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LABORATORY DIELECTRIC MEASUREMENT SYSTEM (LDMS) FOR ASPHALT MIXTURE BULK SPECIFIC GRAVITY DETERMINATION

Final Report for
NCHRP IDEA Project 229

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January 2023

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IDEA PROGRAM PROJECT FINAL REPORT

NCHRP IDEA 20-30/IDEA 229

Prepared for the IDEA Program

Transportation Research Board

The National Academies of Sciences, Engineering, and Medicine

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- Ms. Amy J. Beise (North Dakota Department of Transportation)
- Dr. Shongtao Dai (Minnesota Department of Transportation)
- Mr. Richard Giessel (Alaska Department of Transportation)
- Dr. Jhony Habbouche (Virginia Department of Transportation)
- Mr. Dale Peabody (Maine Department of Transportation)
- Dr. Roger Roberts (GSSI, Inc.)

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I. EXECUTIVE SUMMARY

Bulk specific gravity (G_{mb}) is measured routinely during mixture design and quality assurance processes for asphalt mixtures. The current state of practice for the determination of G_{mb} of compacted asphalt mixtures uses Archimedes' principle and requires measurements of dry, saturated surface dry (SSD), and submerged weights for individual specimens (1,2). This practice requires multiple pieces of equipment (high resolution and accuracy weighing scales, temperature-controlled water bath, bags for sealing method, vacuum sealing machine, etc.) and the accuracy of measurements also depends on the operator experience. These factors can often result in large measurement variability which may require repeated measurements. For some procedures, a tested specimen is required to be dried before being used to conduct a repeated measurement. The current AASHTO (American Association of State Highway and Transportation Officials) specifications for measuring (G_{mb}) are:

- AASHTO T331: Bulk Specific Gravity (G_{mb}) and Density of Compacted Asphalt Mixtures Using Automatic Vacuum Sealing Method
- AASHTO T166: Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens

A dielectric profiling system (DPS) is a new technology that is being used to evaluate variations in the air void content and density of asphalt pavements in the field during and after construction for quality control purposes. The DPS technology utilizes measurement of the dielectric constant of pavement materials using a miniaturized ground penetrating radar (GPR) system. The technology within DPS has been adapted for routine laboratory measurement of dielectric constant of asphalt concrete specimens using a miniaturized source and receiver. This project explores the use of a laboratory dielectric measurement system (LDMS) which measures the dielectric constant of pavement materials using ground penetrating radar (GPR) system for determining G_{mb} measurement as an alternative procedure to the current AASHTO specifications. Due to the minimal equipment needs and low operational cost, routine usage of LDMS has the potential for increased efficiency and accuracy of laboratory G_{mb} measurements.

This project is divided into two stages. Work in Stage 1 focused on establishing the reliability and standardizing procedure for the LDMS. In Stage 2, a protocol was developed to establish the relationship between dielectric value and G_{mb} with the goal of replacing traditional AASHTO procedures for laboratory G_{mb} measurements with laboratory dielectric measurements.

To ensure that the relationship between G_{mb} and dielectric measurements is established accurately, repeatable and reliable testing using the LDMS is required. In Stage 1, asphalt mixtures with a range of aggregate and mixture properties (geology, nominal maximum aggregate size, binder type, reclaimed asphalt pavement (RAP) content, etc.) were collected. Compacted asphalt specimens of various specimen surface conditions and sizes were tested using the LDMS. The collected dielectric results were statistically analyzed to study dielectric measurement repeatability and reliability by grouping measurements at various orientations together and comparing them to all measurements of the corresponding asphalt specimen. Sensitivity analysis was performed to study measurement accuracy and resolution for replicate dielectric measurements. A procedure for conducting the LDMS was developed. Based on the gathered data and statistical analyses performed in this work, it was determined that taking dielectric measurements at any 3 orientations 120 degrees apart (3 measurements total) yields repeatable dielectric measurements with acceptable accuracy for use as standard method for G_{mb} determination of a compacted asphalt mixture specimen.

In Stage 2, a select number of asphalt mixtures along with their component materials (aggregates and RAP) were collected. These asphalt mixtures were selected based on the dielectric results collected in

Stage 1. The collected data were used to refine the testing and analysis procedures for component materials and to enhance existing models to develop and refine the relationship between laboratory-measured dielectric values and bulk specific gravities of compacted asphalt specimens. The Hashin-Shtrikman model was used as part of the analysis for comparing the dielectric of the component materials and the dielectric of the corresponding asphalt mixtures. The Al-Qadi Lahour Leng (ALL) model and the Hashin-Shtrikman (HS) model were investigated and analyzed to establish the relationship between G_{mb} and dielectric measurements. Analysis results showed that there was a good agreement between the dielectric of the component materials and of the corresponding asphalt mixtures for most of the selected mixtures. There was a linear trend between the measured G_{mb} and the predicted G_{mb} using the ALL model. However, further enhancement and refinement to the ALL model are needed in future efforts, as there are deviations between the measured and predicted G_{mb}. The analysis to establish the relationship between G_{mb} and dielectric measurements and predict G_{mb} using the HS model showed significantly improved correlation between measured and predicted G_{mb}. As an outcome of the Stage 2 effort, a procedure using the HS model was developed to determine specimen G_{mb}.

II. IDEA PRODUCT

This project developed a test specification that captures the LDMS testing procedure, asphalt specimen needs, and equipment needs and that discusses analysis procedures that need to be developed for adoption by agencies and contractors. The project outcomes also include establishing the relationship between dielectric constant and G_{mb} and the factors (specimen geometry, surface characteristics, and asphalt mixture types) that influence it. The IDEA products are expected to improve the efficiency and accuracy of laboratory G_{mb} measurements.

III. CONCEPT AND INNOVATION

The specific innovation is a LDMS that is tailored for determining G_{mb} of compacted asphalt specimens. The LDMS is a dielectric profiling system technology that utilizes measurement of the dielectric constant of pavement materials using a ground penetrating radar (GPR) antenna and receiver. The dielectric constant refers to a material's ability to transmit electromagnetic waves through its medium, specifically the propagation velocity. The dielectric constant of an asphalt mixture is derived from the dielectric values of its constituents (air, asphalt binder and aggregate). Air and asphalt binder both have low dielectric values which translate to high propagation velocities. Asphalt binder, independent of viscosity, normally has a dielectric constant between 2.6 and 2.8, while the dielectric of air is 1. Aggregates, due to mineral deposits, tend to have higher dielectric constants ranging from 4.5 to 6.5 which translate to lower propagation velocities (3). For a particular asphalt mixture, as the bulk density increases (larger G_{mb}), the air void levels decrease which would result in an increased dielectric constant.

The LDMS consists of a miniaturized source and receiver system (Figure 1) and runs on a frequency of 1-3 GHz. Several approaches have been developed to relate dielectric properties of asphalt mixtures to air void content including empirical models (3-5) and mix model methods (6-8). The empirical models and the mixing models were developed based on field conditions. The research effort in studying dielectric measurements has been focusing on mainly the field dielectric measurements. Proof of concept work was conducted to show an inverse relationship between laboratory measured dielectric constant and air voids (5). Two methods using ground penetrating radar technology for calculating are surface reflection (SR) and time-of-flight (TOF). The TOF method has been found in previous studies to be more robust for conducting laboratory dielectric measurements than the SR method, which is commonly employed in collecting field dielectric measurement (5). Laboratory dielectric measurement system was used to evaluate the marginal changes in the composition of asphalt mixture in Minnesota (9). The previous works that were done on laboratory dielectric measurement involved the testing of limited range of asphalt mixtures in terms of aggregate properties, mixture properties, asphalt specimen surface conditions and asphalt specimen thicknesses (5,9). Moreover, none of the previous works focused on standardizing measurement method to ensure accurate and repeatable dielectric measurements using the LDMS. The LDMS equipment was provided by Geophysical Survey Systems, Inc. (GSSI) as a prototype for this project and the current price of a LDMS unit is approximately $25,000.

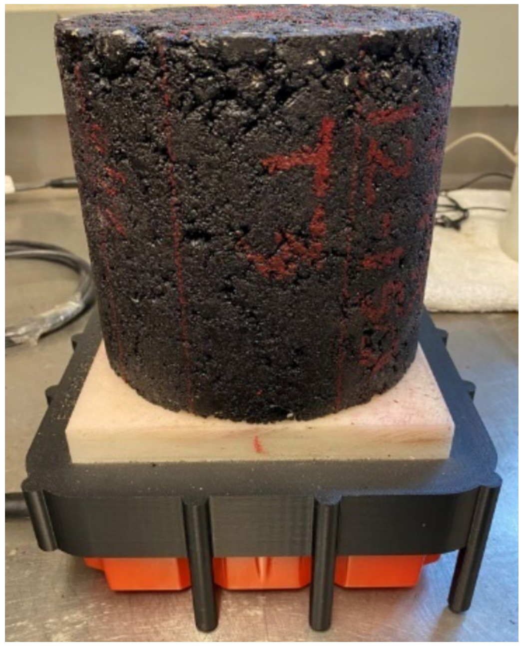


FIGURE 1 Photo of the LDMS setup showing a gyratory compacted asphalt specimen

Implementation of the LDMS has the potential for increased efficiency and accuracy of laboratory G_{mb} measurements as compared to the current AASHTO and ASTM procedures that require multiple pieces of laboratory equipment (high precision scales, water bath with controlled temperature, ability to weigh specimen under water, vacuum sealing devices). Approximately 15 minutes is needed to measure G_{mb} using current procedures while the initial pilot procedure for measurement of asphalt mixture air voids using dielectric measurement approach requires less than 5 minutes for each measurement. Specimens measured using the current procedure also need to be dried (using equipment such as CoreDry or overnight air drying) prior to their use for other mechanical performance testing. Use of the existing procedures with porous asphalt mixtures or those with highly absorptive aggregates require the use of vacuum sealing equipment to avoid substantial measurement errors. Using the repeatability and reproducibility limits published in the current AASHTO and ASTM protocols, the variability in G_{mb} measurements (acceptable range of 0.035 of two G_{mb} results for single operator (1)) can result in as much as 1.75% variation in the resulting calculated air voids. For performance prediction purposes, most agencies require a tolerance of +/- 1.0% for the specimen air voids and may use even a tighter tolerance of +/- 0.5%. The current G_{mb} measurement procedure has the potential to introduce errors larger than the required tolerances by agencies. The dielectric constant-based method has the potential to alleviate many of these challenges and would result in more efficient laboratory operations as well as more economical operation since only one piece of equipment would be needed.

IV. INVESTIGATION

This research study included two stages and seven tasks over two years (2021-2022). At the conclusion of each quarter or each stage, a summary report was prepared and submitted to NCHRP (National Cooperative Highway Research Program) as well as the Expert Advisory Panel of this NCHRP IDEA project for feedback and recommendations for the following quarter or stage. The reports provided an in-depth description of the outcomes from each task as well as to discuss any deviations from the proposed plan. Detailed description of the activities and outcomes of each stage and task are discussed next.

STAGE 1: ESTABLISH MEASUREMENT RELIABILITY AND DRAFT TEST PROCEDURE

This stage focused on establishing the reliability of, and standardized procedures for, the LDMS including evaluation of the impact of specimen geometry, surface condition, and mix design variables on dielectric measurements. A test procedure for measuring the dielectric constant of compacted asphalt mixtures in the laboratory was developed in this stage.

Task 1: Kickoff Meeting with Expert Panel

A kickoff meeting was held on January 15, 2021, that included the UNH Research team and the Expert Advisory Panel to discuss appropriate adjustments to the workplan. Use of multiple antennas for dielectric measurements was discussed and the addition of compacted specimens tested by respective agencies and the UNH team were added to the sampling plan for this purpose. The research team also shared pilot data, the project statement of work, and revised proposal and workplan with the panel.

Task 2: Selection of Materials and Gathering of Existing Data

A survey of state DOTs (sent to AASHTO Committee on Materials and Pavements members) was developed and administered to gather information on aggregate sources and planned mixture production for the 2021 construction season. Results from survey responses were analyzed to provide an overview of mixture types that would be produced in 2021 and to develop a material sampling plan that considers various factors for material selection such as aggregate geological type (related to dielectric constant), nominal maximum aggregate size, use of recycled materials, and binder grade to ensure sampled materials represent the range of common mixtures produced across the United States. Data and materials from projects conducted for the TPF-5(443) pooled fund study (Continuous Asphalt Mixture Compaction Assessment using Density Profiling System) during 2021 construction season were also gathered to complement this project. The TPF-5(443) pooled fund study is a multi-state collaborative project that studies Density Profiling System (field dielectric measurement system that uses SR method) for assessing asphalt pavement compaction as part of quality assurance and acceptance process. Compacted test specimens from Minnesota Department of Transportation (MnDOT) and Alaska Department of Transportation (AKDOT) were also received and used for dielectric value cross comparison (reproducibility) and sensor variability check between laboratories.

Task 3: Collection of Materials

Through survey and follow-up communications with various DOTs (including states in the TPF-5(443) study), mixtures that cover a range of aggregate types (specifically in terms of dielectric values) and mix sizes were identified, sampled, and received by the UNH research team. Compacted test specimens from MnDOT and AKDOT were also received and tested for dielectric value cross comparison (reproducibility) and sensor variability check between laboratories. Table 1 shows a summary of the project mixtures.

Table 1 Project mixtures

State	NMAS (mm)	PG	#G	RAP (% of total weight)	Aggregate Type	Additional Info	Mixture Code
Alaska (AK)	12.5	64-40	75	0%	Andesite (A)	-	AK12A
Connecticut (CT)	4.75	64E-22	75	20%	Traprock (T)	-	CT4T
Florida (FL)	9.5	76-22	75	0%	Limestone (L)	FC	FL9L
	12.5	76-22	100	0%	Limestone (L)	FC	FL12L
Massachusetts (MA)	37.5	64S-28	75	25%	Granite (G)	SBC	MA37G1
	37.5	64S-28	75	25%	Granite (G)	SBC	MA37G2
Maine (ME)	9.5	64E-28	65	15%	Sandstone (S)	-	ME9S
	12.5	64-28	75	0%	Sandstone (S)	ARGG	ME12S
Minnesota (MN)	12.5	58S-28	-	24%	-	WC, TH21	MN12TH21
	12.5	58V-34	-	20%	-	WC, TH60	MN12TH60
New Hampshire (NH)	12.5	64-28	50	20%	Granite (G)	-	NH12G
	12.5	76-28	75	0%	Granite (G)	WC, HS	NH12GHSV
	12.5	76-28	75	20%	Granite (G)	WC, HS	NH12GHSR
	19	58-28		19%	Granite (G)	BC	NH19G
North Dakota (ND)	12.5	58H-34	75	15%	-	-	ND12
Virginia (VA)	25	64S-22	50	26%	Marble (M)	BM	VA25M

ARGG = Asphalt Rubber Gap-Graded; BC = Binder Course, BM = Base Mix; FC = Friction Course; HS = High Strength; NMAS = Nominal Maximum Aggregate Size; PG = Performance Grade; RAP = Reclaimed Asphalt Pavement; SBC = Stabilized Base Course; TH60 = Trunk Highway 60; TH21 = Trunk Highway 21; WC = Wear Course; #G = Number of Design Gyrations; “S”, “H”, “V”, “E” in the binder PG label refer to Standard, High, Very High and Extremely Heavy traffic respectively; “-” = Information not available

Task 4: Specimen Fabrication and Testing

All mixtures were used to fabricate cylindrical test specimens 150 mm in diameter with various heights (100 mm to 180 mm) and covering a range of densities. The specimen geometry was limited to 150 mm diameter due to current limitations of the LDMS equipment (locations of source and receiver antenna). Table 2 shows a summary of all compacted specimens and their respective heights and surface conditions. The dielectric constants of all compacted specimens were measured with the LDMS and bulk specific gravities (G_{mb}) were measured following AASHTO T331 specification. Theoretical maximum specific gravities (G_{mm}) were also measured for all mixtures following ASTM D6857 specification (Maximum Specific Gravity and Density of Asphalt mixtures Using Automatic Vacuum Sealing Method).

Table 2 Number of compacted 150 mm diameter specimens

Mixture Code	Compacted Faces Height (mm)				Cut Faces (120 mm height)	Compacted Specimens Received
	100	120	150	180		
AK12A	-	3	-	-	-	4
CT4T	-	4*	-	-	4*	-
FL9L	-	4	2	-	-	-
FL12L	-	3	2	-	-	-
MA37G1	2	6*	2	2	6*	-
MA37G2	-	3	-	-	-	-
ME9	3	3	-	-	-	-
ME12	4	4	-	-	-	-
MN12TH21	2	3	-	-	-	11*
MN12TH60	-	3	2	-	-	22*
NH12G	2*	7*	4*	3	5*	-
NH12GHSV	-	4	-	-	-	-
NH12GHSR	-	5	-	-	-	-
NH19G	-	4	-	-	-	-
ND12	-	3	-	-	-	-
VA25M	-	4*	-	-	-	-

* Conditions selected for which a total of 160 measurements were collected on each specimen for statistical analysis of measurement repeatability; "-" Specimens are not compacted for the respective geometries

Various specimens of one geometry (150 mm in diameter and 120 mm in height) covering a range of densities from three mixtures were selected to be used to study effects of end-face surface characteristics (cut versus compacted face) on LDMS. Figure 2 illustrates the cutting setup (Figure 2a) and before/after pictures of cut specimens of various aggregate sizes (Figure 2b). In Figure 2a, the specimen to the right is the test specimen, and the specimen to the left is a dummy specimen to ensure an even cut. The study of surface characteristics involved first measuring dielectric and G_{mb} on the specimens with two compacted faces, then with only one face cut, and finally with two faces cut.

(a) **(b)**

FIGURE 2 a) Laboratory cutting setup; b) Specimen face before cutting (top row) and after cutting (bottom row) (left to right: 4.75 mm, 12.5 mm and 37.5 mm)

The thickness measurement procedures are illustrated in Figure 3. Specimen thickness at four locations 90 degrees apart was measured using a caliper with a resolution of 0.01 mm (Figure 3a) and averaged to get a final thickness value for specimens with height of 150 mm and less. For specimens with compacted height of 180 mm, a fixture with a digital depth gauge indicator with a resolution of 0.001 mm was used to measure specimen thickness at the center of the specimen (Figure 3b). The thickness of the metal plate was subtracted from the total thickness to obtain a measurement for the compacted specimen.

(a) Caliper Measurement **(b) Digital Depth Gauge**

FIGURE 3 Thickness measurement setups

Specimens representing a range of mixtures, specimen heights, and surface characteristics were selected to evaluate the repeatability of the dielectric measurement considering various specimen orientations; the conditions included are indicated with an asterisk in Table 2. Figure 4 shows a schematic of the different orientations that include:

1. Top and bottom faces (according to direction of compaction),

2. Rotating measurement orientations (16 total) on each specimen face.

Five replicate measurements were taken at each orientation for a total of 160 individual dielectric measurements (5 replicate measurements × 16 orientations × 2 faces) that were used for statistical analysis conducted under Task 5. Based on the statistical analysis (details in next section), it was determined that testing at any three orientations 120 degrees apart is sufficient; this protocol was used for the remaining specimens/conditions.

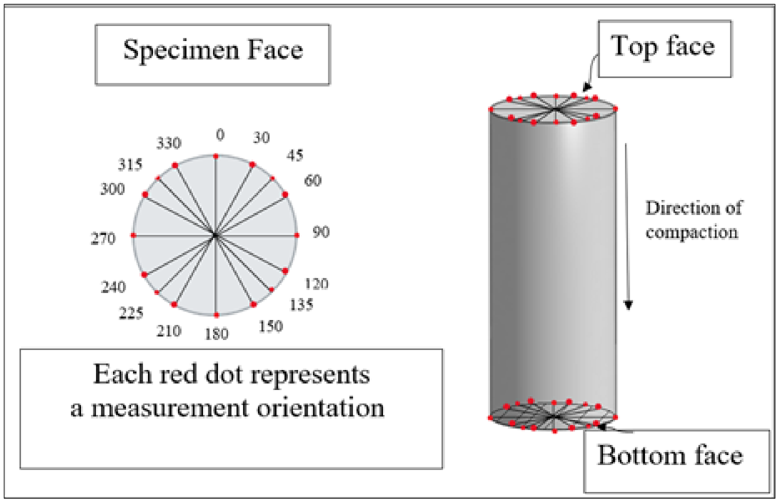


FIGURE 4 Schematic of LDMS testing orientations

Figure 5 shows G_{mb} as a function of the average laboratory measured dielectric value for all specimens (different heights and surface characteristics) including compacted specimens received from MnDOT and AKDOT. Mixtures from the same state are represented using the same color, but different patterns inside the symbols. Different symbols represent the aggregate sizes as specified in Figure 5. The legend in Figure 5 corresponds to the mixture codes in Table 1. The dashed lines represent linear trendlines and Table 3 shows the slopes and intercepts of the trendlines for different mixtures. As G_{mb} decreases (air void increases), laboratory measured dielectric values for each mixture type decrease. Figure 5 and Table 3 show that the relationship between G_{mb} and dielectric value appears to be linear for each mixture and the slopes are visually similar. Figure 5 also shows that the difference in geology/ aggregate types has a significant impact on dielectric values from mixture to mixture. For example, there is a distinct difference in dielectric values between mixtures from Connecticut (predominantly containing traprock aggregate), Virginia (predominantly containing marble aggregate) and New Hampshire/ Massachusetts (predominantly containing granite aggregate). However, for some mixtures from New Hampshire and Massachusetts, despite having similar geology and the trendlines that are closely aligned, they have different slopes which might be due to the effect of other mixture properties or dielectric variability. For some mixtures such as AK12A and ME9S, despite different geology, they have very similar trendlines. The measured dielectric values for compacted mixtures in the 4-6% air void range from approximately 4.5 to 6.5 for the materials evaluated in this study.

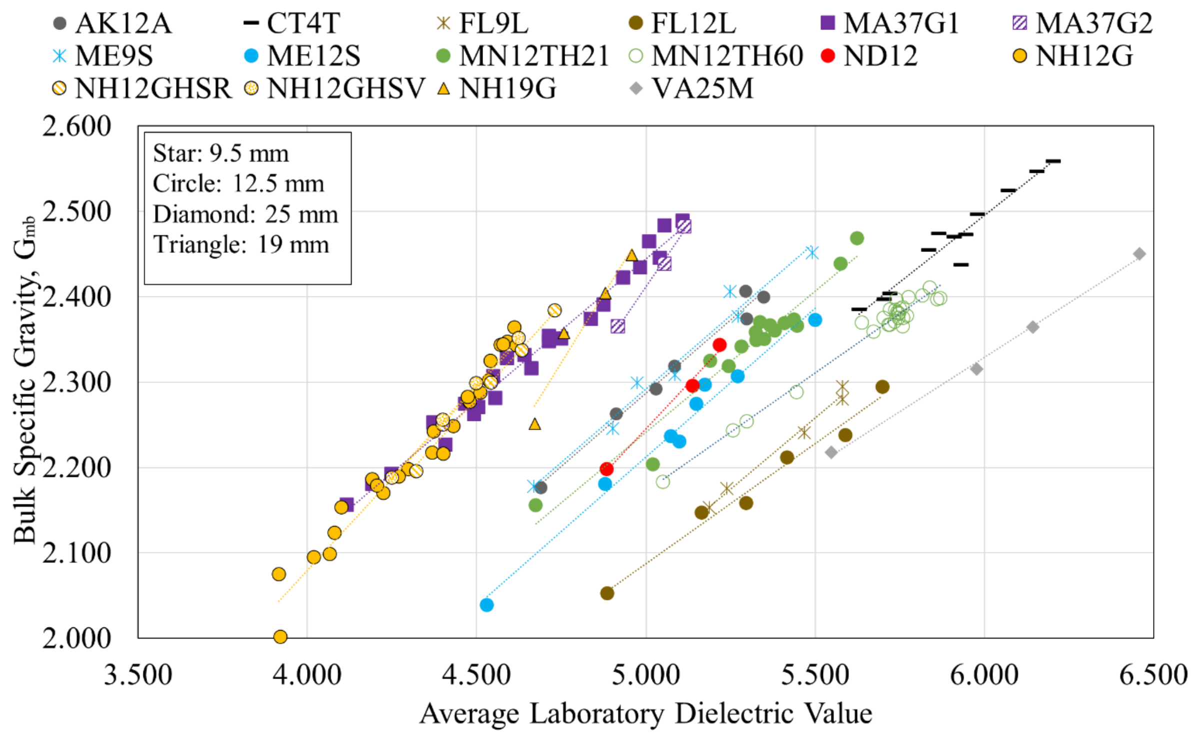


FIGURE 5 Measured G_{mb} as a function of average dielectric values for all compacted specimens

Table 3 Summary of slopes and intercepts for collected mixtures

Mixture Code	Slope (smallest to largest)	Intercepts
VA25M	0.255	0.798
MN12TH60	0.277	0.786
FL12L	0.281	0.683
CT4T	0.312	0.622
MN12TH21	0.330	0.593
FL9L	0.333	0.425
MA37G1	0.334	0.776
AK12A	0.343	0.572
ME9S	0.344	0.574
ME12	0.349	0.467
ND12	0.424	0.125
NH12G	0.430	0.358
NH12GHSV	0.437	0.333
NH12GHSR	0.438	0.309
MA37G2	0.583	-0.504
NH19G	0.641	-0.722

Figure 6 shows the average dielectric values for compacted tested specimens of different heights and surface characteristics. Different mixtures are identified by color and symbols represent specimen height and surface characteristics. The dash lines represent linear trendlines for different mixtures. Visually, different specimen thicknesses and surface characteristics do not appear to have a significant impact on the dielectric measurements. Further statistical analysis to assess the impact of thickness on dielectric measurements is described in subsequent sections.

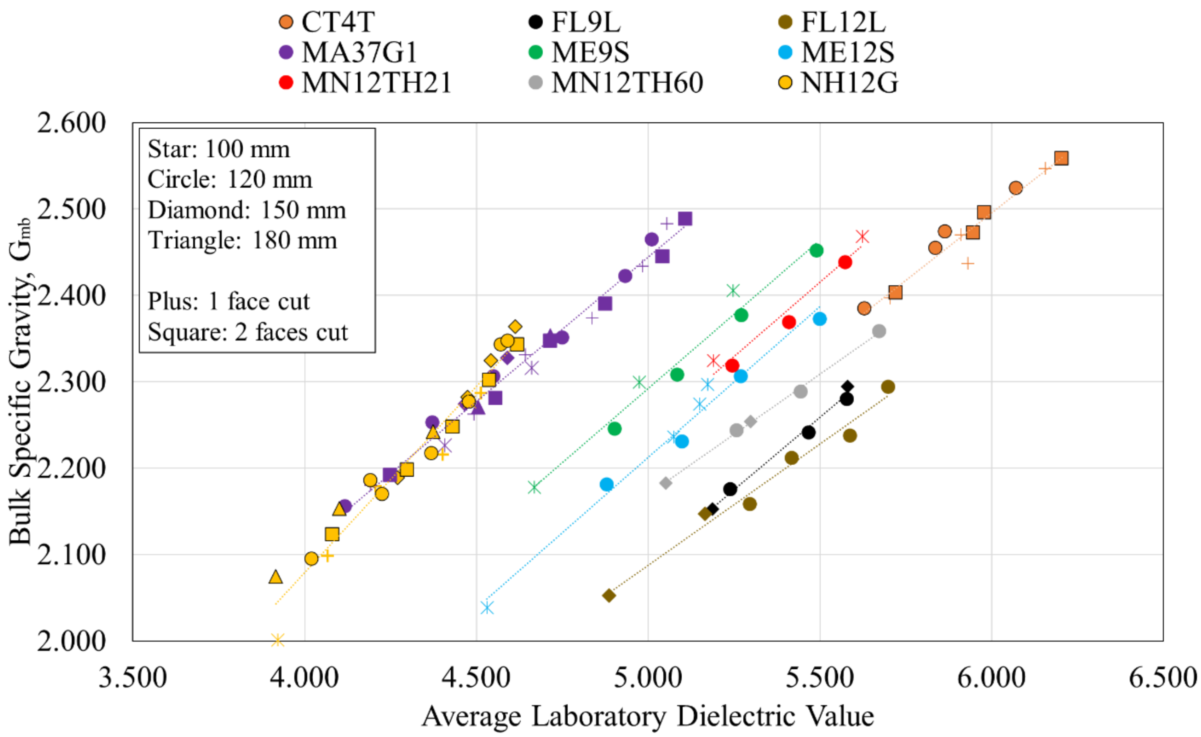


FIGURE 6 Measured G_{mb} as a function of average dielectric values for various compaction heights and surface characteristics

Task 5: Analysis and Development of Draft Test Specification

Based on the testing procedure that involves taking 160 measurements for selected specimens (as indicated with an asterisk in Table 2), dielectric measurement variation within each specimen was evaluated. Dielectric test results for the selected specimens were used to perform statistical analyses to study measurement repeatability and variability. The statistical analysis involved the following calculated parameters:

- Grand average (AVE): average of all 160 measurements for each specimen
- Grand Standard Deviation (STD): standard deviation of 160 measurements for each specimen
- Coefficient of Variation (COV) of all measurements for each specimen
- Overall Range: the maximum value minus the minimum value for all 160 measurements from each specimen, regardless of orientation or face
- Max Individual Orientation Range: the range (max – min) of the five replicate measurements at each orientation was calculated and the maximum value determined for the whole specimen (this value represents maximum deviation that can be observed for a specimen that is tested in repetitive manner as same orientation).

Table 4 shows the summary of the calculated values for each specimen included in this analysis; this includes the results measured only on compacted face surface condition. The Overall Range is larger than the Max Individual Orientation Range for all specimens, indicating that the measurement orientation contributes more variability than the replicate measurements at each orientation. Figure 7 shows that as G_{mb} decreases, dielectric measurement variability increases for a given mixture type as shown by the increase in Overall Range, STD and COV.

The number of instances (converted to percentage) that the range (max-min) of the five-replicate measurements at each orientation is below 0.02 was calculated for each specimen and reported in the last column in Table 4 as the "% of Ranges of All Orientations < 0.02". Per the equipment manufacturer, the acceptable threshold for replicate dielectric measurements at each orientation is 0.02, this parameter was calculated to be used as part of the analysis of measurement repeatability.

In the statistical analysis performed to study measurement repeatability and variability, measurements taken at specific orientation groupings were analyzed to determine the appropriate orientations required to achieve a representative dielectric constant measurement. This analysis was conducted on specimens with compacted faces and Table 5 details the groupings that were used. As testing was done on both faces at the same orientations, the grouping notations are the same for top and bottom faces. The statistical analysis approach uses grand average (AVE) of all measurements and standard deviation (STD) of all measurements (typically 160 per specimen) as representative of the "true" measurement for each specimen and "true" measure of variability.

Table 4 Summary of test results and calculated parameters for specimens with compacted faces

Mix Code	Compaction Height (mm)	G_{mb}	Air Void Content	Dielectric Constants					
				Grand Average (AVE)	Grand Standard Deviation (STD)	Coefficient of Variation (COV)	Overall Range	Max Individual Orientation Range	% of Ranges of All Orientations < 0.02
CT4T	120	2.524*	4.24%	6.071	0.008	0.13%	0.039	0.015	100.00%
		2.474	6.16%	5.865	0.015	0.25%	0.067	0.028	84.38%
		2.385	9.52%	5.630	0.018	0.31%	0.082	0.030	90.63%
NH12G	100	2.277	5.89%	4.480	0.008	0.18%	0.056	0.027	87.50%
	120	2.343	3.13%	4.571	0.008	0.01%	0.046	0.022	96.88%
		2.277*	5.85%	4.480	0.012	0.28%	0.053	0.017	100.00%
		2.217	8.36%	4.369	0.008	0.19%	0.056	0.042	93.75%
		2.170	10.28%	4.226	0.017	0.40%	0.064	0.022	90.63%
		2.095	13.40%	4.020	0.015	0.38%	0.123	0.094	87.50%
	150	2.364*	2.28%	4.613	0.006	0.14%	0.031	0.018	100.00%
		2.325*	3.90%	4.542	0.005	0.12%	0.024	0.010	100.00%
MA37GAI	120	2.465	2.96%	5.011	0.010	0.19%	0.043	0.018	100.00%
		2.351	7.44%	4.750	0.019	0.40%	0.070	0.021	87.50%
		2.253	11.31%	4.373	0.022	0.50%	0.091	0.025	90.63%
		2.156	15.10%	4.118	0.031	0.75%	0.118	0.024	96.88%
VA25M		2.450	4.07%	6.457	0.019	0.30%	0.095	0.024	81.25%
		2.218	12.67%	5.547	0.017	0.31%	0.073	0.019	100.00%
MN12TH21	117.37	2.342*	5.92%	5.282	0.014	0.26%	0.074	0.020	96.88%
	116.19	2.156	13.39%	4.675	0.018	0.40%	0.082	0.030	81.25%
MN12TH60	114.02	2.398*	3.39%	5.871	0.007	0.13%	0.039	0.023	93.75%
	115.26	2.375	4.46%	5.702	0.011	0.18%	0.056	0.038	93.75%

*Specimens selected for study of dielectric measurement accuracy and resolution with respect to the accuracy and resolution of specimen thickness measurement

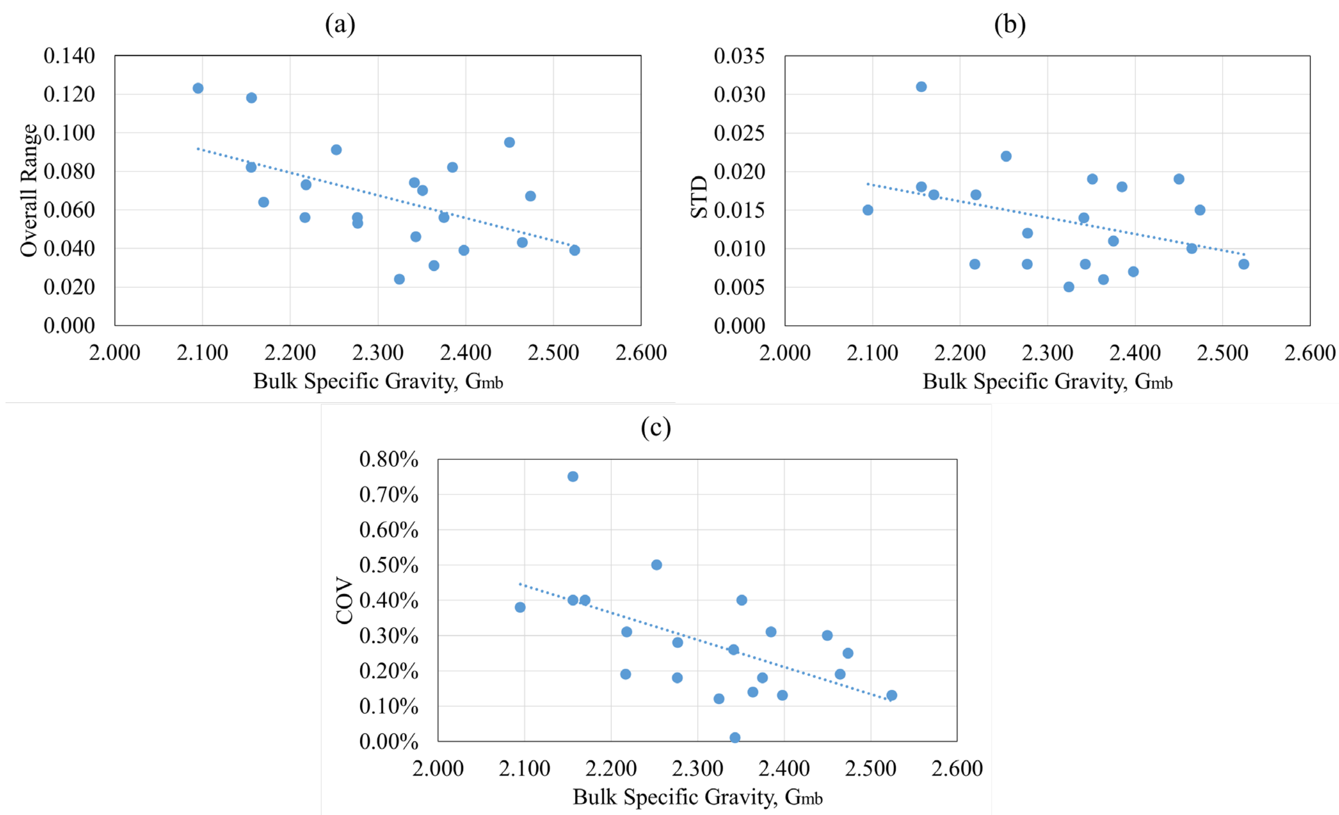


FIGURE 7 Dielectric measurement variability a) Range of individual measurements vs G_{mb}; b) Standard deviation (STD) vs G_{mb}; c) Coefficient of variation (COV) vs G_{mb}

Table 5 Types of groupings of measurements for statistical analysis

Grouping Name	Grouping Type	Measurement Orientations
90DEG (4 pts/8)	90-degree grouping of 4 orientations Total: 8 groups for both faces	(0/90/180/270) (45/135/225/315) (30/120/210/300) (60/150/240/330)
120DEG (3 pts/8)	120-degree grouping of 3 orientations Total: 8 groups for both faces	(0/120/240) (60/180/300) (30/150/210) (90/210/330)
180DEG (2 pts/16)	180-degree grouping of 2 orientations Total: 16 groups for both faces	(0/180) (45/225) (90/270) (135/315) (30/210) (60/240) (120/300) (150/330)
90DEG (2 pts/16)	90-degree grouping of 2 orientations Total: 16 groups for both faces	(0/90) (45/135) (120/210) (225/315) (30/300) (60/150) (180/270) (240/330)
45DEG (4 pts/4)	45-degree grouping of 4 orientations Total: 4 groups for both faces	(0/45/90/135) (180/225/270/315)

After measurement groupings for each grouping type were identified, comparisons were then made between the average calculated from the measurement grouping and the grand average and grand standard deviation in two ways:

1. The difference (error) between the average of each grouping and the grand average of all measurements was calculated as following:

$$\textbf{\textit{Grouping Error}} = |\textbf{\textit{average of grouping}} - \textbf{\textit{grand average}}| \quad (1)$$

The grouping errors were compared to the grand standard deviation by calculating the number of instances (converted to percentage) that the magnitude of the grouping error is below the value of one grand standard deviation interval:

$$\textbf{\textit{Percentage}} \leq \textbf{\textit{1}}\ \boldsymbol{\sigma} = \frac{\textbf{\textit{Total instances of magnitude of error}} \leq \mathbf{1}\ \boldsymbol{\sigma}}{\textbf{\textit{Total number of groupings}}} * \mathbf{100} \quad (2)$$

2. The difference (range) between the maximum average value and the minimum average value from each grouping type was calculated as following:

$$\textbf{\textit{Grouping Range}} = \textbf{\textit{Maximum AVE in the grouping type}} - \textbf{\textit{Minimum AVE in the grouping type}} \quad (3)$$

The grouping range was then compared to the value of one grand standard deviation for each specimen.

Table 6 shows the example calculation for grouping type 120DEG (3 PTS/8) for a CT4T specimen.

Table 6 Example calculation for a CT4T specimen

Face	**120DEG (3 PTS/8) Groupings**	**Average of Grouping**	**Grand Average**	**STD**	**Grouping Error**
Top	(0/120/240)	5.866	5.865	0.015	0.001
	(90/210/330)	5.863			0.002
	(60/180/300)	5.867			0.002
	(30/150/270)	5.872			0.007
Bottom	(0/120/240)	5.871			0.007
	(90/210/330)	5.874			0.010
	(60/180/300)	5.872			0.008
	(30/150/270)	5.868			0.003
Percentage ≤ 1 STD				100%	
Grouping Range				0.011	

The difference (error) between the average of each grouping and the grand average of all measurements was calculated with Eq 1 and 2:

Error of Bottom (0/120/240) = |5.871 – 5.865| = 0.007 < 0.015

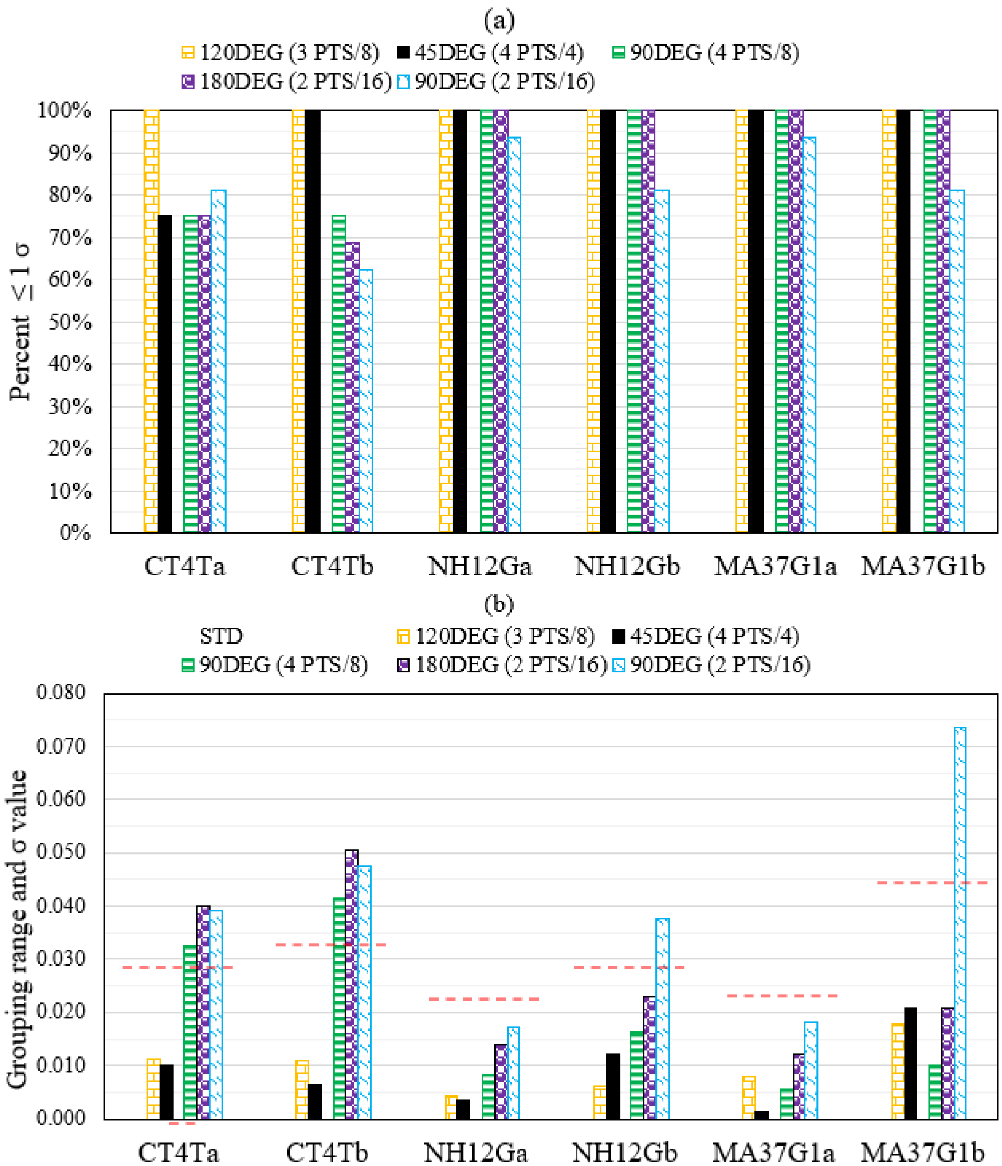
$\textit{Percentage} \leq \textit{1 STD} = \frac{8}{8} * 100 = \textit{100\%}$

The difference (range) between the maximum average value and the minimum average value from each grouping type was calculated with Eq 3:

Range of 120DEG (3 PTS/8) = 5.874 – 5.863 = 0.011< 0.015

Figure 8a shows the results for the statistical analysis of Percentage ≤ 1 STD and Figure 8b shows the results for the statistical analysis of Grouping Range for six specimens from three mixtures (CT4T, NH12G, and MA37G1). The same statistical analyses were performed, and similar results observed on the dielectric results of all other specimens listed in Table 4.

Based on the statistical analysis using one grand standard deviation as the criterion, taking five measurements at each of any three orientations 120 degrees apart (15 measurements total) on any face provides an average dielectric value that is representative of the whole specimen. For the specimens tested, the averages of all groupings in the 120-degree grouping type are within one grand standard deviation of the grand average and are also within one grand standard deviation of each other.



("a" and "b" at end of mixture ID refer to two different specimens for each mixture type)

FIGURE 8 Statistical analysis for dielectric measurements among orientations
a) Percentage ≤ 1 STD; b) Grouping range and STD value

Further sensitivity analysis was performed to study measurement accuracy and resolution for replicate dielectric measurements at 3 orientations 120 degrees apart, this is the grouping type that has been determined to be appropriate for conducting dielectric measurements (details are discussed in the Results and Discussion section). This involves finding all possible measurement combinations using one, two, three or four replicate measurements for 3 orientations that are 120 degrees apart. Table 7 details the measurement combination groups and their respective number of combinations.

Table 7 Measurement combination group for statistical analysis of replicate dielectric measurements at 3 orientations 120 degrees apart

Combination group	Total combinations
Any one measurement at each orientation (3 measurements total for 3 orientations 120 degrees apart)	125
Any two measurements at each orientation (6 measurements total for 3 orientations 120 degrees apart)	1000
Any three measurements at each orientation (9 measurements total for 3 orientations 120 degrees apart)	1000
Any four measurements at each orientation (12 measurements total for 3 orientations 120 degrees apart)	125

Comparisons were then made between the average of each measurement combination to the grand average and grand standard deviation of corresponding specimen (i.e., the average of 160 measurements) in two ways:

1. The difference (dielectric error) between the average of each measurement combination and the grand average of all measurements was calculated as following:

$$\textbf{Dielectric error} = |\textbf{average of each measurement combination} - \textbf{grand average}| \quad (4)$$

   The max dielectric error was then determined out of the dielectric errors of all measurement combinations for each set of 3 orientations 120 degrees apart.

2. The max dielectric error was then compared to the grand standard deviation by computing the normalized max dielectric error:

$$\textbf{Normalized max dielectric error} = \frac{\textbf{Max dielectric error}}{\textbf{Grand standar deviation}} \quad (5)$$

Figure 9 shows the results for the statistical analysis for measurement accuracy and resolution for replicate dielectric measurements at 3 orientations 120-degree apart. The small blue symbols represent the computed max dielectric errors of all set of 3 orientations 120-degrees apart. The larger symbols represent the average of the smaller blue symbols for each specimen. Figure 9a shows that maximum dielectric errors are almost always below 0.02 and Figure 9b shows that most of the normalized dielectric max errors and averaged normalized dielectric max errors are below one grand standard deviation. As the number of measurements at each of any 3 orientations 120-degree apart increases, the max dielectric error appears to decrease. Using one grand standard deviation as the criterion, any of the three recommended options (any one, two or three/ four measurements from 3 orientations 120-degrees apart) appear to be acceptable.

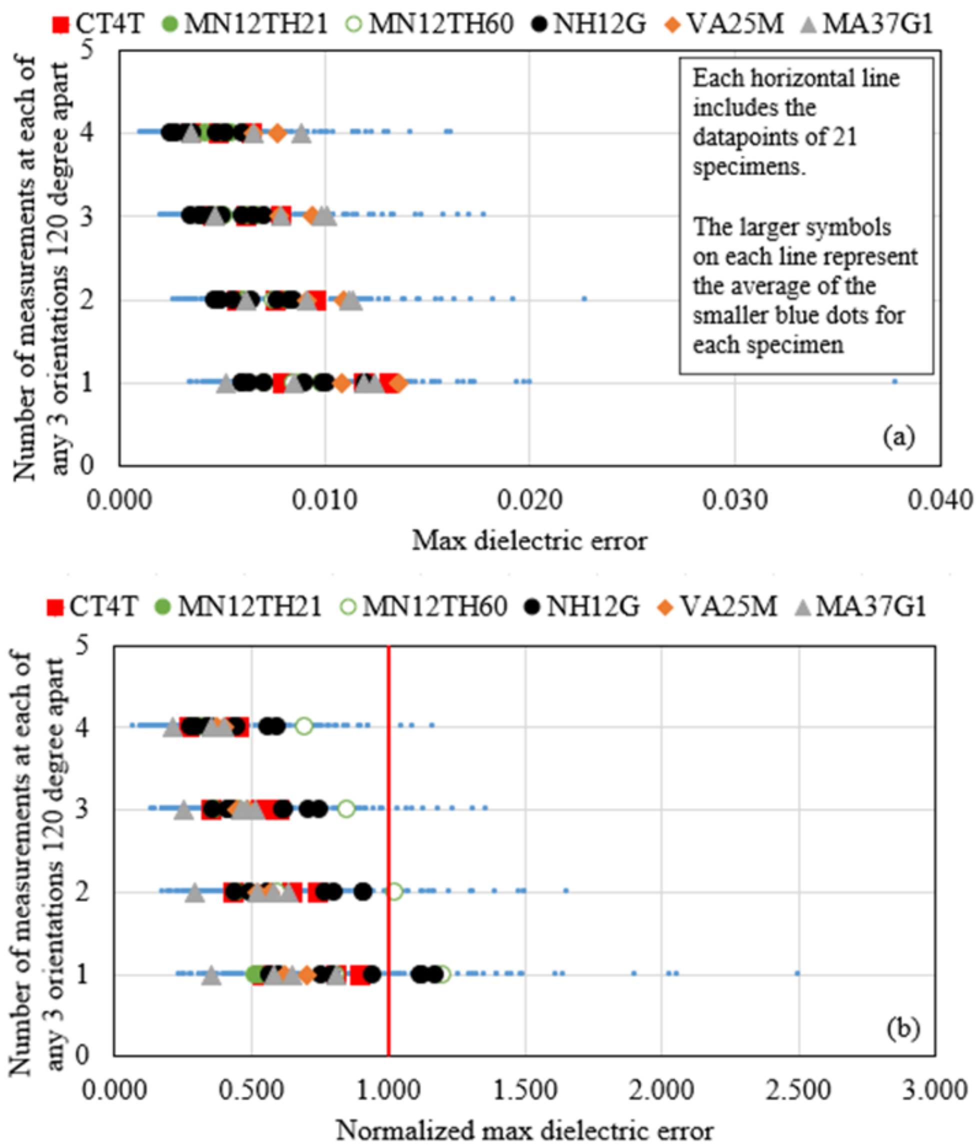


FIGURE 9 Statistical analysis for dielectric measurement accuracy and resolution for replicate dielectric measurements at 3 orientations 120 degree apart in terms of a) Max dielectric error b) Normalized max dielectric error

Based on the statistical analysis performed in this study, the recommended protocol for conducting measurements to achieve representative dielectric constant value for each specimen is as follows:

- Take measurements at each of any 3 orientations 120 degrees apart (3 measurements total).
- If the range of a set of 3 measurements (max value – min value) is more than 0.02, determine the measurement that is 0.02 outside the measurements at the other 2 orientations and replace that measurement with a new measurement at the same orientation.

- If the range of the 2 original measurements and the replace measurement (max value – min value) is still more than 0.02, it is recommended that a second set of measurements be conducted at the same 3 orientations. Of the 6 measurements, the largest and smallest values are to be removed (trimmed average) and average of the remaining 4 are to be used as the representative dielectric value of the whole specimen.

Depending on the operator's experience, conducting individual dielectric measurements takes one to two minutes for each dielectric measurement. Conducting three dielectric measurements total takes at most 6 minutes.

Sensitivity analysis was performed to study dielectric measurement accuracy and resolution with respect to the accuracy and resolution of specimen thickness measurement. The specimens whose dielectric results were used in this analysis are indicated with an asterisk in Table 4. GSSI, Inc. provided the research team with a new version of the PaveScan® software where the thickness measurement can be changed to recalculate the existing dielectric measurement. This discounts dielectric measurement variability coming from collecting entirely new measurements. A similar analysis approach as the sensitivity analysis for replicate dielectric measurements at 3 orientations 120 degree apart was used. Dielectric error was calculated between the recalculated dielectric measurements at various thickness measurements and the grand average at the baseline thickness measurement (i.e., the thickness measurement that was used to calculate the original 160 dielectric measurements of corresponding specimen).

Figure 10 shows the results from the statistical analysis for measurement accuracy and resolution with respect to the accuracy and resolution of specimen thickness measurement. The blue symbols represent the replicate data points at various thickness measurements for select specimens. Each red symbol represents the average of the blue data points at each corresponding thickness measurement. Using the max dielectric error threshold of 0.02 (as represented by the horizontal dashed lines in Figure 10) established from the previous analysis, acceptable resolution of specimen thickness measurements is 0.25 mm (as represented by the vertical dashed lines in Figure 10).

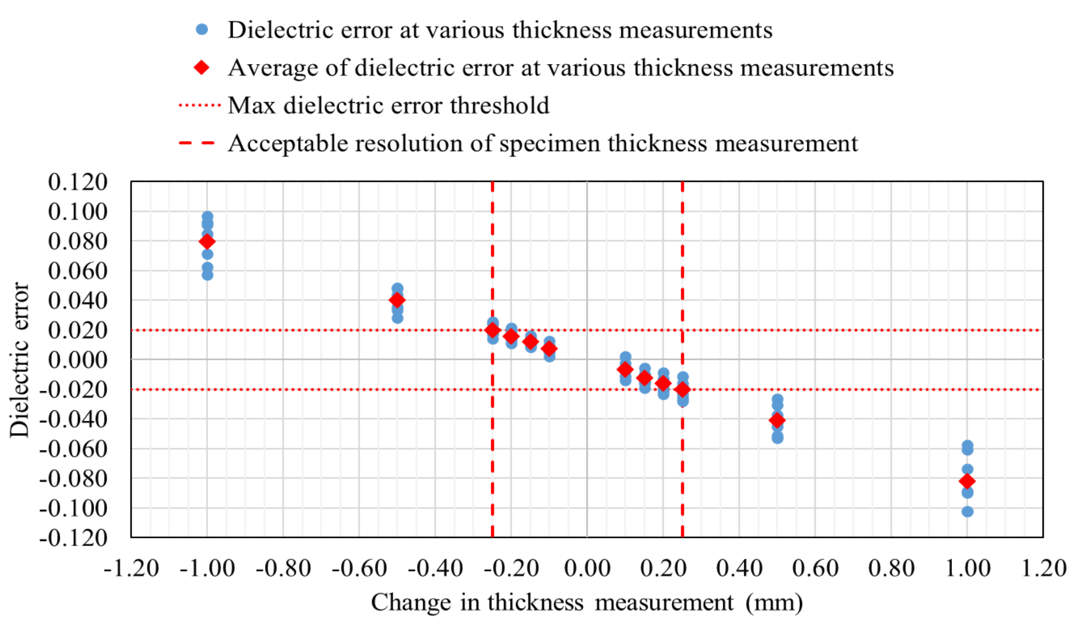


FIGURE 10 Sensitivity analysis with respect to change in thickness measurements

The impact of different surface conditions on the dielectric measurement variability and the dielectric measurement was studied using selected specimens from three mixtures CT4T, NH12G and MA37G1 with 160 measurements using the following calculated parameters:

- Grand average (AVE): average of all 160 measurements for each specimen
- Overall Range: the maximum value minus the minimum value for all 160 measurements from each specimen, regardless of orientation or face
- Top Range: the maximum value minus the minimum value for 80 measurements taken with the top face oriented up (bottom face near the antenna)
- Bottom Range: the maximum value minus the minimum value for 80 measurements taken with the bottom face oriented up (top face near the antenna)

Figure 11 illustrates the measurement variability using ranges (Top Range, Bottom Range and Overall Range) for different surface conditions as identified by color. There are no consistent trends based on end conditions and measurement variabilities are similar for different surface conditions for some specimens. This indicates that the surface condition does not have an impact on measurement variability. Similar observations were made using standard deviation and COV (overall, top, and bottom). However, it appears that as the specimens were cut down at each condition (Compacted → 1 face cut → 2 faces cut), the dielectric value became larger. This can be explained by the changes in G_{mb} as a result of the cutting. Figure 12 presents the data showing that as the percent difference of dielectric of 1 or 2 face(s) cut compared to compacted faces increases, the percent difference of G_{mb} of 1 or 2 face(s) cut compacted faces also increases.

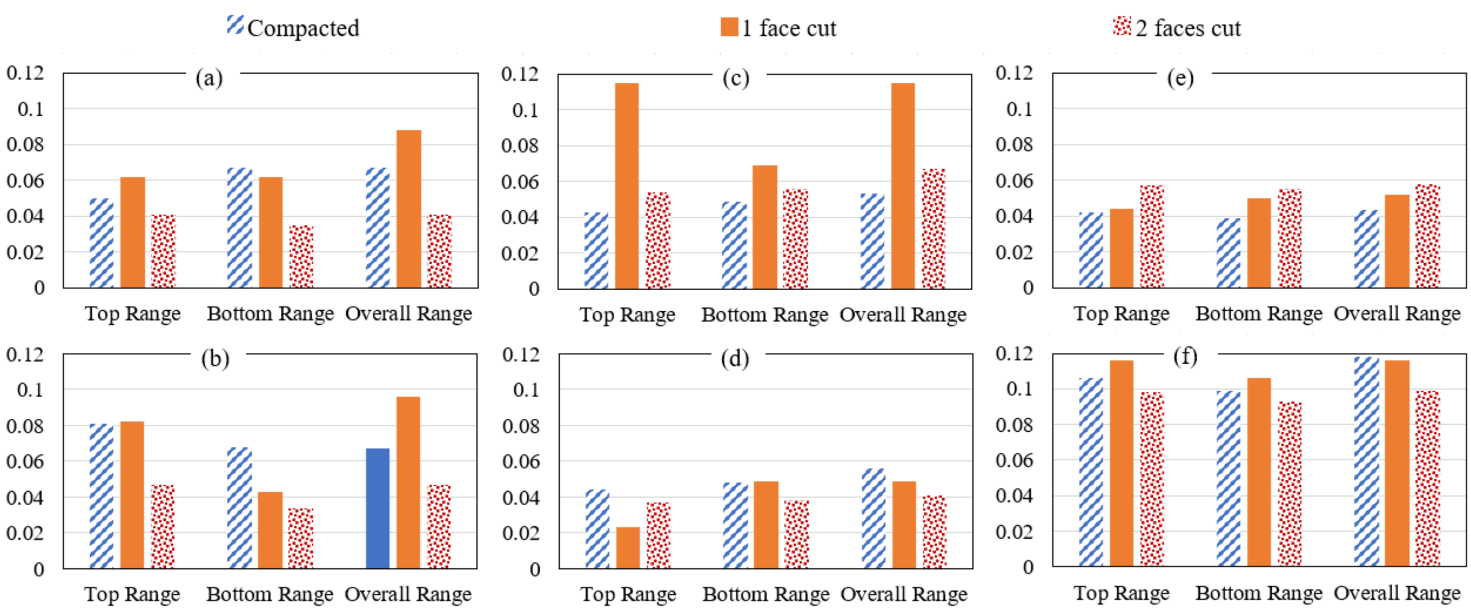


FIGURE 11 Dielectric measurement variability using range (maximum minus minimum measurement) for different surface conditions a) CT4Ta; b) CT4Tb; c) NH12Ga; d) NH12Gb; e) MA37G1a; f) MA37G1b

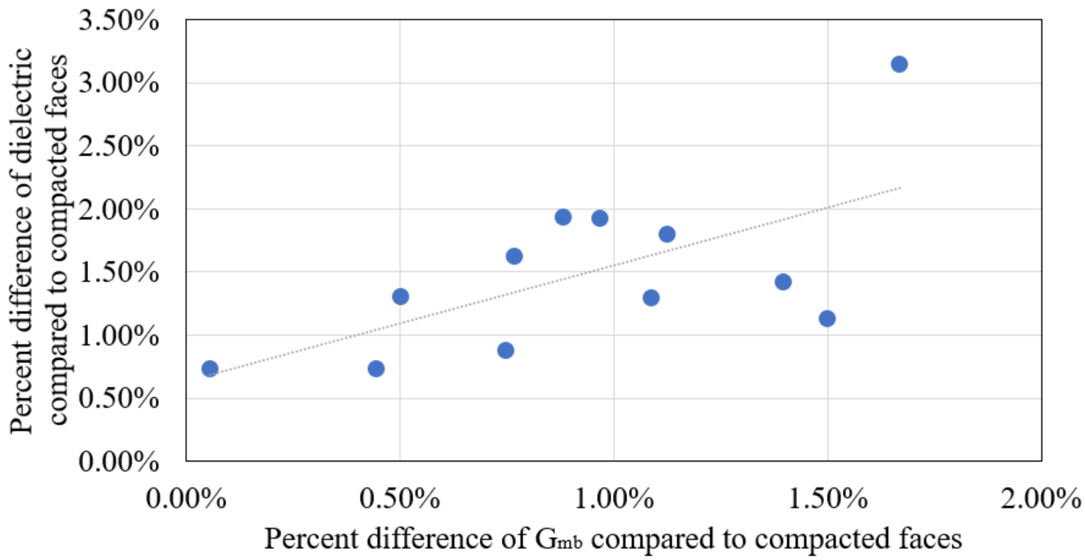


FIGURE 12 Sensitivity analysis with respect to change in surface condition

Dielectric test results for compacted test specimens received from MnDOT and AKDOT were analyzed for measurement reproducibility and sensor variability check between laboratories. Figure 13 shows the comparison between the dielectric results collected by state agencies and the research team (UNH) for compacted specimens received from MnDOT (MN12TH21 and MN12TH60) and AKDOT (AK4A). In Figure 13, different compacted specimens from different mixtures are identified by color. The dielectric results collected by state agencies and UNH appear to be consistent with some deviations, as indicated by the maximum error (i.e., the maximum difference between the dielectric measurements collected by state agencies and UNH) and by the Root Mean Square Error (RMSE). The slight difference in dielectric results could be explained by the following possible reasons:

- Thickness measurement variabilities between labs: The impact of thickness on dielectric measurements is assessed in the sections below. UNH developed a high-resolution thickness measurement device with 0.001 mm resolution.
- Dielectric measurement variability within each specimen: Based on the testing procedure that involves taking 160 measurements for selected specimens, large dielectric measurement variation at different orientations within a specimen was determined as seen in Table 4. Since state agency measurements were conducted using procedures that only take measurements at two orientations (and not three orientations 120-degree apart measurements as recommended in this report), this could cause higher measurement difference.

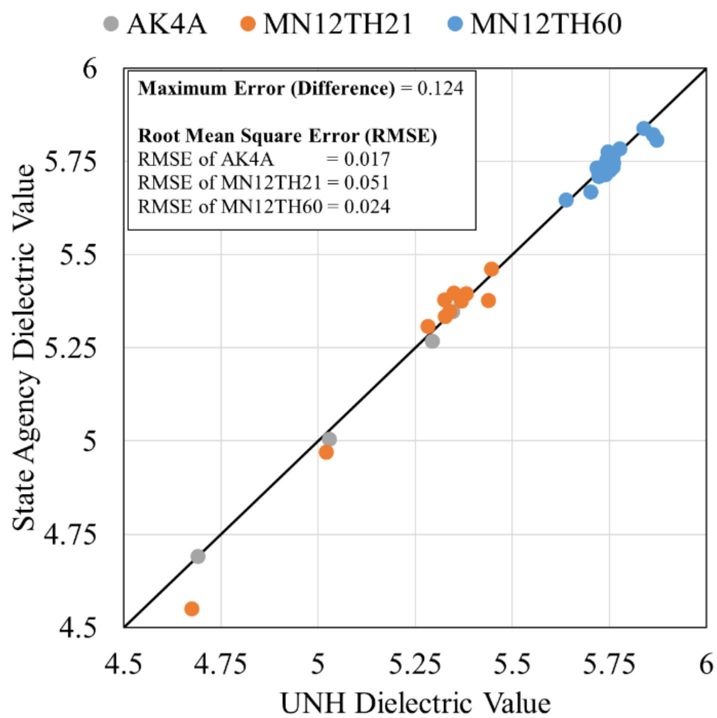


FIGURE 13 State agency and UNH dielectric values for received compacted specimens

Task 6: Stage I Report and Project Progress Review

The research team held a meeting on January 24, 2022 to provide an overview of project accomplishments achieved in Stage 1 and plans for Stage 2 to the Expert Advisory Panel. The research team also addressed questions and comments from the Expert Advisory Panel during the meeting. The research team received authorization to begin Stage 2 work on February 2, 2022.

STAGE 2: DEVELOPMENT OF RELATIONSHIP BETWEEN DIELECTRIC VALUE AND BULK SPECIFIC GRAVITY

From the data gathered in Stage 1, it is clear that a single equation for all aggregate types between dielectric value and G_{mb} is not possible (illustrated in Fig 5 and Fig 6). Any relationship must account for the type of aggregate used in the mixture. Specific tasks to develop a process for determining G_{mb} from measured dielectric value are discussed next.

Task 7: Dielectric Measurement of Component Materials

Component materials for selected Stage 1 asphalt mixtures were collected and tested using LDMS. These asphalt mixtures were selected based on the results collected in Stage 1 representing a range of dielectric values and geology. In order to make the most accurate comparison between the dielectric of the component materials and the dielectric of the corresponding asphalt mixtures, the research team sampled select asphalt mixtures and corresponding component materials during the 2022 construction season. These asphalt mixtures are similar to those collected and tested using the LDMS in Stage 1. Table 8 shows a summary of the identified component materials and corresponding asphalt mixtures.

Table 8 Identified component materials and corresponding asphalt mixtures

State		NMAS (mm)	PG	#G	RAP Amount	Aggregate Type
Connecticut (CT)	Mixture	4.75	64E-22	-	20%	Traprock
	Component materials	9.5 mm crushed aggregate				
		12.5 mm RAP				
		9.5 mm natural sand				
		4.75 mm stone sand				
Maine	Mixture	12.5	76E-28	65	0%	Sandstone
	Component materials	12.5 mm crushed aggregate				
		9.5mm crushed aggregate				
		crusher dust				
		natural sand				
		Dry stone screenings				
New Hampshire (NH)	Mixture	12.5	64-28	75	20%	Granite
	Component materials	4.75 mm washed sand				
		4.75 mm washed manufactured sand				
		4.75 mm dust				
		9.5 mm crushed aggregate				
		12.5 mm crushed aggregate				
		9.5 mm RAP				

NMAS = Nominal Maximum Aggregate Size; PG = Performance Grade; RAP = Recycled Asphalt Pavement; #G = Number of Design Gyrations; “S”, “H”, “V”, “E” in the binder PG label refer to Standard, High, Very High and Extremely Heavy traffic respectively; “-” = Information not available

The component materials and the corresponding asphalt mixtures were tested using the LDMS. Each individual component material was compacted into an acrylic cylinder (per GSSI’s recommendation) wrapped in aluminum foil. The aluminum foil provided boundary for conducting LDMS (5). The process for compacting the component material followed the following steps:

- One third of material was compacted at a time.
- With each layer of material, a steel rod was used to consolidate the material 3 to 4 times at multiple locations around the perimeter and at the center.

- When the material reached the top of the cylinder, the cylinder was overfilled, and a bigger steel rod was used to further consolidate and smoothen the surface by rolling across the surface and removing excess material.
- The component material specimens were prepared to obtain the highest density possible, while ensuring that the metal top plate used during the LDMS testing touches the entire top edge of the acrylic cylinder.

Figure 14 shows an example of compacted specimens of individual component materials in the foil-wrapped acrylic cylinder molds. The dielectric value was measured using the procedure that was recommended in Stage 1 of the project (i.e., measurements were taken 3 orientations 120 degrees apart). The collected asphalt mixtures produced in the 2022 construction season were compacted into specimens at various densities and dielectric values measured using the same procedure in Stage 1.

FIGURE 14 Example of compacted specimens of individual component materials

Two analysis approaches were evaluated by the research team to analyze the measured dielectric of the component materials. The first used the Hashin-Shtrikman (HS) equation (Eq 6) (13) that relates the dielectric value of a material at any air void content to the dielectric of the material at maximum density (zero air void content) to calculate the material maximum density dielectric values using the measured dielectric values and air void contents. For aggregates, this calculates the dielectric value of the rock itself. This calculation was done for the component materials and the three collected asphalt mixtures.

$$\epsilon = \frac{\epsilon_e + \frac{f}{\frac{1}{\epsilon_i - \epsilon_e} + \frac{1-f}{3\epsilon_e}} + \epsilon_i + \frac{1-f}{\frac{1}{\epsilon_e - \epsilon_i} + \frac{f}{3\epsilon_i}}}{2} \quad (6)$$

Where, ϵ = Dielectric of specimen

ϵ_i = Dielectric of air (1.0)

ϵ_e = Dielectric of corresponding material at maximum density

f = Volume fraction of air (% Air void/ 100)

The three measured dielectric values (at 3 orientations 120 degree apart) of each of the component materials were first averaged and used to compute the dielectric of the corresponding materials at maximum density (zero air void content). Table 9 shows the example calculation for the dielectric at maximum density for the NH 4.75 mm washed sand. The dielectric values at maximum density for all component materials of a given asphalt mixture were then used to compute the equivalent mix dielectric at G_{mm} (i.e., composite dielectric of the aggregate) by accounting for the binder content and absorption, the specific gravity and the weight percentage in the blended aggregate of each component (according to mixture design report).

Table 9 Example calculation for the dielectric at maximum density of the NH 4.75 mm washed sand

Parameter	Value
Material mass (M)	3007.7 g
Material bulk specific gravity (G_{sb})	2.634
Volume correction factor for the acrylic container (V_{corr}, provided by GSSI)	0.98877
Material volume (V_m)	1141.87 ml
Cylinder volume (V_c)	1666.4 ml
Air void content ($\%AV = 100*(1 – V_m/(V_c * V_{corr}))$)	30.69%
Averaged measured dielectric value (D_m)	3.224
Corrected averaged measured dielectric value to account for the acrylic cylinder ($D_c = D_m + 0.033*D_m – 0.094$, equation provided by GSSI)	3.236
Material dielectric value at maximum density using Eq 6	5.013

g = gram, ml = milliliter

The equivalent mix dielectric at G_{mm} determined from the component materials are shown in the last row of Table 10 for the CT, ME, and NH mixtures. Table 10 also summarizes the calculation results using Eq 6 for the mix dielectric at G_{mm} using the measured dielectric values of specimens compacted from the three asphalt mixtures produced in the 2022 construction season presented in Table 8.

Table 10 Mix dielectric values at G_{mm} calculated from measured mix dielectric values at various air void contents and equivalent mix dielectric value calculated from component materials

	CT		**ME**		**NH**	
	Mix dielectric values at G_{mm}	**Air void content**	**Mix dielectric values at G_{mm}**	**Air void content**	**Mix dielectric values at G_{mm}**	**Air void content**
	6.338	4.67%	5.462	8.20%	4.904	2.86%
	6.315	5.49%	5.442	8.55%	4.936	6.41%
	6.465	8.79%	5.490	9.84%	4.950	7.00%
	6.544	14.50%	5.456	12.11%	4.975	11.75%
	6.462	15.48%			5.094	11.89%
Average	6.425		5.462		4.972	
Standard deviation	0.096		0.020		0.073	
Range (max – min)	0.229		0.048		0.189	
Coefficient of variation	1.49%		0.37%		1.46%	
Equivalent mix dielectric at G_{mm}	6.162		5.510		4.972	

G_{mm} = Theoretical maximum specific gravity

The second approach calculated equivalent mix dielectric values at G_{mm} from the dielectric value of each component material at maximum density (zero air void content) using the measured dielectric values and densities by accounting for the binder content and absorption, the specific gravity and the weight percentage in the blended aggregate (according to mixture design report) of each component. A mixing model was used to progressively mix the dielectric of each component material using Eq 6. Table 11 shows an example calculation to compute the equivalent mix dielectric values at G_{mm} from the component materials for the NH mixture.

Eq 6 was then again used to calculate the mix dielectric values at specific air void contents for each mixture from the equivalent mix dielectric values at G_{mm}. Table 12 shows an example calculation to calculate mix dielectric values at specific air void contents for the NH mixture and Figure 15 shows the comparison between the calculated and the measured dielectric values along with results of statistical analysis for the three collected mixtures presented in Table 8. The calculated dielectric values for the NH and ME mixtures agree quite well with the measured values, as indicated by the RMSE. However, there are differences (within 5% from the line of equality (LOE)) for the CT mixture between the measured and calculated dielectric values. The reasons for these differences are presently unknown. Differences in gradations and nominal maximum size of mixtures could be potential reasons, however, further evaluation is necessary to test this hypothesis.

Table 11 Example calculation for the NH mixture to compute equivalent mix dielectric values at G_{mm} from the component materials

Mixture binder content (A)					5.6					
Binder specific gravity (B)					1.026					
Binder dielectric (C)					2.8					
Binder volume % Absorption (D)					0.57					
Component material	**Aggregate bulk specific gravity (Gsb) (E)**	**Material dielectric value at maximum density (F)**	**Solid weight percentage (G)**	**Total weight fraction (H)**	**Volume** $(\mathrm{I})_i = \frac{(H)_i}{(\mathrm{E})_i}$	**Fraction of the whole volume** $(\mathrm{J})_i = \frac{(I)_i}{41.35}$	**Fraction of inclusion volume (i.e., f in Eq 6)** $(\mathrm{K})_i = \frac{(\mathrm{J})_i}{\sum_{n=i}^{1}(\mathrm{J})_n}$	**Inclusion dielectric (i.e., ϵ_i in Eq 6) (L)**	**Host dielectric (i.e., ϵ_e in Eq 6) (M)**	**Mixed dielectric (i.e., ϵ in Eq 6) (N)**
4.75 mm Washed sand	2.634	5.013	14.73	13.91	5.28	0.13	0	0	5.013	5.013
4.75 mm Washed manufactured sand	2.731	6.055	21.43	20.23	7.41	0.18	0.58	6.055	5.013	5.605
4.75 mm Dust	2.647	5.558	1.95	1.84	0.69	0.02	0.052	5.558	5.605	5.603
9.5 mm Rock	2.574	5.193	17	16.05	6.23	0.15	0.32	5.193	5.603	5.470
12.5 mm Rock	2.579	5.228	25	23.60	9.15	0.22	0.32	5.228	5.470	5.392
9.5 mm RAP	2.637	5.282	19.89	18.78	7.12	0.17	0.20	5.282	5.392	5.370
Binder				5.6	5.46	0.13	0.13	2.8	5.370	4.960
Total				**100**	**41.35**	**1.00**				
Mix dielectric without binder absorption calculated using Eq 6 (O)										**4.960**

Mix dielectric that accounts for void space occupied by the binder that is calculated using Eq 6 (P) Where, ϵ = Mix dielectric that accounts for void space occupied by the binder ϵ_i = Dielectric of air (1.0) ϵ_e = Mix dielectric without binder absorption f = Binder volume % absorption (% Air void/ 100)	**4.919**
Change in dielectric due to the added void space (Q) = (O) – (P)	0.041
Correction for G_{sb} calculation (R)	-0.030
Mix dielectric with binder absorption (S) = (O) + (Q) + (R) **(i.e., equivalent mix dielectric values at G_{mm})**	**4.972**

i = each component material

Table 12 Example calculation for the NH mixture produced in 2022 construction season for calculation of mix dielectric values at specific air void contents and comparison to measured specimen dielectric

Air void content	**Equivalent mix dielectric value at G_{mm} calculated from component materials (A)**	**Mix dielectric value calculated using Eq 6 (B)**	**Measured specimen dielectric value (C)**	**Percent Difference** $\left(\frac{(B)-(C)}{(B)} \times 100\right)$
2.86%	4.972	4.769	4.705	-1.34%
6.41%		4.530	4.499	-0.70%
7.00%		4.492	4.473	-0.41%
11.75%		4.198	4.200	0.05%
11.89%		4.190	4.280	2.11%

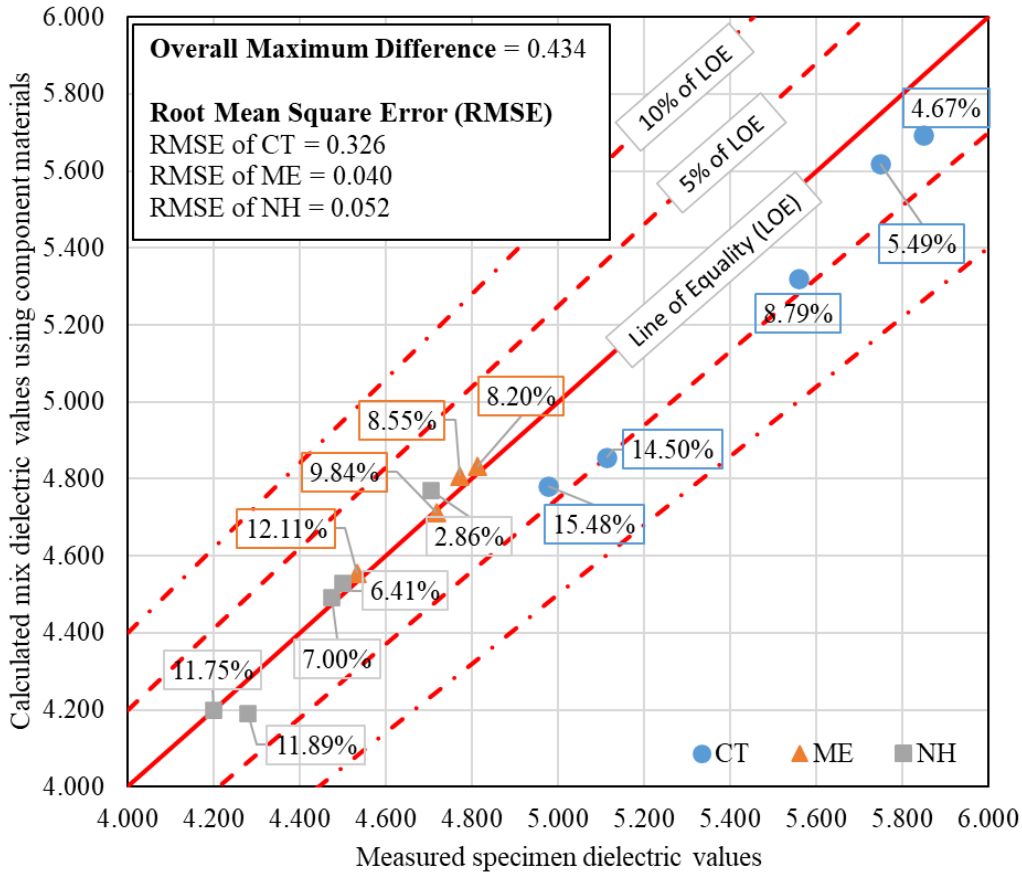


Figure 15: Mix dielectric values calculated from measurements on component materials and the measured specimen dielectric values (Individual specimen air void contents shown in text boxes)

Task 8: Correlation between Asphalt Specimen Dielectric Constant and Bulk Specific Gravity

With the collected dielectric data for the component materials, two analysis approaches were evaluated. The first approach used the Al-Qadi Lahour Leng (ALL) (8) model (Eq 7) to correlate dielectric value and G_{mb}.

$$G_{mb} = \frac{\frac{\epsilon_{AC}-\epsilon_B}{3\epsilon_{AC}-2.3\epsilon_B} - \frac{1-\epsilon_B}{1+2\epsilon_{AC}-2.3\epsilon_B}}{\left(\frac{\epsilon_S-\epsilon_B}{\epsilon_S+2\epsilon_{AC}-2.3\epsilon_B}\right)\left(\frac{1-P_B}{G_{se}}\right) - \left(\frac{1-\epsilon_B}{1+2\epsilon_{AC}-2.3\epsilon_B}\right)\left(\frac{1}{G_{mm}}\right)} \tag{7}$$

Where, ϵ_{AC} = Measured specimen dielectric value

ϵ_B = Dielectric of binder

ϵ_S = Composite dielectric of the aggregate (i.e., equivalent mix dielectric at G_{mm})

P_B = Binder content

G_{se} = Effective Specific Gravity of Aggregate

G_{mm} = Measured theoretical maximum specific gravity of mixture using ASTM D6857

Table 13 shows example calculations to calculate the predicted G_{mb} using the ALL model for the NH mixture. Figure 16 shows the comparison between the measured G_{mb} and the predicted G_{mb} along with statistical measures for the three mixtures presented in Table 8. Figure 16 shows that there are differences between the measured and predicted G_{mb} for all three mixtures at all points and more than the acceptable range of 0.035 of two G_{mb} results (AASHTO T331). The differences between the measured and predicted G_{mb} for the ME and NH mixtures are similar while that for the CT are larger.

Table 13 Example calculation to calculate the predicted Gmb using the ALL model for the NH mixture produced in 2022 construction season

Mixture	NH							
ε_{AC}	**Measured % AV**	**Measured G_{mb}**	**G_{mm}**	**P_b**	**G_{se}**	ε_S	ε_B	**Predicted G_{mb}**
4.700	2.86%	2.380	2.450	5.6	2.67	4.972	2.800	2.498
4.499	6.41%	2.293						2.429
4.473	7.00%	2.278						2.421
4.200	11.75%	2.162						2.335
4.287	11.89%	2.159						2.361

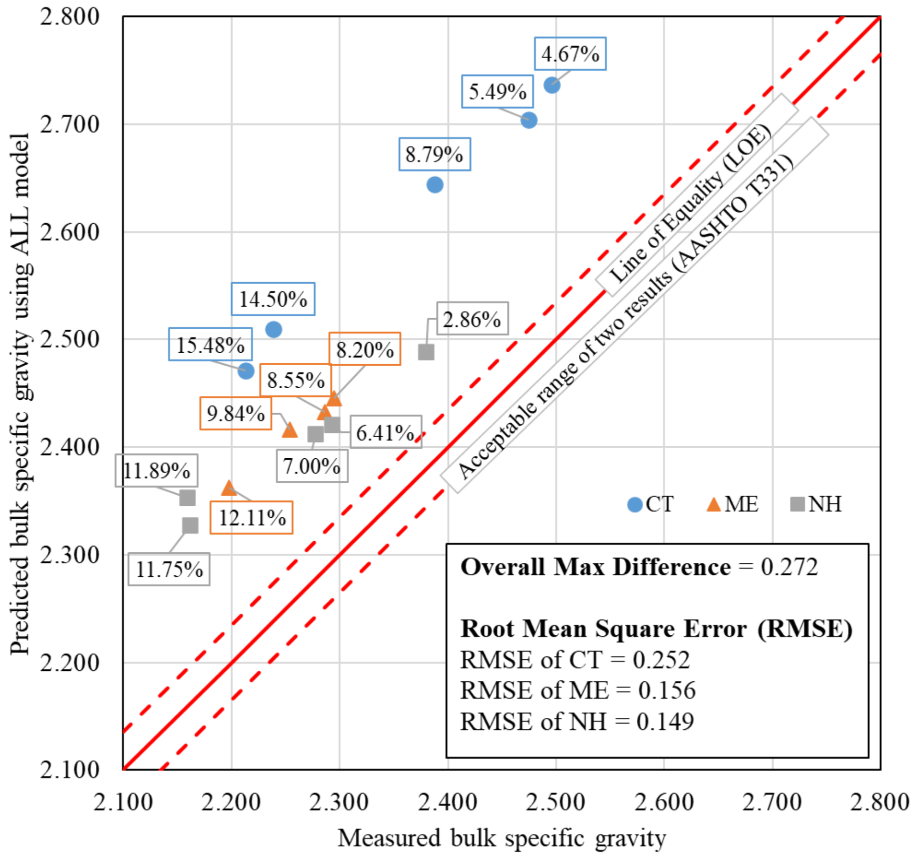


FIGURE 16 Measured G_{mb} and Predicted G_{mb} using ALL model (Individual specimen air void contents shown in data point labels)

The second approach involved using the Hashin-Shtrikman (HS) equation (Eq 6). With known composite dielectric of the aggregate (i.e., equivalent mix dielectric at G_{mm} condition) and the specimen dielectric, Eq 6 was used to back calculate the specimen air void content which was then used in Eq 8 calculate G_{mb}.

$$G_{mb} = G_{mm}(1 - \%AV) \quad (8)$$

Where, G_{mm} = Measured theoretical maximum specific gravity of mixture using ASTM D6857

Table 14 shows example calculations for the NH mixture. Figure 17 shows the comparison between the measured G_{mb} and the predicted G_{mb} along with statistical measures for the three collected mixtures presented in Table 8.

Table 14 Example calculation for the NH mixture produced in 2022 construction season

Mixture	NH					
ε	**ε_e**	**f using Eq 6**	**G_{mm}**	**Predicted G_{mb} using Eq 8**	**Measured G_{mb}**	**Difference**
4.700	4.972	0.0386	2.450	2.355	2.380	0.025
4.499		0.0689		2.281	2.293	0.012
4.473		0.0729		2.271	2.278	0.007
4.200		0.1171		2.163	2.162	0.001
4.287		0.1027		2.198	2.159	0.039

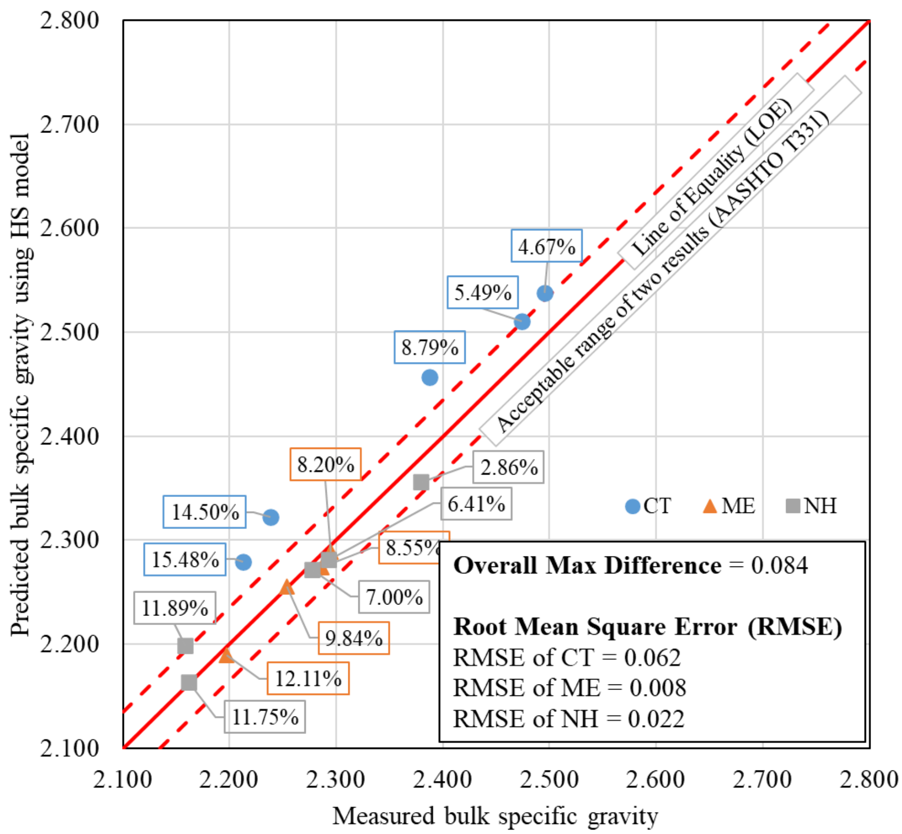


FIGURE 17 Measured G_{mb} and Predicted G_{mb} using HS model (Individual specimen air void contents shown in text boxes)

Figure 17 shows that the measured and predicted G_{mb} for ME and NH mixtures agree quite well, as indicated by the RMSE, and mostly within the acceptable range of 0.035 of two G_{mb} results (AASHTO T331) for all but one point. There appears to be deviation between the measured and predicted G_{mb} for the CT mixture which is consistent with the analysis comparing the mix dielectric computing component materials and the specimen dielectric in Task 7. Generally, it appears that there is higher deviation between the measured and predicted G_{mb} for the specimens at higher air void content than for those at lower air void content. The HS model appears to perform better than the ALL model.

Based on the analyses performed in Task 7 and Task 8, the recommended protocol for determining G_{mb} using the LDMS is as follows:

- Fabricate mixture specimens at air void contents close to the in-production target level and test them using the LDMS.
- Fabricate component material specimen(s) for the corresponding mixture and test them using the LDMS.
- Convert the dielectric of the component materials to the composite dielectric of the aggregate.
- Use the composite dielectric of the aggregate along with specimen dielectric, the Hashin-Shtrikman model and the measured G_{mm} to determine specimen G_{mb}.

The length of time to establish G_{mb} using the LDMS varies depending on the operator's experience, the tested asphalt mixture and its number of component materials. However, once the composite dielectric of the aggregate is determined, the determination of G_{mb} of each mixture specimen should not take more than 8 to 10 minutes.

V. PLANS FOR IMPLEMENTATION

Successful transfer of the LDMS to practice will require effective communication and training on the new test and analysis procedure. One product of the research includes a draft AASHTO specification and procedure based on the results of this project. The draft AASHTO specification includes the procedure for conducting dielectric measurements using the LDMS and the procedure for determining G_{mb} from the measured dielectric value. Web-based/video materials targeted for agency and contractor engineers and technicians were developed to explain the LDMS approach as well as provide detailed testing and measurement procedures. These training materials will alleviate potential impediments to implementation due to lack of familiarity and experience with the LDMS. A simplified tool to calculate G_{mb} of asphalt mixtures using measurements from LDMS (such as an Excel spreadsheet) was developed. The research team will work with partner agencies including those that are participating in the TPF-5(443) pooled fund study to pilot these training materials.

Currently, the UNH research team also is collaborating with the TPF-5(443) pooled fund study in a project called "Density Profiling System (DPS) Pooled Fund Study Data Statistical Analysis and Protocol Recommendations" (MnDOT Contract 1036343 WO5) which reviews and analyzes a substantial amount of field dielectric measurements collected for the TPF-5(443) pooled fund study. One of the outcomes of this project includes establishing a relationship between the laboratory dielectric measurements and field dielectric measurements. The protocol for conducting laboratory dielectric measurements developed in this study is being adapted and used in the pooled fund study.

VI. CONCLUSIONS

This project was undertaken to formalize laboratory dielectric measurement methodology that will yield replicable and accurate results. The dielectric measurements are expected to be used for routine laboratory G_{mb} evaluation of asphalt mixtures during mix design and quality assurance processes. A total of 16 mixtures with a range of aggregate and mixture properties (geology, nominal maximum aggregate size, binder type, RAP content, etc.) were identified for sampling. Data and compacted specimens from the TPF-5(443) pooled fund study were also gathered. All mixtures were used to fabricate test specimens of various geometries and surface conditions (cut versus compacted faces) covering a range of densities. The LDMS was used to evaluate the dielectric constant measurements of asphalt mixtures with a range of aggregate properties and mixture properties, various specimen geometries, and specimen surface conditions. Bulk specific gravities were measured for all tested specimens. The dielectric results were statistically analyzed to evaluate measurement repeatability and variability by grouping measurements at various orientations. A draft AASHTO procedure for conducting the LDMS was developed. Based on the gathered data and statistical analyses performed in this work, it was determined that taking dielectric measurements any 3 orientations 120 degrees apart (3 measurements total) yields repeatable dielectric measurements with acceptable accuracy for use as standard method for G_{mb} determination of compacted asphalt mixture specimen. The length of time to conduct three dielectric measurements should be at most 6 minutes. The protocol for conducting dielectric measurements using the LDMS is summarized and presented in the schematic (Figure 18) below.

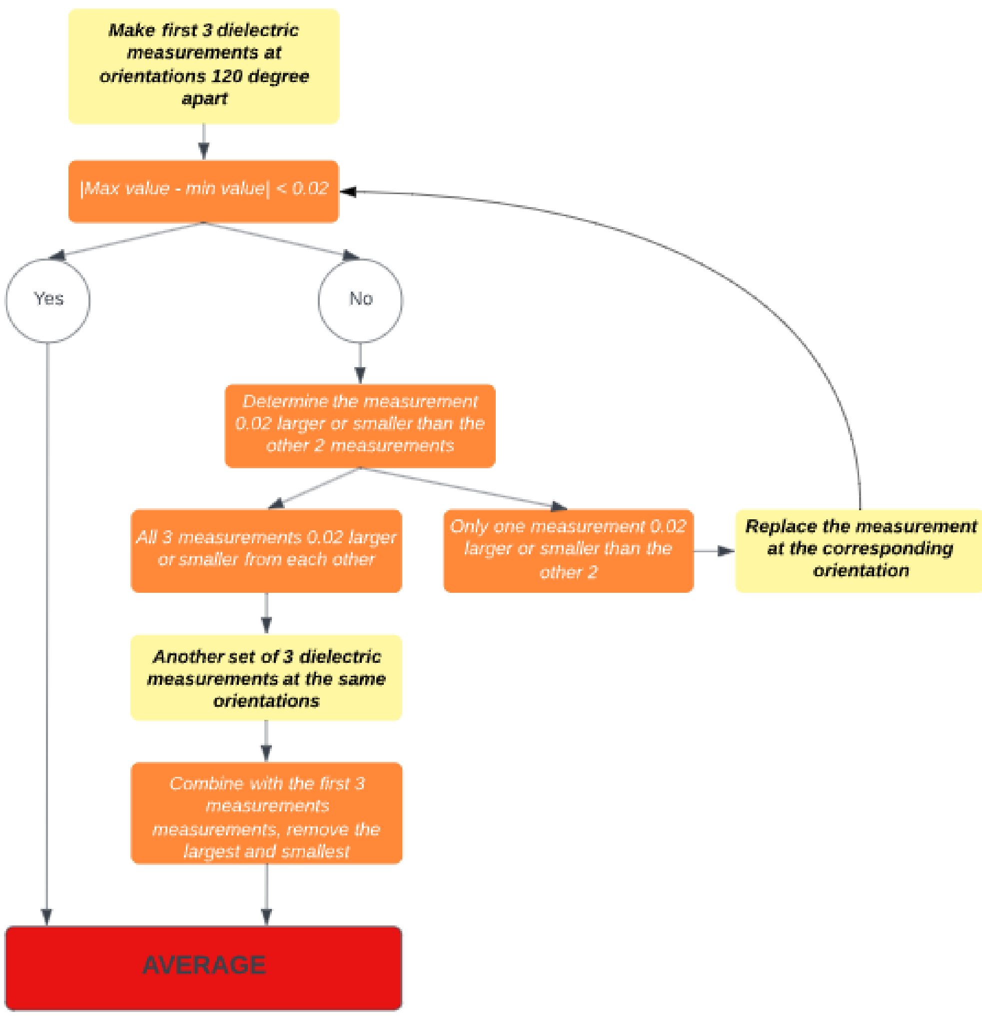


FIGURE 18 The recommended protocol for conducting measurements to achieve representative dielectric constant value

Based on the dielectric measurements collected in this study and the statistical analyses, it can be observed that as the G_{mb} decreases (air void increases), the dielectric values decrease, and dielectric measurement variability increases for a given mixture type. The relationship between G_{mb} and dielectric value is linear for each mixture type with most of the mixtures evaluated in this study having similar slopes. However, the aggregate type/geology has a significant impact on the magnitude of dielectric values from mixture to mixture, with values ranging from 4.5 to 6.5 for specimens in the 4-6% air void content range. While the different surface conditions did not appear to have an effect on the dielectric measurement variability, the dielectric value increased as selected asphalt specimens were cut from compacted faces to both faces cut. A maximum dielectric error of 0.02 between replicate measurements on a specimen was determined to be the acceptable threshold (based on equipment accuracy) and the corresponding acceptable resolution of specimen thickness measurement is 0.25 mm.

A relationship between dielectric value and G_{mb} was established with the goal of replacing traditional AASHTO procedures for measuring laboratory G_{mb} measurements with laboratory dielectric measurements. Two analysis approaches were evaluated.

The first analysis approach used the mixture properties (binder content, the G_{mm} and G_{se} of the mix). and the collected dielectric results for the component materials (aggregates, reclaimed asphalt pavement (RAP), and asphalt binder) and the specimens with the HS model (Eq 6) and the ALL model (Eq 7). Analysis results showed that there is a good agreement between the dielectric value of the mixture predicted from the component materials and the corresponding measured value from the asphalt mixtures for two of the three mixtures evaluated. There is a linear trend between the measured and predicted G_{mb} using the ALL model. However, there are differences between the measured and predicted G_{mb} such that the differences are larger than the acceptable range of 0.035 of two G_{mb} results (AASHTO T331).

The second analysis approach used the collected dielectric results for the component materials and the specimens with just the HS model (Eq 6). Analysis results showed that there is good agreement between the measured and predicted G_{mb} such that the differences are within the acceptable range of 0.035 of two G_{mb} results (AASHTO T331). The length of time to establish G_{mb} using the LDMS depends on the operator's experience, the tested asphalt mixture and its number of component materials. However, once the composite dielectric of the aggregate is determined, the determination of G_{mb} of each mixture specimen should not take more than 8 to 10 minutes. The protocol for determining G_{mb} using the LDMS is summarized and presented in the schematic (Figure 19) below.

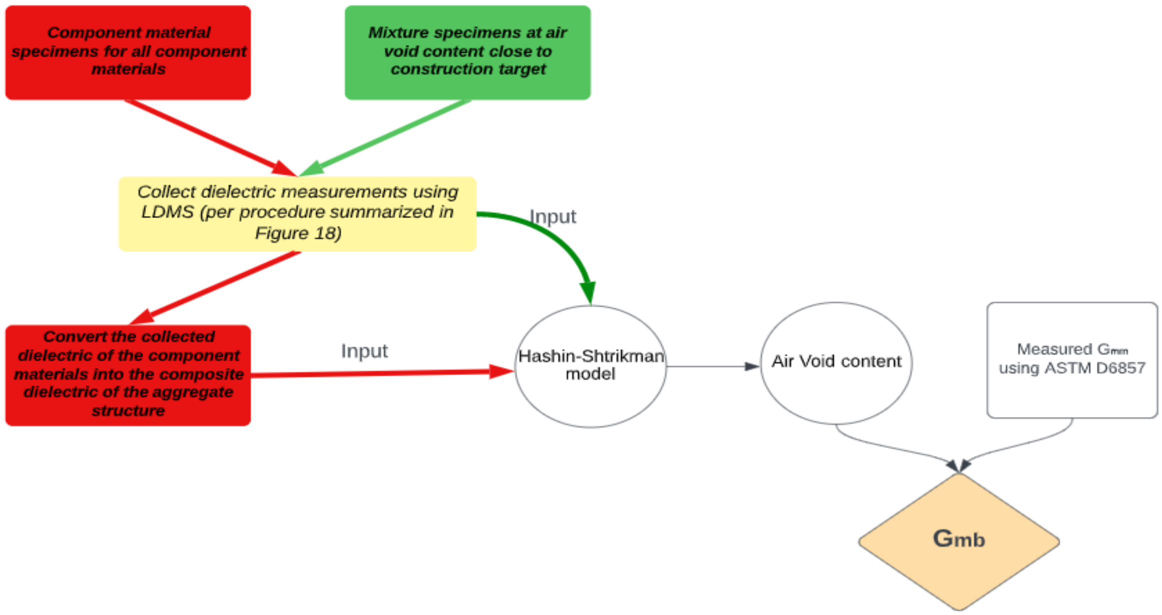


FIGURE 19 The recommended protocol for determining G_{mb} using the LDMS

A draft AASHTO specification and procedure based on the results of this project has been developed. Web-based/video materials targeted to explain the LDMS approach as well as provide detailed testing and measurement procedures and a simplified tool (Excel based) to calculate G_{mb} of asphalt mixtures using measurements from LDMS were developed. The research team will work with partner agencies including those that are participating in the TPF-5(443) pooled fund study to pilot these training materials. The UNH research team also is collaborating with the TPF-5(443) pooled fund study in a project called "Density Profiling System (DPS) Pooled Fund Study Data Statistical Analysis and Protocol Recommendations" (MnDOT Contract 1036343 WO5) which reviews and analyzes a substantial amount of field dielectric measurements collected for the TPF-5(443) pooled fund study. One of the outcomes of this project includes establishing a relationship between the laboratory dielectric measurements and field dielectric measurements. The protocol for conducting laboratory dielectric measurements developed in this study is being adapted and used in the pooled fund study.

FUTURE WORK

The current proposed procedure (using the Hashin-Shtrikman model) to determine G_{mb} requires the fabrication of specimens of component materials for a given mixture. There are several potential shortcomings of this procedure. Specimens of component materials requires compacting as much material as possible into an acrylic mold wrapped in aluminum foil. Component materials, especially RAP, that are produced in construction plant may not be completely identical to the materials used to produce a mixture. The analysis in Task 7 showed that the conversion process worked for two out of three analyzed mixtures. The process of compacting specimens of the component materials and the conversion process requires multiple steps, material properties and measurements which may cause error in accuracy depending on the experience of the operator/ analyst. To alleviate these shortcomings, the conversion process from the measured dielectric of the component materials for a given mixture to the composite dielectric of the aggregate structure for the corresponding mixture may need adjustments for better accuracy.

Mix dielectric at G_{mm} calculated from measured specimen dielectric may also be explored in future work to replace the composite dielectric of the aggregate as one of the inputs for determining G_{mb} of specimens. In Task 7, mix dielectric values at G_{mm} calculated from measured specimen dielectric values at various air void contents were variable for a given mixture type. Sensitivity analysis will need to be performed to determine the reliability of the predicted G_{mb} measurement using mix dielectric at G_{mm} as the input, instead of the composite dielectric of the aggregate structure.

The ALL model that incorporates the mixture properties along with dielectric to determine G_{mb} needs refinement. The analysis result in Task 8 showed that there are more errors in the predicted G_{mb} when the ALL model was used compared to when the HS model was used. Machine learning methods such as SVEM, as opposed to mechanical model such as the HS model or mixing model such as the ALL model, may also be explored to improve predictability of G_{mb}.

The contribution of the component materials, especially RAP, to the dielectric of an asphalt specimen at a given air void content also needs further investigated in future work. Similar mixture that is produced with and without RAP may be obtained to explore the effect of RAP on the dielectric and resulting G_{mb} result. Conducting dielectric measurements to determine density of other types of asphalt mixtures such as those with steel slag or pervious mixtures may also be explored in future work.

Due to recent developments of DPS technology, surface reflection method which is used to collect field dielectric measurements needs to be evaluated for possible adaptation for use in conducting laboratory dielectric measurements.

VII. INVESTIGATORS' PROFILES

Dr. Jo E. Sias – Principal Investigator

Dr. Sias obtained her Masters and Ph.D. degrees from North Carolina State University in Civil Engineering in 1996 and 2001 respectively. At present, she is a Professor in the Department of Civil and Environmental Engineering at UNH and directs the UNH Center for Infrastructure Resilience to Climate. Dr. Sias's research work has focused on characterization of asphalt mixtures in the laboratory, particularly with respect to cracking performance. She has led over 30 regional and national research studies and authored over 75 journal articles on topics related to asphalt mixtures and pavements. Dr. Sias has held leadership positions in several national and international professional organizations. She is an associate editor for the international journal Road Materials and Pavements Design (RMPD) and currently serves on the Board of Directors for the Association of Asphalt Paving Technologists (AAPT). She is member of the flexible pavement working group for the National Road Research Alliance (NRRA) and the Federal Highway Administration (FHWA) Asphalt Pavement and Materials Technical Feedback Group (TFG).

Dr. Eshan V. Dave – Co-Principal Investigator

Dr. Dave obtained his Masters and Ph.D. degrees from University of Illinois at Urbana-Champaign in Civil Engineering in 2003 and 2009 respectively. At present, he is an Associate Professor in the Department of Civil and Environmental Engineering at UNH. Prior to this, he was assistant and associate professor of civil engineering at the University of Minnesota Duluth from 2010 to 2015. Dr. Dave's research interests include performance evaluation of pavements, testing and modeling of pavement materials, and effects of climatic events on pavement longevity. He was principal investigator for a National Road Research Alliance pooled fund study assessing evolution of density of asphalt mixtures at MnROAD using the DPS technique. He has led over 20 regional and national research studies. Dr. Dave is active member and holds leadership positions at several national and international research committees and organizations, such as, ASTM International, International Society of Asphalt Pavements (ISAP), International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) and the Transportation Research Board (TRB). He is member of the pavement maintenance and preservation working group for the National Road Research Alliance and part of the expert task group for the FHWA's Long Term Infrastructure Performance (LTIP) program.

VIII. GLOSSARY AND REFERENCES

GLOSSARY

Archimedes' principle. A principle that describes the upward buoyant force exerting on a body immersed in a fluid. The buoyant force equals to the weight of the fluid that the body displaces.

Bottom Range. the maximum value minus the minimum value for 80 measurements taken with the bottom face oriented up (top face near the antenna).

Coefficient of variation (COV). The ratio of the standard deviation to the mean.

Dielectric measurement combination. Any combination of one/two/three/four measurement(s) at each orientation.

Dielectric error. The absolute difference of the average of each dielectric measurement combination and the grand average.

Equivalent mix dielectric at G_{mm}. The mix dielectric values computed from the component materials or the composite dielectric of the aggregate(s).

Grand average (AVE). Average of all 160 measurements for each specimen.

Grand standard deviation (STD). Standard deviation of 160 measurements for each specimen.

Material dielectric at maximum density. The dielectric of the individual component material at zero percent air void. It is computed from the measured dielectric of the corresponding individual component material by using the Hashin-Shtrikman equation.

Max dielectric error. The maximum of all dielectric errors for a given specimen.

Max individual orientation range. The range (max – min) of the five replicate measurements at each orientation was calculated and the maximum value determined for the whole specimen (this value represents maximum deviation that can be observed for a specimen that is tested in repetitive manner as same orientation).

Mix dielectric values at G_{mm}. The measured dielectric of the asphalt specimen at a given air void content is used to compute mix dielectric value G_{mm} for the corresponding asphalt specimen.

Normalized max dielectric error. The ratio of max dielectric error to the grand standard deviation for a given specimen.

Orientation. The arbitrary angles/ degrees where dielectric measurements are collected. These are marked on an asphalt specimen. A reference point is marked on the test equipment where the orientation mark is lined up to.

Overall range. The maximum value minus the minimum value for all 160 measurements from each specimen, regardless of orientation or face.

Top Range. the maximum value minus the minimum value for 80 measurements taken with the top face oriented up (bottom face near the antenna)

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IX. APPENDIX: RESEARCH RESULTS

SIDEBAR INFO

Program Steering Committee: NCHRP IDEA Program Committee

Month and Year: December 2022

Title: Lab Dielectric Measurement System (LDMS) for Asphalt Mixture Bulk Specific Gravity Determination

Project Number:

Start Date: January, 01st, 2021

Completion Date: December, 31st, 2022

Product Category: New or improved tool and procedure

Principal Investigator:

Jo E. Sias

Professor and Graduate Coordinator

Past President, Association of Asphalt Paving Technologists

Director, UNH Center for Infrastructure Resilience to Climate

Department of Civil and Environmental Engineering

Email: jo.sias@unh.edu

Phone: 603-862-3277

WHAT WAS THE NEED?

Bulk specific gravity (G_{mb}) is routinely measured during mixture design and quality assurance processes to ensure adequate and uniform density in asphalt pavements. The traditional procedures, AASHTO (American Association of State Highway and Transportation Officials) T 166 and AASHTO T 331, used to measure G_{mb} require not only high level of operator experience needed for consistent SSD measurements, but also multiple pieces of laboratory equipment and can have substantial measurement error with some types of asphalt mixtures. To alleviate these challenges this project explores a laboratory dielectric measurement system (LDMS) for determining the G_{mb} of compacted asphalt specimens as an alternative and more efficient approach to the traditional test procedures.

WHAT WAS OUR GOAL?

The goal was to replace traditional AASHTO procedures for measuring laboratory G_{mb} measurements with laboratory dielectric measurements so that the efficiency and accuracy of laboratory G_{mb} measurements increase.

WHAT DID WE DO?

Stage 1 of the project focused on developing a repeatable and reliable testing procedure using the LDMS to ensure that the relationship between G_{mb} and dielectric measurements is established accurately. Asphalt mixtures with a range of aggregate and mixture properties (geology, nominal maximum aggregate size, binder type, RAP content, etc.) were collected. Compacted asphalt specimens of various specimen surface conditions and sizes were tested using the LDMS. The collected dielectric results were statistically analyzed to study dielectric measurement repeatability and reliability by grouping measurements at various orientations together and comparing them to all measurements of the corresponding asphalt specimen. Sensitivity analysis was also performed to study measurement accuracy and resolution for replicate dielectric measurements.

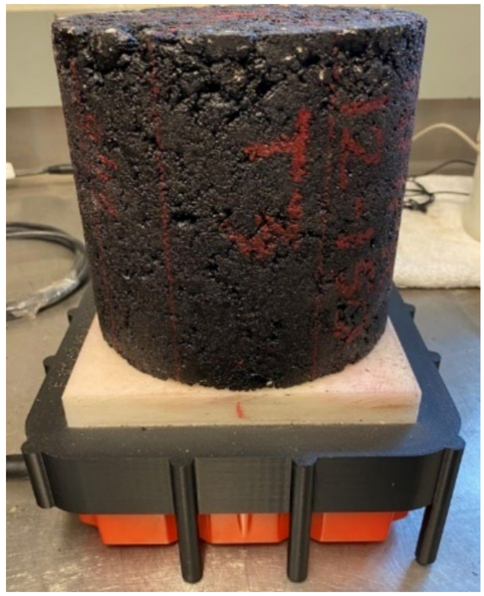


Photo of the LDMS setup showing a gyratory compacted asphalt specimen

In Stage 2 of the project, a procedure for calculating G_{mb} from measured dielectric values was established with the goal of replacing traditional AASHTO procedures for measuring laboratory G_{mb} measurements with laboratory dielectric measurements. Component materials (aggregates and reclaimed asphalt pavement (RAP)) for the selected number of asphalt mixtures from Stage 1 were tested using the LDMS. The collected data were used to refine the testing and analysis procedures for component materials and to develop the procedure for determining G_{mb}.

WHAT WAS THE OUTCOME?

In Stage 1 of the project, a draft AASHTO procedure for conducting the LDMS was developed. Based on the gathered data and statistical analyses performed in this work, it was determined that taking dielectric measurements any 3 orientations 120 degrees apart (3 measurements total) yields repeatable dielectric measurements with acceptable accuracy for use as standard method for G_{mb} determination of compacted asphalt mixture specimen. In Stage 2 of the project, the procedure for determining G_{mb} from laboratory-measured dielectric values was developed using a combination of existing equations and models.

WHAT IS THE BENEFIT?

The proposed LDMS will enable quick and repeatable G_{mb} measurements. The system is minimally dependent on operator experience and it is very portable, unlike the specific gravity measurement equipment that is currently in use.

LEARN MORE

X. APPENDIX: MIXTURE DESIGN REPORT FOR THE NEW HAMPSHIRE MIXTURE

S34-22P
12.5 mm 75 gyr
TRB 0.96
Washed Gradation

Pike Industries Inc
Region 1
Materials Division

Plant: 722 **Description:** 75 gyr 12.5 mm **State:** NH *Date:* 02/09/22
Location: Portsmouth, NH **Mix Code:** 124 **Type:** Surface **Item:** 0
Design Type: SP **Nominal Max Size:** 1/2" 12.5 mm

Agg Source	Madbury	Hooksett	Hooksett	Portsmouth	Eliot	Eliot	0	0	0	Portsmouth	0		
Agg Type	WS	WMS	Dust	BHF	9.5	12.5	19	25.0	37.5	RAP	0	Total	Aim
37.5 (1 1/2")	100	100	100	100	100	100	0	0	0	100	0	100.0	100.0
25 (1")	100	100	100	100	100	100	0	0	0	100	0	100.0	100.0
19 (3/4")	100	100	100	100	100	100	0	0	0	100	0	100.0	100.0
12.5 (1/2")	100	100	100	100	100	98	0	0	0	100	0	99.5	99.5
9.5 (3/8")	100	100	100	100	99	57	0	0	0	98	0	88.8	88.8
4.75 (# 4)	98	96	96	100	31	8	0	0	0	72	0	59.0	59.0
2.36 (#8)	81	73	75	100	8	4	0	0	0	54	0	42.6	42.6
1.18 (#16)	65	52	55	100	5	3	0	0	0	43	0	32.6	32.6
0.6 (#30)	50	34	41	100	4	2	0	0	0	32	0	23.9	23.9
0.3 (#50)	29	23	29	99	3	2	0	0	0	22	0	15.8	15.8
0.15 (#100)	8.7	11.7	21.0	97.0	2	2	0	0	0	13	0	8.5	8.5
0.075 (#200)	2.2	5.9	14.1	86	2.1	1.6	0.0	0.0	0.0	8.5	0.0	4.98	5.0
Agg. Designation	1	2	3	4	1	1		0		1		Total AC:	5.60
Fines Factor 0.0									Rap AC	4.80	0.00	% Virgin AC:	4.64
% Aggregate	14.73	21.43	1.95	0.86	17.0	25.0		0.0		19.0	0.0	TRB:	0.96
Sand Ratio	37.8	55.0	5.0	2.2					% Rap	20.0	0.0	BRV:	0.17
Fine Angularity	45.9	52.8	51.2	47.2								50.0	
Agg Bulk SpG	2.634	2.731	2.647	2.581	2.574	2.579	2.598		2.900	2.637		2.631	
Agg Apparent SpG	2.665	2.765	2.737		2.665	2.669	2.667		2.929	2.744			

Mixture Summary Report for Varying %AC Analysis

Project Name:	12.5 mm 75 gyr trb 0.96	**N Initial:**	7
Workbook Name:	S34-22P NDes 12.5mm 75 Gyr.)	**N Design:**	75
Technician:	SMP	**N Max:**	75
Date:	1/14/22	**Nom. Sieve Size:**	12.5 mm
Asphalt Grade:	PG 64-28	**Compaction Temperature:**	142-146
		Mixture Temperature:	153-159
Design ESAL's (millions):	.3	**Depth from Surface (mm):**	30 mm
Design Temperature:	°C	**Mold Size:**	150 mm

Property	Results: Blend 1	5.6% PGAB	Blend 3	Blend 4	Criteria
%AC		5.6			
%Air Voids (V_a)		3.8			4.0 %
%VMA		15.5			14.0 % Min.
%VFA		75.2			65.0 % Min. 78.0 % Max.
Dust/Asphalt Ratio		1.0			0.6 - 1.2 %
Max. Specific Gravity (G_{mm})		2.450			
Bulk Specific Gravity (G_{mb})		2.356			
%G_{mm} @ N_{ini}		88.8			90.5 % Max.
%Gmm @ Ndes		96.2			96.0 % Max.
Effective Sp. Gravity of Blend (G_{se})		2.670			---
Sp. Gravity of Binder (G_b)		1.026			---
Sp. Gravity of Aggregate (Gs_b)		2.631			---

Standard Specification for

Measurement of Dielectric Constant of Compacted Asphalt Mixtures using Laboratory Dielectric Measurement System (LDMS)

AASHTO Designation: M xxx-yy[1]

Technical Subcommittee: No., Name

Release: Group n (Month yyyy)

AASHTO

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

Standard Specification for

Measurement of Dielectric Constant of Compacted Asphalt Mixtures using Laboratory Dielectric Measurement System (LDMS)

AASHTO Designation: M xxx-yy

AASHTO

Technical Subcommittee: No., Name [with line break if needed to keep space around logo]

Release: Group n (Month yyyy)

1. SCOPE

1.1. This method covers the procedure for conducting laboratory dielectric measurement of compacted asphalt mixtures using the Laboratory Dielectric Measurement System (LDMS).

1.2. The values stated in SI units are to be regarded as the standard.

2. REFERENCED STANDARDS

2.1. *AASHTO Standards*:

- T 312, Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor

2.2. *ASTM Standards*:

- D3549/D3549M, Standard Test Method for Thickness or Height of Compacted Asphalt Mixture Specimens
- D8, Standard Terminology Relating to Materials for Roads and Pavements

3. TERMINOLOGY

3.1. *Definitions:*

3.1.1. Dielectric constant – the speed at which electromagnetic waves travel through a particular medium.

3.1.2. Orientations – Angle measured along the tangential direction of a cylindrical specimen with respect to the plane formed by axial and radial directions.

4. TEST SPECIMENS

4.1. Test specimens may be laboratory-compacted dense graded asphalt mixtures or cores obtained from field compacted dense graded asphalt mixtures. Cores shall be taken from pavements with a core drill, diamond or carborundum saw, or by other suitable means.

4.2. Size of Specimens – (1) specimens must be cylindrical with a diameter of 150 mm; and (2) the thickness of specimens be minimum of 100 mm or minimum of 1.5 times the maximum aggregate size.

4.3. Care shall be taken to avoid distortion, bending, excessive creep or cracking of specimens during and after the removal from the mold. Specimens shall be stored in a safe, cool place.

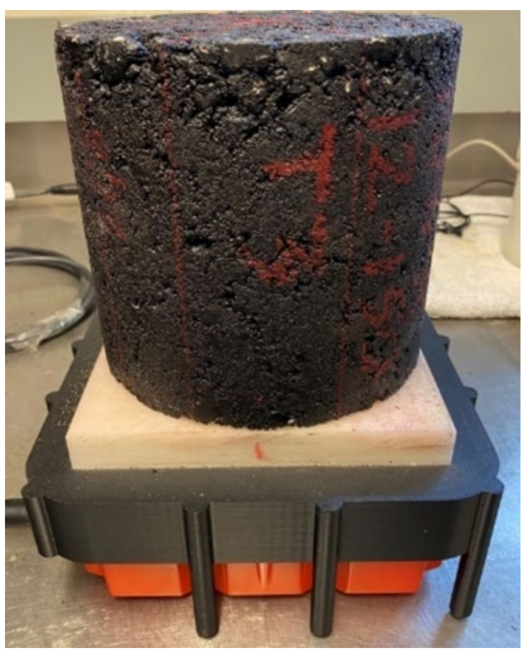
4.4. Specimens shall be free from foreign materials such as seal coat, tack coat, foundation material, soil, paper, or foil.

4.5. If desired, specimens may be cut by sawing or other suitable means. Care should be exercised to ensure sawing does not damage the specimens.

5. APPARATUS

5.1. Laboratory dielectric measurement system – a system that measures the dielectric constant of pavement materials using ground penetrating radar (GPR) technology. The LDMS consists of a miniaturized GPR source and receiver. The LDMS runs on a frequency of 1-3 GHz. The LDMS also consists of a metal plate used for providing boundary conditions for conducting the measurement.

Figure 1— Photo of the LDMS setup showing a gyratory compacted asphalt specimen



6. PROCEDURE FOR CONDUCTING LABORATORY DIELECTRIC MEASUREMENT

6.1. *Thickness of Specimens*—The procedure for determining the thickness or height of test specimens shall follow ASTM D3549/D3549M. A max dielectric error threshold of 0.02 corresponds to a resolution of 0.25 mm for specimen thickness measurements.

6.2. Measurements shall be taken at each of any three orientations 120 degrees apart (three measurements total). The first orientation can be randomly chosen by the operator.

6.2.1. If the range of a set of three measurements (maximum value – minimum value) is less than 0.02, the three measurements shall be averaged to obtain the representative dielectric measurement of the test specimen.

6.2.2. If the range of a set of three measurements (maximum value – minimum value) is more than 0.02, determine the measurement that is 0.02 outside the measurements at the other two orientations and replace that measurement with a new measurement at the same orientation.

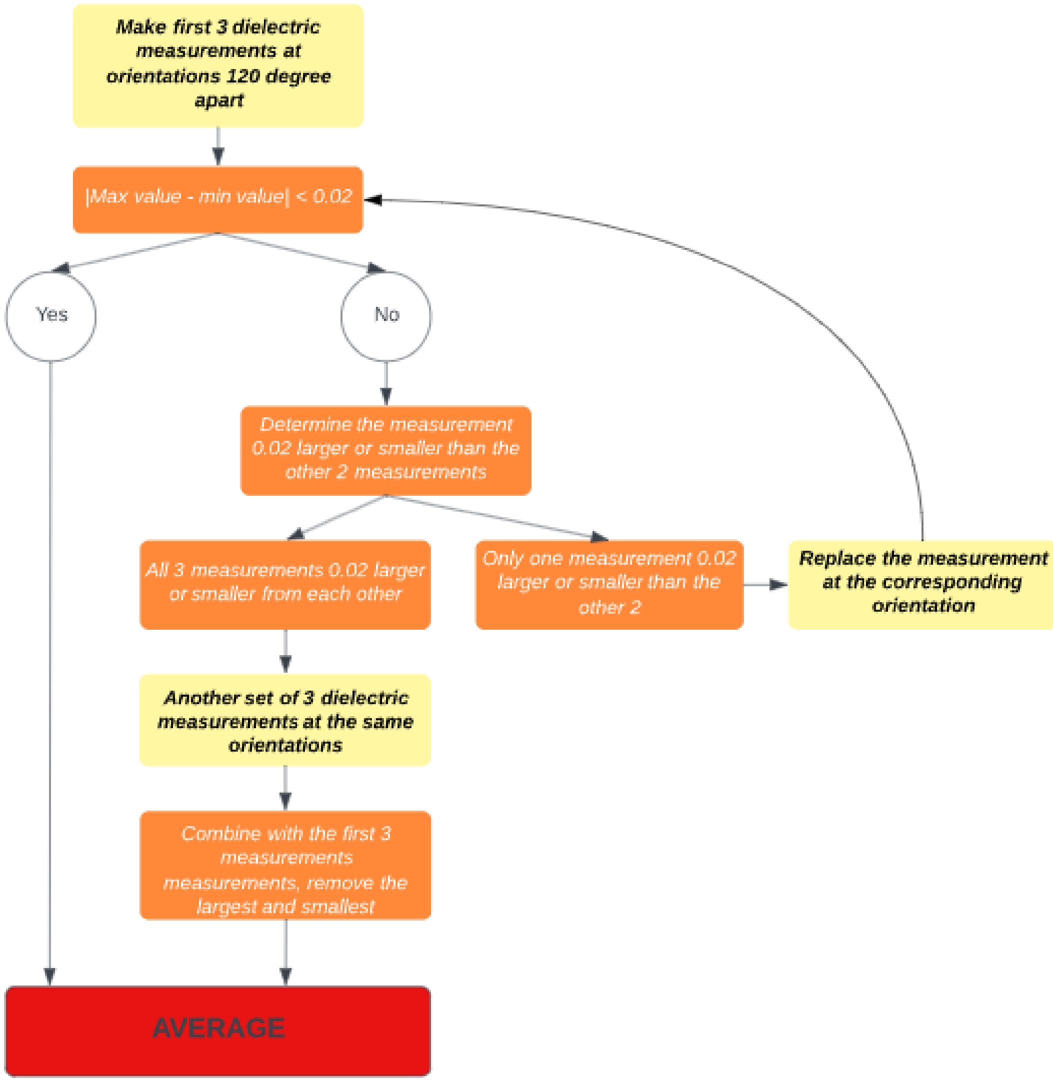
6.2.2.1. If the range of the two original measurements and the replacement measurement (maximum value – minimum value) is less than 0.02, the three measurements shall be averaged to obtain the representative dielectric measurement of the test specimen.

6.2.2.2. If the range of the two original measurements and the replace measurement (maximum value – minimum value) is still more than 0.02, it is recommended that a second set of measurements be conducted at the same three orientations. Of the six measurements, the largest and smallest values are to be removed (trimmed average) and average of the remaining four measurements are to be used as the representative dielectric value of the whole specimen.

6.2.3. If each of the three original measurements are different by more than 0.02, it is recommended that a second set of measurements be conducted at the same three orientations. Of the 6 measurements, the largest and smallest values are to be removed (trimmed average) and average of the remaining four measurements are to be used as the representative dielectric value of the whole specimen.

6.3. The procedure for conducting dielectric measurements using the LDMS is summarized in Figure 2.

Figure 2— Schematic for conducting dielectric measurements


Make first 3 dielectric measurements at orientations 120 degree apart
|Max value - min value| < 0.02
Yes
No
Determine the measurement 0.02 larger or smaller than the other 2 measurements
All 3 measurements 0.02 larger or smaller from each other
Only one measurement 0.02 larger or smaller than the other 2
Replace the measurement at the corresponding orientation
Another set of 3 dielectric measurements at the same orientations
Combine with the first 3 measurements measurements, remove the largest and smallest
AVERAGE