The exponential model is the most commonly used in practice, but the HD model shows an improved fit to the experimental data of numerous projects (Hoegh et al., 2018). The HD model represents the data between approximately 4% and

12% air void content well. There is, however, a relatively large deviation from the data outside of this air void range. The proposed MnDOT model provides a better fit with the field core data at large air void contents (>12%). In order for a coreless calibration model to be effective at converting measured dielectric values to air void contents, the model needs to be accurate across all expected field data. The incentive structure used by the Minnesota Department of Transportation penalizes pavement that is at high air void contents, so the HD model, which overestimates the slope of the data at high air voids, would result in an excessive penalty as compared to the actually achieved in place compaction. For widespread implementation of GPR as a means of assessing pavement compaction, it is necessary that the method to convert dielectric to air void is accurate throughout all reasonable air void contents.

Example using the Proposed Model: Monte Carlo Simulation

The proposed model was compared to the Hoegh-Dai model, and the traditional exponential model, to evaluate the sensitivity of the models to variation in the measured air void and dielectric constant of the pucks. All models were fit using the same 1000 simulated air void and dielectric values. **Figure 3** shows a comparison between the models and the stability of the models from the expected variation in dielectric and air void measurements. As evident in the figure, the new model has a significantly smaller spread in the high and low dielectric regions with 0.74% air void variation at a dielectric of 4 compared to 7.59% air void variation for the exponential fit and 3.83% air void variation for the HD model.

Another assessment of the quality and stability of the models is the ability of the simulated fits to match field cores taken on the project. The stability is assessed using the percentage of the 1000 simulated fits that fall within the uncertainty of the field cores. **Figure 3** shows the field cores taken on the TH 371 project with their associated uncertainties in measurement. All three models correctly fall within uncertainty of the five higher dielectric cores 100 percent of the time. But, none of the models are within the lowest dielectric core. As previously stated, this core likely has an underestimated air void content, so the Corelok corrected core is included in the figure (Cooley et al., 2003). When this value is assessed, the three models diverge in their percentage within uncertainty. The MnDOT model has 100% of the fits within the Corelok corrected core while the exponential model has only 21.2% within the core's uncertainty and the HD model has 29.5%. For this analysis, the percentage of fits falling within the uncertainty of the corrected core (shown with a solid red dot in **Figure 3**) can be determined by connecting the ends of the horizontal and vertical error bars. This creates a rectangle of uncertainty for the measured field core. All fits that fall anywhere within this rectangle are considered to be within the uncertainty of the field core measurement. For the cases of the exponential and HD models, only 21.2% and 29.5% of the 1000 simulated fits are within this rectangle of uncertainty. Since the Corelok test method is recommended for high air void content cores (Cooley et al., 2003). Therefore, air void content determined from Corelok is a better representation of the true air void content of the core. This analysis shows that the proposed improved model has significant improvement over the other two models.

Figure 3 depicts the results of the Monte Carlo simulation by displaying all 1000 of the fits created by the method. While **Figure 3** gives a good qualitative view of the improved stability of the MnDOT model, it is also useful to quantitatively assess the spread of values that random puck variation can cause. The 95th percent confidence interval is reported as twice the standard deviation of the fits at each dielectric value. The assumption that the data has a normal distribution is a common assumption made when evaluating the quality of the placed asphalt (Breakah, Kandil, Williams, & Shane, 2007). Many agencies use the percent within limits method to evaluate the quality of the pavement while also allowing for material variation. This method requires the assumption that the compaction follows a normal distribution. Therefore, the use of twice the standard deviation of the fits for the 95th percent confidence interval is valid. The confidence of each fit across the range of reasonable dielectric values is shown in **Figure 4**.

All three models perform to a satisfactory level within the central region of the dielectric range of the pucks. The confidence interval is within the uncertainty of the air void measurements, so the variation in the fits is small enough that it will have little to no influence on the predicted air voids around this region. At the low end of the reasonable dielectric measurements for the project, the new model has a drastically improved confidence level, on the order of a 5 times smaller spread. This increase in stability is important as it indicates that the new model will be more stable to random uncertainty in the laboratory puck data, particularly for pucks or cores with large air void content. This is especially critical in assisting the feasibility of widespread implementation of the density profiling method in a field environment where the number of fabricated asphalt sample pucks used for calibration of the model may be limited.

Example using the Proposed Model: Mix Sensitivity Assessment

The TH 371 project had several days of testing with variation in the mix from day-to-day, so the models were fit to each testing day and assessed for stability across mixes. The objective would be for the fit to match the field core data well without a dependence on the day of paving that the laboratory pucks were made. For the TH 371 project, the field cores were taken on October 1st and 6th. The results from the laboratory pucks that were tested on these days were fit to investigate how well the model fits between two days of paving. **Figure 5** displays the models' sensitivity to slight mix changes and other daily fluctuations that could be expected.

Similar to the assessment completed for the puck uncertainty sensitivity, the 95th percent confidence interval is also assessed for changes to the mix design. **Figure 6** depicts the confidence window for the HD and new model. Again, the new model has an improved stability when compared to the HD model. Further assessment can be completed by determining the acceptable change in mix that can still fall within the confidence window to allow the same calibration curve to be used.

Example using the Proposed Model: Parameter Sensitivity

As discussed above, the parameter a was fixed to a value of 0.2, corresponding to the maximum expected air void content of a field core. In order to assess whether this assumption allowed for an optimal fit, a was allowed to vary from a value of 0.15 to 0.5, and the densities obtained from the collected gyratory pucks were used for regression analysis. The various fits were compared to the collected field core density data. **Figure 7a** shows the resulting regression curves of various a values. It can be seen that the specific a value of *0.2* sets the upper asymptote of the logistic function. Too low of a value creates excessive curvature that does not fit the trend observed in the cores at high end of air void content, and too high of a value increases the slope of the fit at the low dielectric region, fitting the data poorly.

A similar assessment was completed for the remaining parameters. **Figures 7b-d** show all of the remaining parameters and the fits resulting from fixing each parameter at a specific value while a is set to 0.2. One of the most important trends evident from this analysis is that the parameter g can be varied significantly, and the other parameters adjust to result in an insignificant amount of variation in the fit, as shown in **Figure 7d** by the small change in the fit caused by a three orders of magnitude change in g. This suggests that it could be possible to fit the data without changing the value of g. Fixing the value of g results in a slight increase in the sum of the difference of squares for the data set, so the optimal solution is still found by allowing *g* to vary.

Unlike *g*, the parameter *c* plays a significant role in the quality of the fit. The parameter *c* increases the slope of the fit and can result in overestimation of the air void content of the pavement for low dielectric values.

The range of values presented in this analysis should offer reasonable starting points (or initial guesses) that are required to complete the parameter optimization. It is important to note, however, that the parameters can vary between mix designs, so there may be a specific mix design that results in parameters exceeding the expected range.

Model Verification on Multiple Projects

In order to confirm that the proposed model is not uniquely suited for the chosen highway, TH 371, the ability of the new improved MnDOT model was used to match field cores collected on TH 60, TH 55 and TH 61. The four selected projects have significantly different mix designs and aggregate sources, so the model is tested to see if it can remain flexible enough to handle various asphalt mixes. For brevity, only the two majority aggregate sources are listed for each project. The remaining aggregate sources are available upon request. TH 371 has the mix designation SPWEA340C with ½ inch maximum aggregate size and PG 58-34 binder. The majority aggregate source components were 30% Powers BA Sand and 22% Powers ½ Rock. TH 60 uses mix designation SPWEB440 with ¾ inch maximum aggregate size and PG 58H-28 (MSCR) binder. The majority source components were 33% SRP WMS (36) and 21% SRP ¾ DF (18). TH 55 has mix designation SPWEA340 with ½ inch maximum aggregate size and PG 58-34 binder. The majority source components were 29% Naak Nat Fine 3A-BA19-0029 and 22% Naak Washed Cr. Fines 3A-BA19-0028. TH 61 uses mix SPWEB440 with ¾ inch maximum aggregate size and PG 58S-28 (MSCR) binder. The majority source components were 38% Doane ¾ Bit Rock and 34% Doane Man Sand.

Although the mix components and specific mix designs are included in this manuscript, it is important to note that the calibration methodology accounts for the aggregate dielectric properties as part of the bulk production mix from the specific day of paving where DPS data was collected. Based on the results shown in **Figure 8**, the regression curves on the three projects correspond very well with the field core density results. The predictions are within the uncertainty of the collected field cores, suggesting that the model improves on the current state of the art models and is applicable to more than just the TH 371 project.

CONCLUSION

A new model is proposed to establish calibration relationship between dielectric measurement and field HMA compaction density. The MnDOT model improves on the exponential and HD models in its ability to correctly convert collected GPR field data to in place air voids, especially at the extremes. The incentive structure used by the Minnesota Department of Transportation (and many other state departments of transportation) penalizes pavement that is at high air void contents, so the HD model, which overestimates the slope of the data at high air voids, could result in an excessive penalty as compared to the actually achieved in place compaction. The increased accuracy of the MnDOT model will reduce misrepresentation of the actual compaction of the pavement. The improvements of the new model were evaluated and verified using a novel, statistical analysis procedure. The statistical approach employed Monte Carlo simulations to assess the variability in the fit that can occur due to slight fluctuations in the measured puck values. This assessment shows that the MnDOT model falls within expected uncertainty of all of the field cores (after correcting the highest air void content core for the saturated surface dry method) while the HD model only falls within 29.5% of the time. Additionally, assessment of the spread of the Monte Carlo simulated fits shows that the MnDOT fit has the least variation across all expected field air void content ranges. Next, the models are tested across the same asphalt mix design on different production days to determine if slight variation in the mix would make the conversion no longer useful. This analysis also shows improved stability for the MnDOT model compared to the HD model. Field core validation results showed that the stability of the MnDOT model allowed for accurate prediction of in-place air voids even when the mix from a different day of production was used to convert the GPR collected data to air voids. The final step in the model testing procedure is to determine the sensitivity of the models to their parameters. This step verifies that all parameters are necessary and contribute to the quality of the fit that is created. This complete testing procedure confirms that the MnDOT model is a better tool for use in coreless calibration of collected GPR data to air void contents than the currently available models. The techniques used to complete this assessment can also be employed to assess future proposed models or in assessing the magnitude of mix design change that is required for recalibration of the conversion using SGC specimens.

Future research efforts will focus on obtaining more of the high and low air void content field cores to further verify the improvements made by the MnDOT model. The assessment presented in this report was supported by only three field cores at the extremes of the measured air void content. Thus, future work will attempt to sample more cores with greater than 12% air void content and less than 4% air void content. For the high air void content cores, field cores can be taken from low compaction regions such as pavement on road shoulders. On the other extreme, the real-time display of the DPS can be used to identify regions with very high compaction for coring.

DATA AVAILABILITY

All data, models, or code generated or used during the study are available from the corresponding author by request. This includes Microsoft Excel Macros to run fit optimization and Matlab code to create the Monte Carlo simulations and visualize the results.

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AUTHOR CONTRIBUTIONS

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

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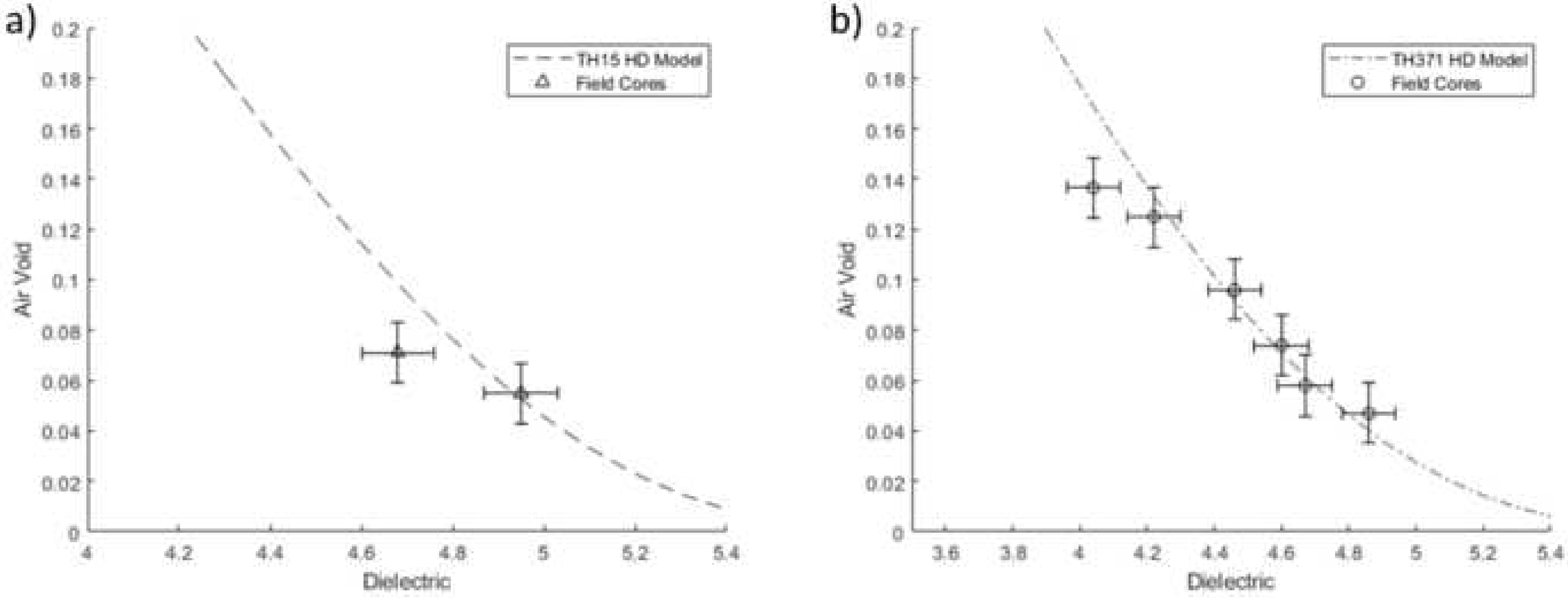
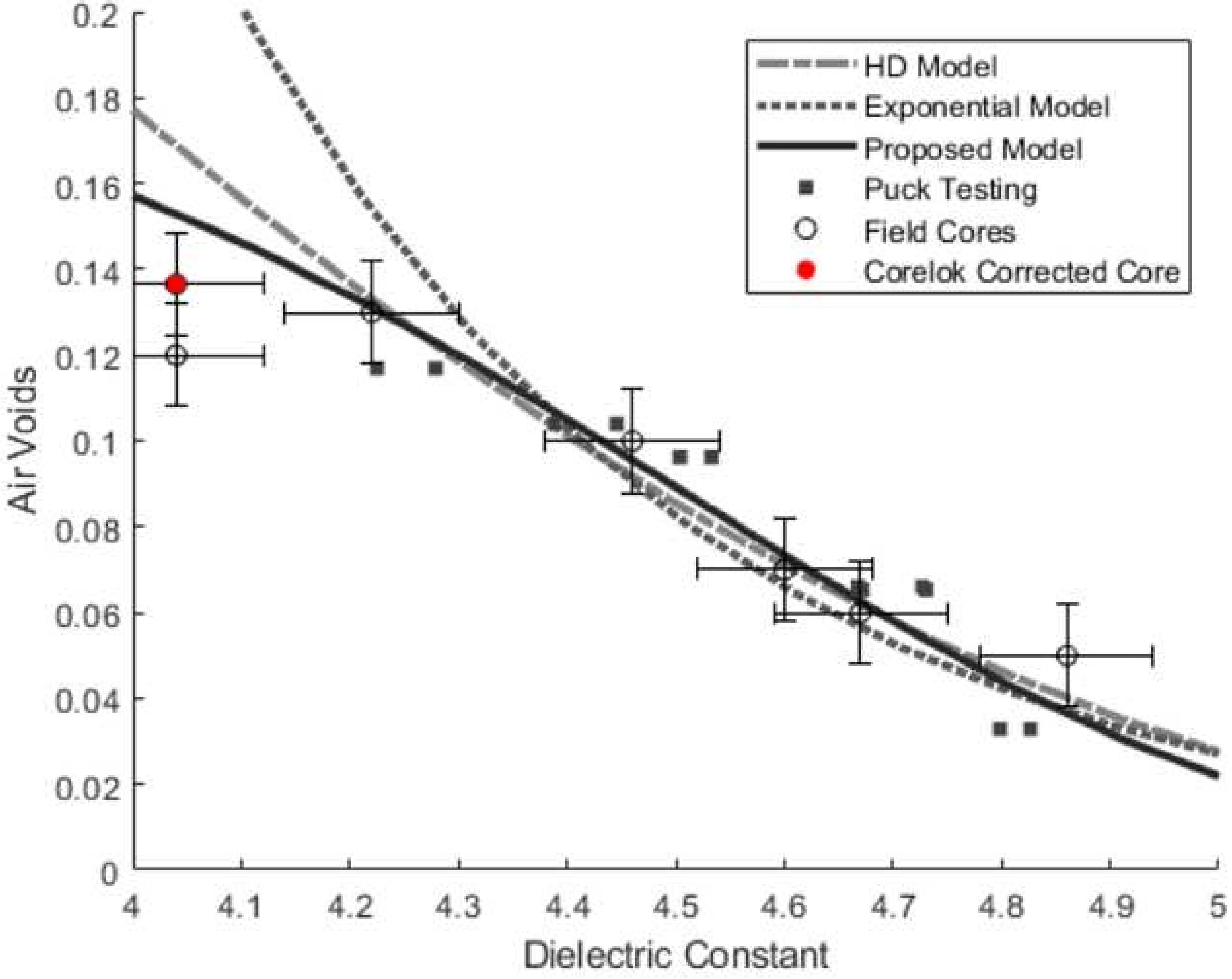
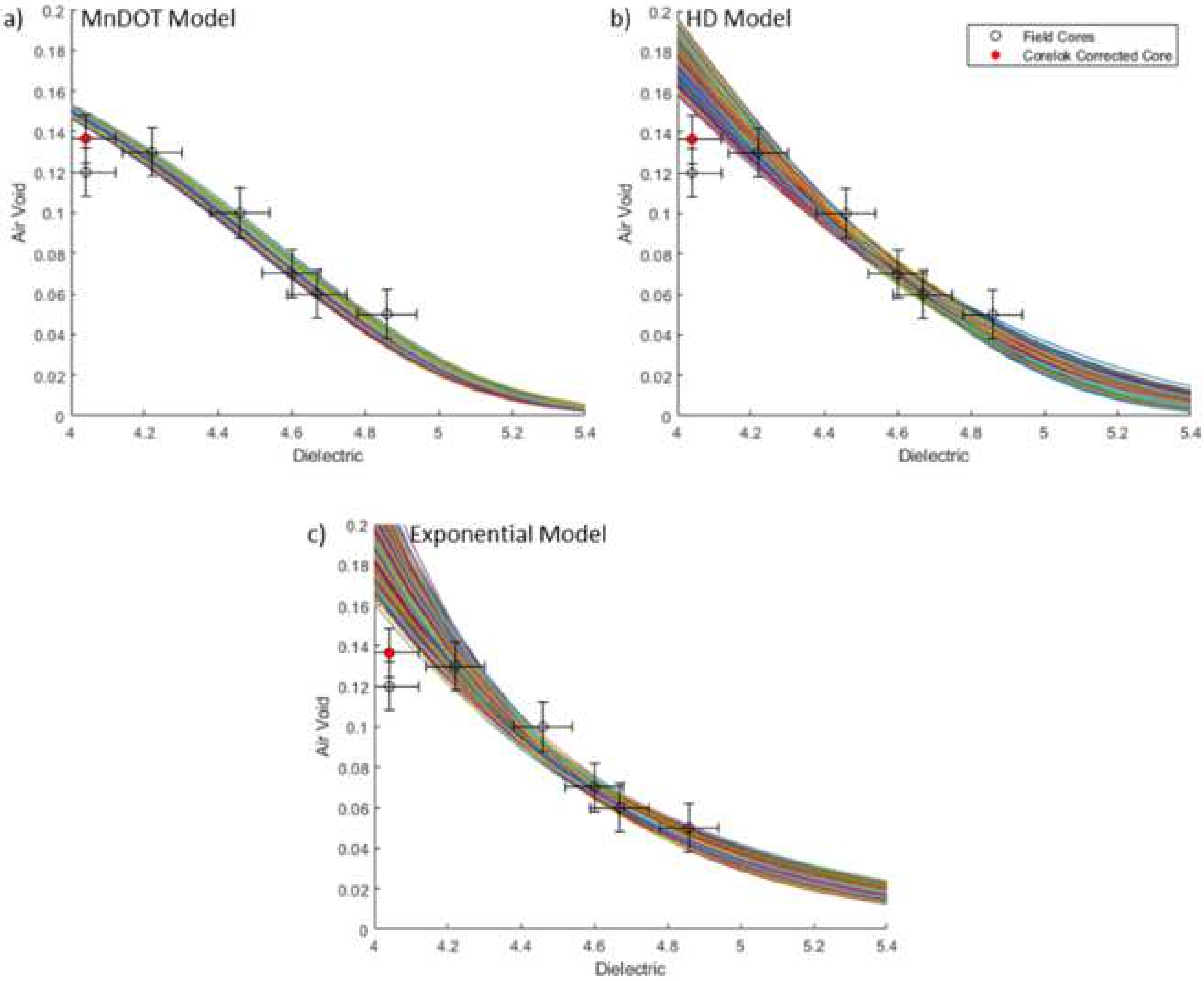
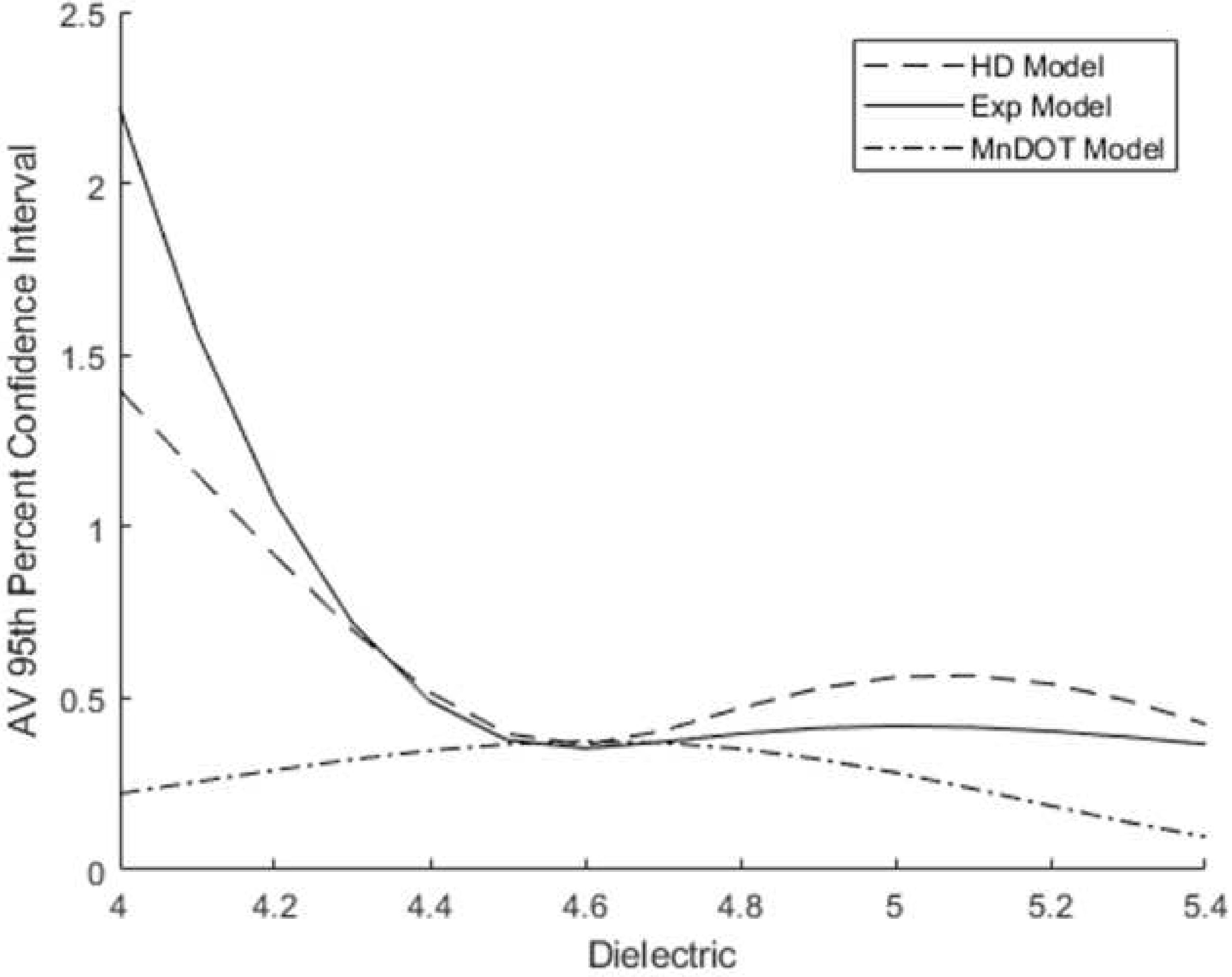
Table 1: Starting Values for the Monte Carlo Simulation

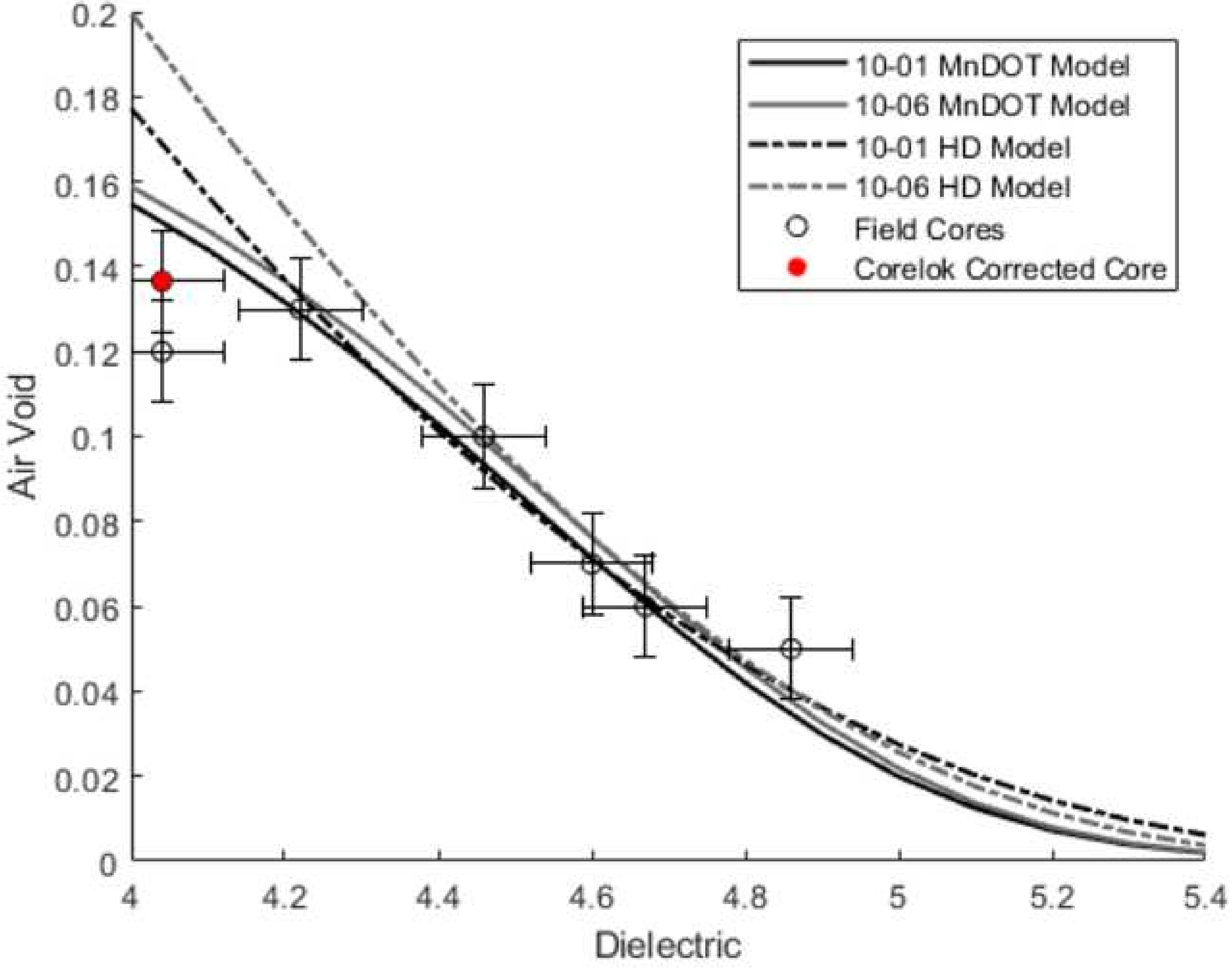
Air void	Dielectric constant
3.29%	4.80
3.29%	4.80
3.29%	4.80
3.29%	4.83
3.29%	4.83
3.29%	4.83
6.53%	4.67
6.53%	4.67
6.53%	4.73
6.60%	4.67
6.60%	4.67
6.60%	4.73
9.63%	4.53
9.63%	4.53
9.63%	4.50
11.69%	4.28
11.69%	4.23
11.69%	4.23
10.40%	4.39
10.40%	4.45
10.40%	4.45


a)
Air Void
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
4
4.2
4.4
4.6
4.8
5
5.2
5.4
Dielectric
TH15 HD Model
Field Cores
b)
Air Void
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
3.6
3.8
4
4.2
4.4
4.6
4.8
5
5.2
5.4
Dielectric
TH371 HD Model
Field Cores

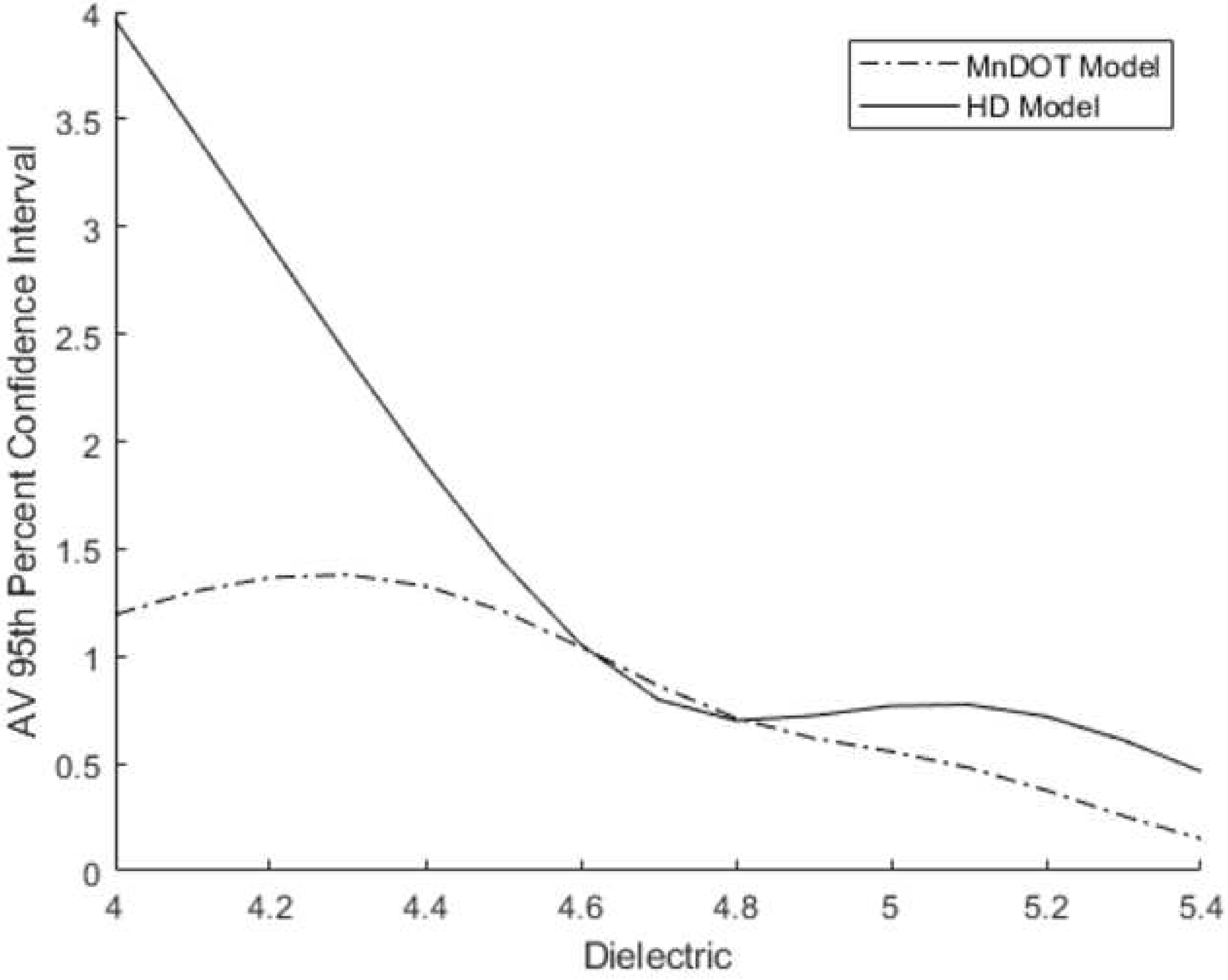

0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Air Voids
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Dielectric Constant
HD Model
Exponential Model
Proposed Model
Puck Testing
Field Cores
Corelok Corrected Core

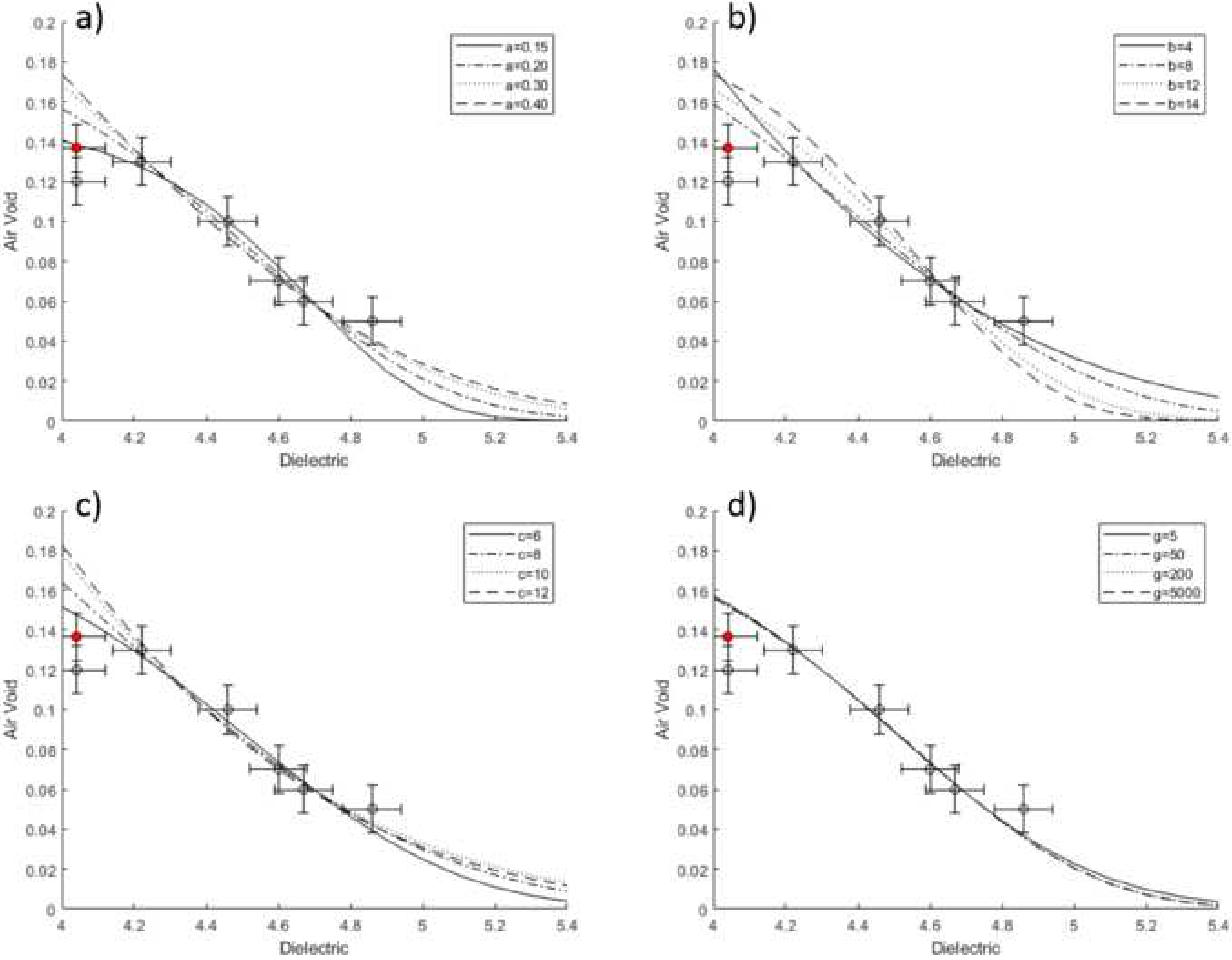

a)
MnDOT Model
b)
HD Model
c)
Exponential Model
Field Cores
Corelok Corrected Core
Air Void
Dielectric
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
4
4.2
4.4
4.6
4.8
5
5.2
5.4


HD Model
Exp Model
MnDOT Model
AV 95th Percent Confidence Interval
2.5
2
1.5
1
0.5
0
4
4.2
4.4
4.6
4.8
5
5.2
5.4
Dielectric



10-01 MnDOT Model
10-06 MnDOT Model
10-01 HD Model
10-06 HD Model
○ Field Cores
● Corelok Corrected Core
Air Void
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Dielectric
4
4.2
4.4
4.6
4.8
5
5.2
5.4


MnDOT Model
HD Model
AV 95th Percent Confidence Interval
0
0.5
1
1.5
2
2.5
3
3.5
4
Dielectric
4
4.2
4.4
4.6
4.8
5
5.2
5.4


a)
b)
c)
d)
Air Void
Dielectric
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
4
4.2
4.4
4.6
4.8
5
5.2
5.4
a=0.15
a=0.20
a=0.30
a=0.40
b=4
b=8
b=12
b=14
c=6
c=8
c=10
c=12
g=5
g=50
g=200
g=5000

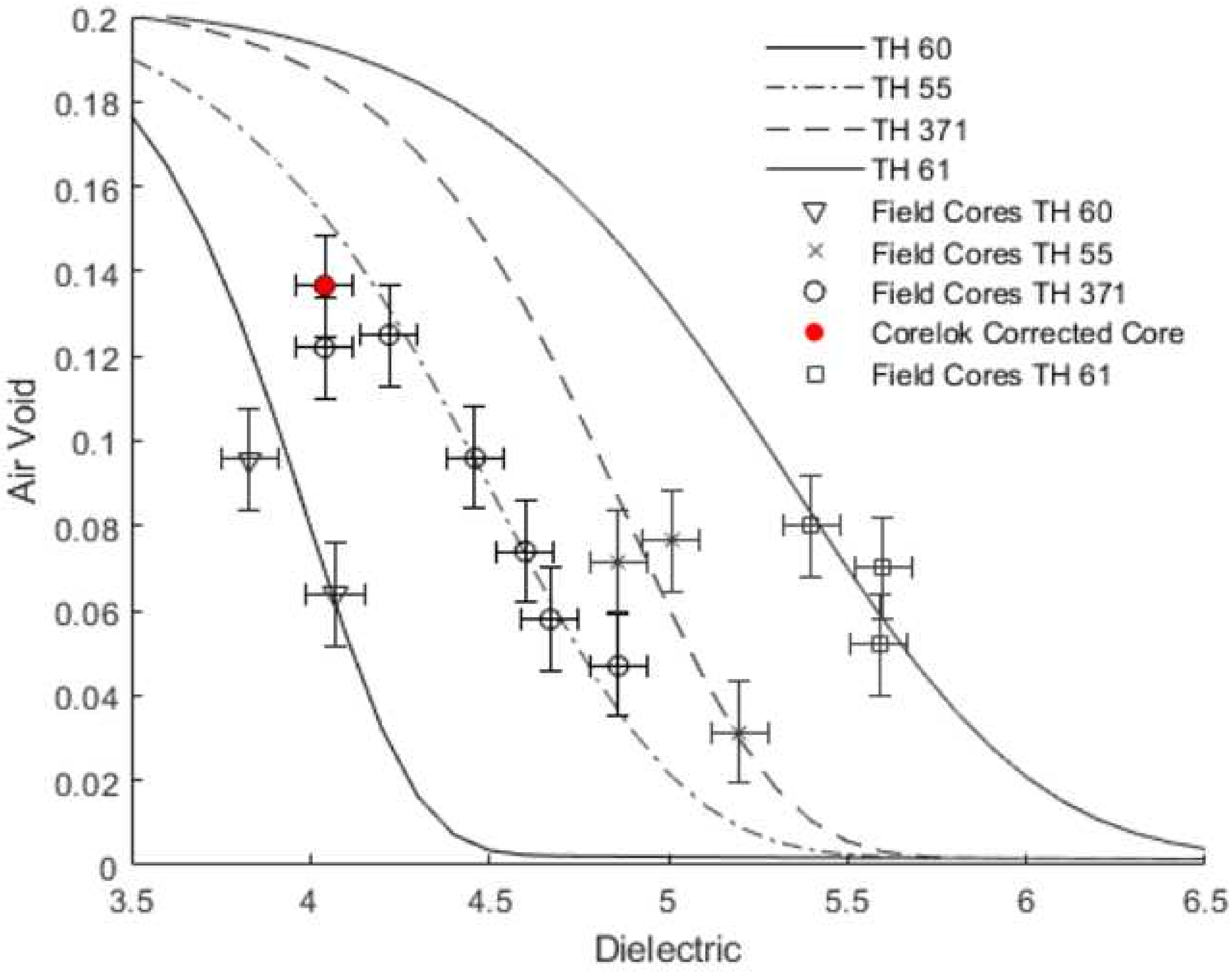

0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Air Void
3.5
4
4.5
5
5.5
6
6.5
Dielectric
TH 60
TH 55
TH 371
TH 61
Field Cores TH 60
Field Cores TH 55
Field Cores TH 371
Corelok Corrected Core
Field Cores TH 61

FIGURE CAPTIONS

Fig. 1. Deficiency of the HD model with fitting field core data. 1a) shows the HD model for TH 15 and 1b) shows the HD model for TH 371.

Fig. 2. Comparison of three empirical fits for experimental data collected on highway 371 in Hackensack, MN from October 1, 2019.

Fig. 3. Comparison of fit stability for a Monte Carlo simulation of 1000 puck dielectric and air void measurements. 3a) shows 1000 simulated fits for the MnDOT model, 3b-c) show the same simulated results for the HD and exponential models, respectively.

Fig. 4. 95th percent confidence interval for the Monte Carlo simulation results.

Fig. 5. Model sensitivity to mix design.

Fig. 6. 95th percent confidence interval for the HD and new models across four different days of paving.

Fig. 7. Plots depicting various fits of gyratory puck data at fixed values of four of the fit parameters. 7a-d) show the sensitivity of the MnDOT model to the parameters *a*, *b*, *c*, and *g* parameters.

Fig. 8. Proposed model fits for TH 371, TH 55, TH 60 and TH 61.