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**The Surface Reflectivity of Common
Construction Materials Measured in the
W-Band (75-110 GHz)**

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LIST OF ACRONYMS

711 HPW/RHDR	Air Force Research Laboratory, 711th Human Performance Wing, Airman Systems Directorate, Bioeffects Division, Radio Frequency Bioeffects Branch
ACI	American Concrete Institute
ADT	Active Denial Technology
ASTM	American Society for Testing and Materials
GDIT	General Dynamics Information Technology
GRL	Gated-Reflect-Line
HERTF	High Energy Research and Technology Facility
IDA	Institute for Defense Analysis
MUT	Material Under Test
RF	Radiofrequency
SPG	Surface Profile Gage
SSPC	Society for Protective Coatings
TRL	Thru-Reflect-Line
TSRL	Tri-Service Research Laboratory
TxDOT	Texas Department of Transportation
USG	United States Gypsum
VNA	Vector Network Analyzer
w/c	Water To Cement Ratio

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EXECUTIVE SUMMARY

For Active Denial Technologies, the reflectivity of a surface can be a significant factor in the amount of energy that is incident on a target and its surroundings. To improve the Active Denial Technology End-to-End Model, better surface reflectivity models need to be developed. To accomplish this goal, the surface reflectivity of common surfaces must be measured. This document describes the measurement of the relative complex permittivity for common construction materials in the W-band (75-110 GHz). These measurements are performed in free-space with a network analyzer. The results are compiled into a set of permittivities at 95 GHz and translated into reflectivity coefficients as a function of incident angle. The materials measured include acrylic, gypsum drywall, plywood, cement and clay bricks, glass, sand, concrete, and asphalt.

1.0 INTRODUCTION

Active Denial Technology (ADT) systems emit electromagnetic energy at 95 GHz. Depending upon the emission profile and the position of the target, the energy may reflect off of surrounding surfaces. These reflections can have non-negligible contributions to the energy incident on the target and surrounding objects. Measuring and understanding the surface reflectivity properties of common materials will provide data to improve the ADT End-to-End Model. This report presents measurements of the dielectric properties for a variety of common materials in the W-band (75 to 110 GHz). These measurements are used to derive surface reflectivity values.

2.0 METHODS

In this study, the surface reflectivity values are derived from the dielectric properties of the material under test (MUT). To measure the dielectric properties, a free-space method with a network analyzer is used. The analyzer acts as both a radiofrequency (RF) source and receiver that measures the transmission and reflection of the RF signals, the scattering parameters (S-parameters), in both magnitude and phase. These S-parameters are closely related to the dielectric values and require a model to translate from the S-parameters into dielectric values, or relative complex permittivities. For these measurements, the models built into the network analyzer are used and the materials are assumed to have a complex permeability equal to the complex permeability of free-space.

From the permittivity values, the Fresnel equations are used to determine the reflection coefficients,

$$R_s = \frac{\cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}} \quad (1a)$$

$$R_p = \frac{\epsilon_r \cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\epsilon_r \cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}, \quad (1b)$$

where R_s and R_p are the Fresnel's reflection coefficients for an electromagnetic wave incident at an angle θ ($\theta = 0^\circ$ at normal incidence) with the interface between air and a dielectric medium with a relative complex permittivity ϵ_r and a complex permeability that is approximately equivalent to the permeability of free space μ_0 . The coefficients R_s and R_p represent the case when the electric field is normal or parallel with the incident plane, respectively. This is convenient because the polarization of the incident field can be broken down into a linear combination of the two orthogonal polarization states.

The permittivity and power reflection coefficients ($|R_s|^2$ and $|R_p|^2$) are reported for the following materials: acrylic, drywall, plywood, clay brick, cinder block (cement brick), asphalt, concrete, sand, and glass. Details about the selection and physical properties of these materials are found in Appendix A, and the details about the network analyzer setup for the different materials are found in Appendix B.

3.0 RESULTS

The network analyzer's built-in model, Transmission Epsilon Fast Model in the Agilent 85071 Software, was used to calculate the relative complex permittivities from the S-parameters. The relative complex permittivity values are shown for each measured sample in Appendix C. For each measured material sample, both real ϵ'_r and imaginary ϵ''_r parts of the relative complex permittivity are shown. Questionable permittivity values include:

- The clay brick measurement RedBrick1_5512_p1. This measurement was an outlier with respect to the other clay brick measurements. A re-measurement of RedBrick1 reported permittivity values consistent with the values shown in Figure C-25 (excluding the outlier).
- The measurements of the concrete samples exhibited weak transmission measurements. This effect is seen in the permittivity values, which include the transmission measurements in their calculation. In particular, Conc1-2, Conc3-1, and Conc5-2 measurements are questionable and have been noted for low transmission results and shown in Figs. C-10, C-13, and C-9, respectively.

Permittivity measurements for each material type have been collated. The results at 95 GHz are presented in Table 1, where the mean real $\bar{\epsilon}'_r$ and imaginary $\bar{\epsilon}''_r$ parts of the relative complex permittivity values are shown with the mean magnitude of the relative complex permittivity $|\bar{\epsilon}_r|$, the standard error of the mean magnitude, and the mean power reflection coefficients at normal incidence. These calculations exclude the questionable permittivity values mentioned above.

The power reflectivity coefficients for each material type at 95 GHz are shown in Appendix D, where the Fresnel reflection coefficients, Equation 1, have been calculated with the measured permittivity values. The questionable measurements have been excluded from the calculations.

As a simple example on how one could use the reflectivity coefficients, let's consider a wave that is incident on a clay brick paver. This wave has an incident irradiance I_i and is incident at an angle θ_i , where normal incidence is $\theta_i=0$. The angle γ_i is the angle between the $\mathbf{E}$ vector of the incident wave and the incident plane. Following Born and Wolf, 1999, the cross-sectional areas of the incident and reflected beams are equal, and the relative amount of reflected irradiance $\mathbf{R} = I_r/I_i = |R_p|^2 \cos^2 \gamma_i + |R_s|^2 \sin^2 \gamma_i$, where I_r is the reflected irradiance.

Table 1. Relative Complex Permittivities at 95 GHz

Material	$\bar{\epsilon}_r'$	$\bar{\epsilon}_r''$	$ \bar{\epsilon}_r $	$SE_{ \bar{\epsilon}_r }$	$ R_{s,\theta=0} ^2, R_{p,\theta=0} ^2$
Acrylic	2.60	0.022	2.60	8E-5	0.055
Drywall	2.17	0.040	2.17	0.003	0.037
Birch Plywood	1.79	0.138	1.80	0.018	0.022
Maple Plywood	1.71	0.113	1.71	0.007	0.018
Clay Brick	4.52	0.080	4.52	0.006	0.130
Cinderblock	5.44	0.682	5.48	0.016	0.162
Asphalt (B)	7.43	0.273	7.43	0.083	0.214
Asphalt (C)	7.09	0.228	7.09	0.076	0.206
Asphalt (D)	7.17	0.296	7.18	0.105	0.208
Concrete (w/c=0.30)	8.20	0.714	8.23	0.012	0.234
Concrete (w/c=0.35)	5.89	0.599	5.92	0.003	0.175
Concrete (w/c=0.40)	8.00	0.699	8.03	0.028	0.229
Concrete (w/c=0.50)	7.53	0.647	7.56	0.086	0.218
Concrete (w/c=0.60)	7.51	0.761	7.55	0.011	0.218
Quikrete Fine	2.43	0.011	2.43	0.006	0.048
Quikrete Medium	2.72	0.048	2.72	0.008	0.060
Sand Express	2.80	0.063	2.80	0.007	0.063
Glass	6.67	0.213	6.68	0.002	0.195

The mean relative complex permittivities at 95 GHz for each material type is presented, where $\bar{\epsilon}_r'$ and $\bar{\epsilon}_r''$ the real and imaginary parts, respectively. The means of the permittivity magnitudes $|\bar{\epsilon}_r|$ and the corresponding standard errors $SE_{|\bar{\epsilon}_r|}$ and mean power reflection coefficients $|R_s|^2, |R_p|^2$ at normal incidence are shown, too. The means are calculated with the inputs from each measurement of a given material type. Poor measurements have been excluded from the tabulated values that are presented. Please see the body of the report for more details.

4.0 DISCUSSION

The consistency of the measurements followed the homogeneity of a given material, where the more homogeneous materials such as acrylic and glass showed very consistent results across different measurements and materials that were more heterogeneous exhibited greater variation from one measurement to the next.

From the measurements, there is no obvious correlation between the asphalt mixture types and their permittivity values. The same is true for the concrete with differing water-to-cement ratios (w/c) and their permittivity values. However, the permittivity of sand did show a dependence with gradation.

The surface roughness may also have a significant effect on the measurements of the asphalt and concrete. There are studies showing how the roughness modifies the reflection coefficients in frequencies above 100 GHz. For example, Piesiewicz, Jansen, Mittleman, et al., 2007 showed the effects on ingrain-wallpaper and plaster. They show how a Rayleigh surface roughness factor can be used to correct for the surface roughness effects on the reflection coefficients. This could be a

future direction of the work.

The surface roughness and absorption properties of concrete most likely played a role in the weak transmission measurements of the concrete samples. While the presented permittivity values may be affected by the transmission measurements, there could be two solutions to verify or correct the permittivity values. The first would be to use a model that ignores the transmission S-parameters to calculate the permittivity values. If that does not work, another solution would be to produce thinner samples. However, thinner samples could be too brittle to handle.

5.0 CONCLUSION

This report serves as an appendix of dielectric properties for common construction materials exposed to electromagnetic energy emitted by an ADT system. We used a network analyzer operating in the W-band (75-110 GHz) to measure the relative complex permittivity for acrylic, drywall, plywood, clay brick, cinder block, asphalt, concrete, sand, and glass. These permittivity values are used to calculate the reflectivity values presented in this report. In addition, the material properties can be used as input parameters for various computational models. For ADT End-to-End modeling, the reflectivity values enable quick estimations of the energy reflected off surfaces.

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APPENDIX A - MATERIALS

A.1 Material Selection

Institute for Defense Analysis (IDA) provided a list of suggested materials ranked based on preference, with importance listed in descending order. The list is presented in Table A-1.

Table A-1. IDA Material Suggestions

Rank	Material
1	Sand
2	Soil
3	Concrete
4	Asphalt
5	Glass
6	Bricks (Clay & Cement)
7	Plastic
8	Carbon composite
9	Plywood
10	Drywall

The list of materials suggested by IDA.
Preference is listed in descending order.

Of the list provided by IDA, we measured the surface reflectivity properties of sand, concrete, asphalt, glass, bricks, plastic, plywood, and drywall. Materials have been selected to represent materials that are commonly found in possible ADT scenarios. Details about the selected materials can be found in the subsections below.

A.1.1 Sand

For sand materials, Quikrete Commercial Grade Sand Fine (No. 1961), Quikrete Commercial Grade Medium #30 Grit, and Sand Express Blast Sand Medium have been selected. These are dry, clean silica sands with the gradations listed in Table A-2. Sands are typically regionally sourced for cost and logistics reasons. The Quikrete and Sand Express Medium sands were purchased from Home Depot and Lowe's in Albuquerque, New Mexico, respectively. The Fine graded sand was purchased from Ace Hardware in Virginia. The different grades of sand will provide an estimate on how the surface roughness may effect the surface reflectivity. The selected sands can be categorized from fine to coarse in the following order: Quikrete Fine, Quikrete Medium, and Sand Express Medium, respectively.

A.1.2 Concrete

To acquire samples of concrete that represent concrete commonly found in construction, we used TerraCon Consultants, Inc. (TerraCon) to source raw materials and create the concrete. TerraCon provided ten concrete samples with types I and II cement and commercially available course and fine aggregates. When the concrete was being mixed, the w/c was varied for every two samples. The w/c values are 0.30, 0.35, 0.40, 0.50, and 0.60. Each sample aged for 28 days in a humidity controlled curing environment. The surface of the samples were finished with a trowel in

Table A-2. Sand Grades

Material	Sieve Number	Filter Size (mm)
Sand Express Medium	#12-#60	1.7-0.25
Quikrete Medium	#30	0.6
Quikrete Fine	#30-#70	0.6-0.2

The predominant sand sizes for the Quikrete Commercial Grade Fine, Quikrete Commercial Grade Medium #30 Grit, and Sand Express Blast Sand Medium. The gradation breakdown of the Sand Express Blast Sand Medium by sieve number is 0.0% #8, 1.0% #12, 11.0% #16, 38.0% #20, 38.0% #30, 8.0% #40, 3.0% #50, 0.5% #60, 0.0% #70, and 0.5% in the pan.

accordance with American Concrete Institute (ACI) standard 301. The samples have been labeled to match the w/c values, where labels (1-1, 1-2), (2-1, 2-2), (3-1, 3-2), (5-1, 5-2), and (6-1, 6-2) correspond to w/c = 0.35, 0.50, 0.60, 0.30, and 0.40, respectively. Additional concrete details may be found in subsection A.3.

A.1.3 Asphalt

To acquire samples of asphalt that represent asphalt commonly found in construction, we used TerraCon to source raw materials and create the asphalt. TerraCon provided nine asphalt samples as three sets of three samples. Each set was formed with a different type of asphalt, Texas Department of Transportation (TxDOT) Type B dense-grade hot-mix asphalt, TxDOT Type C dense-grade hot-mix asphalt, and TxDOT Type D dense-grade hot-mix asphalt. The asphalt datasheets may be found in subsection A.4.

A.1.4 Glass

A single pane of clear, transparent glass with the dimensions of 8 in. × 10 in. × 0.125 in. was purchased from Home Depot (Model # 90810).

A.1.5 Bricks

Bricks constructed out of concrete and clay have been measured. The concrete brick, or cinder block, is a 4 in. × 8 in. × 16 in. solid block purchased from Home Depot (Model # 30168621). The brick was constructed following the American Society for Testing and Materials (ASTM) C 90 standard.

The clay bricks are Marion Ceramics Thin Brick Tile Pavers in Academy Gray (760) and Plantation Red (200). These bricks were procured from the Acme Brick Tile and Store in San Antonio, TX. They have the following dimensions 1/2 in. × 3 5/8 in. × 7 5/8 in. and follows the ASTM C-902, Class SX, Type 3 standard.

A.1.6 Plastic

For plastic measurements, a sheet of EVONIK Cyro Acrylic was selected.

A.1.7 Plywood

Two types of plywood were selected, maple plywood and birch plywood. The maple plywood is the Columbia Forest Products PureBond Maple Plywood, Grade C-3, from Home Depot (Model # 1511004). The plywood came in the dimensions 3/4 in. × 4 ft. × 8 ft. It was constructed in 5-layers and the layers were bonded together with soy-based products. The birch plywood is the Sanded Plywood, Common, 5.2 mm × 2 ft. × 4 ft. from Home Depot (Model # 1511004). It had a single-layer construction.

A.1.8 Drywall

The drywall measured was United States Gypsum (USG) Company's USG Gypsum Drywall Patching 5/8 in. × 2 ft. × 2 ft. from Home Depot (Model # 141125).

A.1.9 Sand Containers

Containers to hold sand have been constructed out of Rexolite® 1422 and Styrofoam. The Rexolite 1422 container was constructed out of a 1/8 in. × 36 in. × 36 in. sheet with a thickness tolerance of +0.008/-0.000 in. The Rexolite 1422 was procured from Boedeker Plastics, Shiner, TX. The Styrofoam container was constructed out of a Hobby Lobby Styrofoam sheet.

A.2 Material Preparation

Samples have been prepared to have large, smooth planes normal to the antennas, where the surface area of the planes are prepared to be larger than the beam profile to reduce the effects from diffraction at the edges of the sample.

In order to measure the materials on the optical table, the materials were prepared to present a flat plane in-between the Vector Network Analyzer (VNA) antennas and either fit inside a sample holder or on the table itself. To fit inside the sample holder (Oriel Corp. 4 in. diameter sample holder system), samples needed to be prepared in a cylinder form factor with a 4 in. diameter. Materials prepared to fit inside the cylinder sample holder were the acrylic, asphalt, concrete, drywall, glass, and plywood samples. The bricks (cinder block and clay) were prepared as rectangular planes and measured directly on the table. Sand is a special case because of its loose consistency. Two separate material containers and methods were used in measuring the sand's dielectric properties. The two containers were constructed from Rexolite 1422 and Hobby Lobby Styrofoam, respectively.

Because concrete is brittle in thin samples and a thin sample could crack under the stress of transportation and handling during measurement, the thickness of the concrete and asphalt has been designed to maximize thickness while being thin enough for a signal to traverse through the medium. The suggested range of transmission signals to aim for in the network analyzer is -10 to -30 dB, where a maximum of -70 dB has been achieved before. Power drop follows $PowerDrop(dB) = \alpha \cdot 8.868 \cdot t$, where α is the absorption coefficient (cm^{-1}) and t is thickness (cm). The materials considered for thickness values include asphalt, concrete, bricks, and gypsum plaster. The dielectric properties, maximum thickness to reach a 70 dB power loss, and the expected power loss for a thickness of 1 in. is presented in Table A-3. With each material projected to satisfy the -70 dB limit with a thickness of 1 in., the materials samples were designed to be 1 in.

thick or thinner.

Table A-3. Estimation of Power Loss

Material	f (GHz)	α (cm ⁻¹)	Max. t (cm)	Loss (dB)	Source
Asphalt	94	0.55	14.35	12.4	Sarabandi, Li, and Nashashibi, 1997
Concrete Slab	95.9	0.43	18.35	9.69	Sato et al., 1995
Sand-Lime Brick	100	1.71	4.7	38	Piesiewicz, Jansen, Wietzke, et al., 2007
Clay Brick	100	0.86	9.4	19	Piesiewicz, Jansen, Wietzke, et al., 2007
Gypsum Plaster	100	0.51	15.4	11	Piesiewicz, Jansen, Wietzke, et al., 2007

The maximum material thickness to achieve a transmission measurement with the network analyzer and the estimated power loss after the signal traverses through 1 in. of the material for a given frequency f . These transmission values are estimated from the dielectric properties provided by the sources listed in the table.

The materials in the cylindrical form factors had their thickness measured every 72° along the circumference. The materials in the rectangular plane form factor had their thickness measured at the center of each edge between incident surfaces. The gauges used to measure the thickness are the Mitutoyo IP-65 micrometer and Craftsman Model 1-35-6112 caliper.

The mass of each sample has been measured with a RADWAG WTC 2000 at High Energy Research and Technology Facility (HERTF). This scale has a repeatability of 0.01 g and linearity of ± 0.03 g, while supporting masses up to 2 kg. Because HERTF is in a high-altitude desert, the scale could be systematically displaced in the mass measurement. The gravity value has a dependence on latitude and altitude. For example, the variation in gravity between HERTF and Tri-Service Research Laboratory (TSRL) is on the order of 0.001 m/s². Depending upon where the scale had been calibrated, the mass measurements could be off by a larger, or smaller, factor. There is a favorable trade-off between TSRL's lower latitude and HERTF's higher altitude with respect to each other's location.

The thickness and mass of each material is presented in Table A-4. For sand, mass measurements were not reported and the thickness measurement represents the inner distance between the planes of the Styrofoam container.

Table A-4. Physical Properties

Material	Thickness Measurements (in.)	Mean Thickness (in.)	Mass (g)
Acrylic (1)	0.4430, 0.4440, 0.4438, 0.4434, 0.4430	0.44344	108.11
Acrylic (2)	0.444, 0.444, 0.443, 0.444, 0.445	0.444	108.31
Drywall (1)	0.6296, 0.6286, 0.6282, 0.6213, 0.6236	0.6267	85.22
Drywall (2)	0.6295, 0.6236, 0.6072, 0.6124, 0.6282	0.6202	85.3
Birch (1)	0.200, 0.198, 0.200, 0.199, 0.199	0.1992	18.23
Birch (2)	0.1981, 0.1979, 0.1976, 0.1976, 0.1992	0.1981	19.05
Maple (1)	0.7256, 0.7267, 0.7257, 0.7273, 0.7261	0.7263	70.54
Maple (2)	0.727, 0.729, 0.738, 0.730, 0.728	0.7304	71.88
Red Brick (1)	0.5511, 0.5494, 0.5544, 0.550	0.5512	524.76
Red Brick (2)	0.5648, 0.5523, 0.5588, 0.5497	0.5564	533.76
Gray Brick (1)	0.5711, 0.5773, 0.5733, 0.5740	0.5739	552.12
Gray Brick (2)	0.5818, 0.5729, 0.5727, 0.5784	0.5764	555.96
Cinderblock (1)	0.2331, 0.2299, 0.2268, 0.2358	0.2314	109.37
Cinderblock (2)	0.2385, 0.2362, 0.2648, 0.2529, 0.2328	0.2451	120.46
Asphalt (B1)	1.068, 1.018, 1.010, 1.105, 1.126	1.0654	494.81
Asphalt (B2)	1.03, 1.049, 1.081, 1.088, 1.068	1.063	476.25
Asphalt (B3)	0.950, 0.954, 0.958, 1.015, 0.982	0.9728	423.23
Asphalt (C1)	1.098, 1.148, 1.119, 1.03, 1.08	1.095	472.98
Asphalt (C2)	1.130, 1.131, 1.090, 1.079, 1.098	1.1056	507.53
Asphalt (C3)	1.035, 1.081, 1.074, 1.110, 1.112	1.082	457.83
Asphalt (D1)	1.096, 1.144, 1.126, 1.135, 1.086	1.1174	490.68
Asphalt (D2)	0.942, 0.965, 1.002, 1.005, 0.991	0.981	426.25
Asphalt (D3)	1.011, 0.998, 0.964, 0.957, 0.954	0.9768	434.12
Concrete (1-1)	1.011, 1.050, 1.070, 1.045, 1.02	1.0392	483.54
Concrete (1-2)	1.005, 1.054, 1.045, 1.024, 1.015	1.0286	461.82
Concrete (2-1)	0.96545, 0.99215, 1.02265, 1.0184, 0.98995	0.99772	457.87
Concrete (2-2)	0.9801, 0.96605, 0.98475, 1.0164, 1.00865	0.99118	452.47
Concrete (3-1)	1.075, 1.047, 1.038, 1.039, 1.063	1.0524	481
Concrete (3-2)	1.004, 1.011, 1.060, 1.073, 1.019	1.0334	463.5
Concrete (5-1)	1.076, 1.021, 1.011, 1.029, 1.058	1.039	479.08
Concrete (5-2)	1.074, 1.029, 1.023, 1.033, 1.069	1.0456	482.94
Concrete (6-1)	1.035, 1.010, 0.986, 1.001, 1.020	1.01	459.11
Concrete (6-2)	1.054, 1.022, 1.018, 1.016, 1.007	1.0234	471.27
Glass	0.0881, 0.08815, 0.08815, 0.0882, 0.088	0.08812	44.87
Sand Express Medium	0.4753	0.4753	N/A
Quikrete Medium	0.4753	0.4753	N/A
Quikrete Fine	0.4753	0.4753	N/A

The thickness and mass of the materials measured with the VNA.

A.2.1 Surface Profile

Ideally, the MUT would have a flat surface, but that is not the case. To characterize the surface profile of the MUT, a depth meter, DeFelsko PosiTector[®] Surface Profile Gage (SPG), was used. The reason for choosing this method, as opposed to a stylus or laser speckle interferometry, is because of its versatility and cost effectiveness. The versatility is necessary because of the wide range of material types, and the versatility is enabled by the ability to easily swap probes on the SPG. The probe models SPG CS1 and SPG TS1 were selected to measure a wide range of peak-to-valley surface profile height, where the probes cover the ranges 0-1500 μm and 0-6000 μm with the reported accuracies of $\pm(5 \mu\text{m}+5\%)$ and $\pm(25 \mu\text{m}+1\%)$, respectively. Measurements were performed in mils (0.001 in.). The probes cover the ranges 0-60 mils and 0-250 mils with the reported accuracies of $\pm(0.2 \text{ mils}+5\%)$ and $\pm(1 \text{ mil}+1\%)$, respectively.

To closely follow commonly used standards (e.g., ASTM D4417, Australian Standard AS 3894.5, South African National Standard (SANS) 5572, and Society for Protective Coatings (SSPC)), multiple readings are performed on a given material. The depth readings were performed in an alignment holder for more consistent measurements. The tool is presented in Figure A-1. Samples were measured 200 times on each side, where the measurements were broken down into four different regions with ten different locations and five measurements were taken at each location. A diagram of the pattern is shown in Figure A-2.

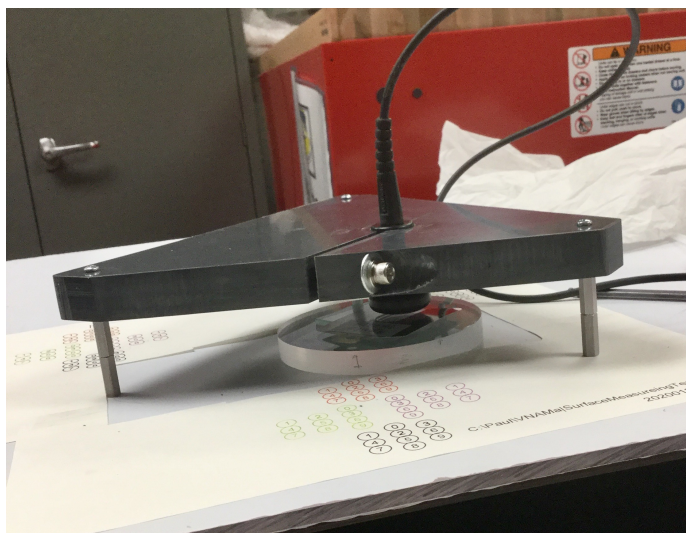


Figure A-1. The alignment tool used with the depth probe to measure the surface profile. The material being measured is acrylic sample # 1.

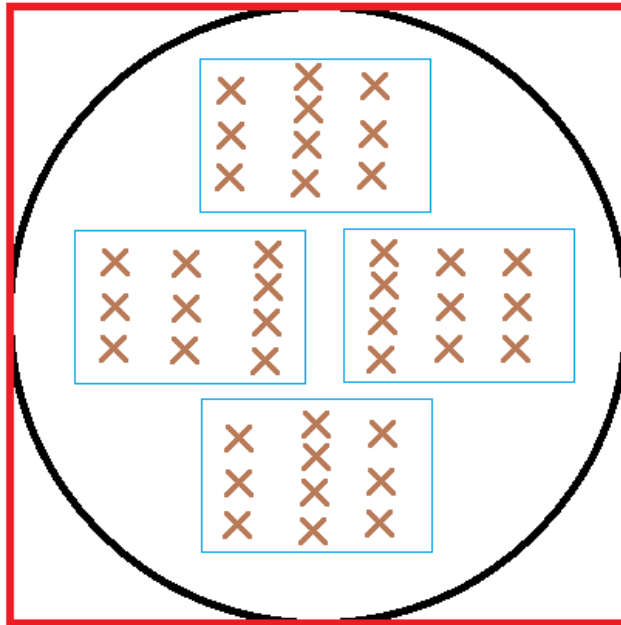


Figure A-2. The sampling pattern used to measure the surface profile of a material (outlined in black or red depending on the material's form factor). Five measurements are taken at each location (X). There are ten locations for each region (blue box).

The surface profile measurements from the CS1 probe on birch plywood (1), gypsum drywall (1), acrylic (1), concrete (5-2), and asphalt (C2) are shown in Tables A-5, A-6, A-7, A-8, and A-9, respectively. Because the rough side of the asphalt sample had several measurements that exceeded the upper, the TS1 probe was used to measure and the results are shown in Table A-10, where only one location was too deep to measure. Readings from the two probes, from the same asphalt sample, are shown in Figure A-3. When comparing the smooth side measurements, the depth readings appear to follow the same trend. However, the rough side exhibits a different trend between probe measurements. The probe tips have different shapes and could produce different results on a rougher surface than a smoother surface. Also, the depth probe has a non-negligible spring force behind it. The pressure from the measurement could be causing significant deformations that are being picked up by preceding measurements. The short probe was used to measure the sample first. This effect is something to consider for all measurements since five depth measurements are made at a given location. Surface profile measurements were not performed on every material sample, only the materials specifically aforementioned in this paragraph were measured.

Table A-5. Birch Plywood Depths

Side	Region	Peak-to-Valley (mils)
1	1	5.4, 4.5, 3.58, 4.72, 3.86, 2.46, 3.64, 2.72, 2.18, 1.52
	2	1.9, 2.4, 1.12, 0.74, 1.68, 2.34, 1.82, 3.02, 2.04, 1.78
	3	2.02, 1.54, 1.7, 1.14, 2.92, 2.92, 1.6, 3.44, 3.68, 2.54
	4	0.76, 3.24, 1.36, 0.02, 3.44, 4.8, 1.44, 4.52, 3.22, 1.22
2	1	1.8, 1.86, 1.76, 1.72, 1.48, 1.84, 1.92, 1.34, 1.7, 2
	2	1.86, 3.44, 3.1, 2.3, 2.42, 2.48, 2.1, 1.76, 2.3, 1.06
	3	2.7, 2.98, 2.72, 2.38, 3, 2.9, 2.98, 3.26, 5.42, 4.92
	4	1.44, 1.84, 1.28, 1.84, 0.78, 0.88, 1.3, 1.08, 1.24, 1.64

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise.

Table A-6. Gypsum Drywall Depths

Side	Region	Peak-to-Valley (mils)
1	1	4.06, 4.72, 3.62, 5.58, 4.56, 4.6, 4.84, 4.02, 5.14, 4.46
	2	4.64, 5.1, 5.22, 5.56, 6.56, 6.22, 4.24, 6.94, 6.28, 6.66
	3	6.5, 6.98, 6.16, 6.9, 7.52, 7.98, 7.86, 9, 10.3, 10.46
	4	5.96, 6.2, 4.64, 3.78, 5.72, 6, 5.28, 7.6, 6.64, 6.94
2	1	5.52, 4.28, 3.62, 3.66, 3.42, 2.62, 4.18, 4.58, 3.5, 3.84
	2	4.6, 4.06, 5.18, 4.6, 2.8, 4.92, 5.5, 4.4, 5.76, 8.58
	3	6.94, 9.28, 9.36, 5.56, 10.96, 11.24, 9.3, 9.96, 10.38, 12.62
	4	5.96, 4.6, 6.18, 4.86, 5.82, 5.28, 6.48, 8.14, 6.62, 6.14

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise.

Table A-7. Acrylic Depths

Side	Region	Peak-to-Valley (mils)
1	1	2.56, 1.38, 1.12, 2.72, 2, 0.84, 2.44, 2.72, 2.96, 3
	2	3.14, 0.66, 1.72, 0.78, 1.44, 0.82, 2.12, 1.9, 3.74, 2.64
	3	1.72, 1.92, 3.82, 2.48, 3.04, 2.24, 1.48, 0.94, 0.64, 3.32
	4	0.88, 2.12, 1.26, 1.72, 1.44, 2.1, 2.2, 2.2, 2.64, 1.72
2	1	1.36, 2.72, 0.38, 0.08, 0.28, 1.1, 1.58, 0.86, 0.72, 1.94
	2	1.58, 0.74, 1.22, 1.46, 1.06, 0.34, 1.08, 0, 0.64, 1.7
	3	1.36, 2.32, 1.94, 1.6, 0.5, 1.3, 0.82, 0.66, 0.24, 1.7
	4	0.86, 0.4, 0.96, 1.1, 0.26, 1.12, 0.46, 0.52, 1.54, 0.56

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise.

Table A-8. Concrete Depths

Side	Region	Peak-to-Valley (mils)
1	1	9.36, 9.16, 9.32, 8.48, 8, 8.54, 9.48, 5.72, 8.56, 9.98
	2	9.72, 16.28, 9.9, 8.12, 8.14, 8.94, 7.16, 8.7, 8.64, 6.6
	3	7.34, 5.6, 6.28, 6.96, 5.5, 3.8, 6.72, 5.18, 3.5, 4.9
	4	6.56, 6.66, 7.02, 7.78, 5.26, 5.9, 6.54, 6.2, 7.04, 6.02
2	1	7.32, 4.88, 8.66, 7.28, 6.08, 6.06, 9.38, 5.12, 5.52, 10.74
	2	10.1, 13.62, 15.34, 7.34, 8.28, 8.72, 8.62, 9.64, 10.52, 8.28
	3	11, 19.14, 15.74, 9.54, 25.98, 15.88, 9.98, 17.26, 8.42, 7.4
	4	5.48, 14.16, 9.18, 5.88, 17.24, 9.58, 4.3, 21.14, 11.42, 7.62

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise.

Table A-9. Asphalt Depths with Short Probe

Side	Region	Peak-to-Valley (mils)
Smooth	1	13.7, 7.68, 7.66, 7.92, 11.5, 7.36, 7.6, 7.72, 6.8, 4.86
	2	6.32, 8.2, 2.98, 6.26, 4.12, 3.86, 4.06, 3.48, 4.9, 5.04
	3	8.66, 8.24, 9.38, 5.66, 7.36, 6.7, 4.98, 14, 6.94, 6.04
	4	7.18, 19.16, 10.28, 7.16, 16, 7.92, 10.7, 16.04, 12.2, 8.4
Rough	1	LIMIT, LIMIT, 24.44, LIMIT, 44.06, 13.2, 19.46, 53.56, 26.14, LIMIT
	2	LIMIT, 53.62, 55.76, 27.14, 21.14, 20.26, 19.96, LIMIT, 54.56, LIMIT
	3	22.26, LIMIT, 45.32, 18.48, 29.24, LIMIT, 32.82, 53.32, 56.26, 32.5
	4	36.86, 14.18, LIMIT, 26.2, 21.06, 14.36, 26.04, 17.34, 29.48, LIMIT

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise. LIMIT represents an invalid reading from the depth being too deep.

Table A-10. Asphalt Depths with Long Probe

Side	Region	Peak-to-Valley (mils)
Smooth	1	7.6, 10.4, 10.6, 6.4, 17.2, 12.2, 5.2, 14, 9.4, 4.6
	2	6.4, 8.6, 5, 4.8, 4.6, 4.8, 4.8, 5.8, 5, 5.2
	3	6, 10.2, 7, 6, 11.2, 6, 7.6, 11.2, 5, 7.6
	4	13.2, 21.2, 10.8, 9.6, 17.8, 12.6, 10.8, 16, 12.4, 11.4
Rough	1	LIMIT, 143, 76, 105.2, 43.6, 10, 21.6, 70.4, 37.2, 109.2
	2	202.4, 20.8, 32.2, 28.2, 24.8, 18, 28.8, 25, 8.8, 79.4
	3	31.4, 93.8, 64.4, 22, 28.6, 66.8, 43.6, 53.4, 100.8, 76.4
	4	25, 18.4, 106.8, 22.6, 47.6, 12, 21.4, 54.12, 35, 43.6

The mean peak-to-valley measurements at each given location in the four regions on a side of the material. The region number starts at the 12 o'clock position and rotates clockwise, where measurements in the network analyzer started at the 9 o'clock position and rotated clockwise. LIMIT represents an invalid reading from the depth being too deep.

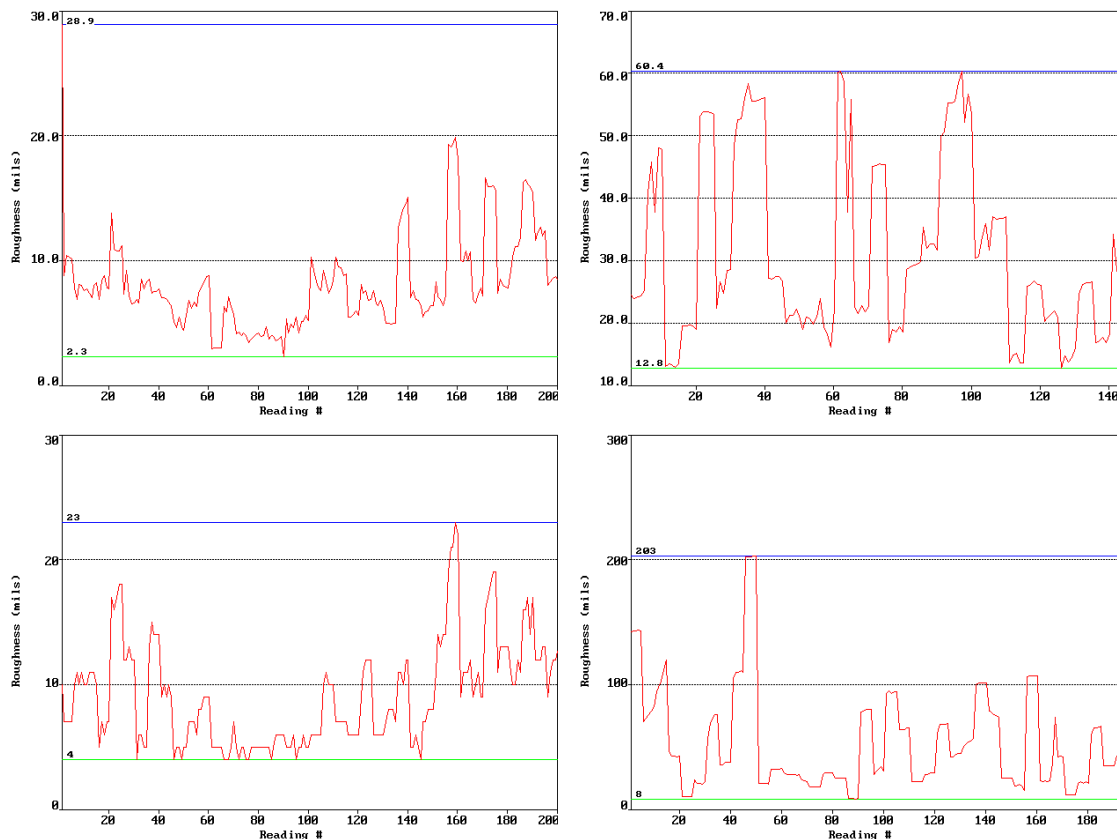


Figure A-3. The depth probes measurements for Asphalt C2. Left, the measurements on the smooth side of the sample. Right, the measurements on the rough side of the sample. Top, measurements made by the CS1 (short) probe. Bottom, measurements made by the TS1 (long) probe.

A.3 Concrete Datasheets

Inserted in the immediately proceeding pages are the concrete datasheets. These datasheets indicate the materials used to construct the concrete and to vary the w/c ratio.



Report Number: FB196108-Concrete
Service Date: 11/26/2019
Report Date: 12/23/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Batch Weight per Cubic Yard

Mix Design: w/cm = 0.35

Materials	Source	Volume (ft ³)	S.S.D Weight Per Cubic Yard (lbs)
Cement	Portland, Type I/II	3.31	650
Fly Ash			
Coarse Aggregate	1" Crushed Limestone	10.63	1718
Fine Aggregate	#4 River Sand	8.60	1406
Fine Aggregate			
Water	San Antonio Water System	3.65	227.5
Admixture (Air)			
Admixture (Water Reducing)	Glenium 7920		52 oz
Air Content		0.81	
Total		27.0	4002
Slump:	1"	Sp Gr (Fine) Man. Sand	2.62
Air Content: (%)	3.5%	Absorption (%)	1.50
Unit Weight: pcf	147.7	Fineness Modulus	3.08
Water Cement Ratio:	0.35	Sp Gr (Coarse)	2.59
		Absorption (%)	2.40
Date Samples Cast	11/21/2019		
Lab ID	Scott #1		

Remarks: Aggregate weights shown are for saturated surface dry conditions. Corrections for moisture content in the aggregates were made and the mixing water adjusted accordingly.



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Service Date: 11/26/2019
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Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Batch Weight per Cubic Yard

Mix Design: w/cm = 0.40

Materials	Source	Volume (ft ³)	S.S.D Weight Per Cubic Yard (lbs)
Cement	Portland, Type I/II	4.13	813
Fly Ash			
Coarse Aggregate	1" Crushed Limestone	10.56	1706
Fine Aggregate	#4 River Sand	6.70	1095
Fine Aggregate			
Water	San Antonio Water System	5.21	325
Admixture (Air)			
Admixture (Water Reducing)			
Air Content		0.40	
Total		27.0	3939
Slump:	4"	Sp Gr (Fine) Man. Sand	2.62
Air Content: (%)	2.4%	Absorption (%)	1.50
Unit Weight: pcf	145.9	Fineness Modulus	3.08
Water Cement Ratio:	0.40	Sp Gr (Coarse)	2.59
		Absorption (%)	2.40
Date Samples Cast	11/26/2019		
Lab ID	Scott #6		

Remarks: Aggregate weights shown are for saturated surface dry conditions. Corrections for moisture content in the aggregates were made and the mixing water adjusted accordingly.



Report Number: FB196108-Concrete
Service Date: 11/26/2019
Report Date: 12/23/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Batch Weight per Cubic Yard

Mix Design: w/cm = 0.50

Materials	Source	Volume (ft ³)	S.S.D Weight Per Cubic Yard (lbs)
Cement	Portland, Type I/II	3.31	650
Fly Ash			
Coarse Aggregate	1" Crushed Limestone	9.77	1579
Fine Aggregate	#4 River Sand	7.90	1292
Fine Aggregate			
Water	San Antonio Water System	5.21	325
Admixture (Air)			
Admixture (Water Reducing)			
Air Content		0.81	
Total		27.0	3846
Slump:	3-1/4"	Sp Gr (Fine) Man. Sand	2.62
Air Content: (%)	2%	Absorption (%)	1.50
Unit Weight: pcf	144.3	Fineness Modulus	3.08
Water Cement Ratio:	0.50	Sp Gr (Coarse)	2.59
		Absorption (%)	2.40
Date Samples Cast	11/21/2019		
Lab ID	Scott #2		

Remarks: Aggregate weights shown are for saturated surface dry conditions. Corrections for moisture content in the aggregates were made and the mixing water adjusted accordingly.

Report Number: FB196108-Concrete
 Service Date: 11/26/2019
 Report Date: 12/23/2019



Client

Glenda Walker
 General Dynamics Information Technology, Inc.
 101 Station Drive
 Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Batch Weight per Cubic Yard

Mix Design: w/cm = 0.60

Materials	Source	Volume (ft ³)	S.S.D Weight Per Cubic Yard (lbs)
Cement	Portland, Type I/II	3.05	600
Fly Ash			
Coarse Aggregate	1" Crushed Limestone	9.6	1551
Fine Aggregate	#4 River Sand	7.76	1269
Fine Aggregate			
Water	San Antonio Water System	5.77	360
Admixture (Air)			
Admixture (Water Reducing)			
Air Content		0.82	
Total		27.0	3780
Slump:	5 3/4"	Sp Gr (Fine) Man. Sand	2.62
Air Content: (%)	1.75%	Absorption (%)	1.50
Unit Weight: pcf	144.9	Fineness Modulus	3.08
Water Cement Ratio:	0.60	Sp Gr (Coarse)	2.59
		Absorption (%)	2.40
Date Samples Cast	11/21/2019		
Lab ID	Scott #3		

Remarks: Aggregate weights shown are for saturated surface dry conditions. Corrections for moisture content in the aggregates was made and the mixing water adjusted accordingly.



Report Number: FB196108-Concrete
Service Date: 11/26/2019
Report Date: 12/23/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Batch Weight per Cubic Yard

Mix Design: w/cm = 0.30

Materials	Source	Volume (ft ³)	S.S.D Weight Per Cubic Yard (lbs)
Cement	Portland, Type I/II	5.51	1083
Fly Ash			
Coarse Aggregate	1" Crushed Limestone	10.56	1706
Fine Aggregate	#4 River Sand	5.32	870
Fine Aggregate			
Water	San Antonio Water System	5.21	325
Admixture (Air)			
Admixture (Water Reducing)			
Air Content		0.40	
Total		27.0	3984
Slump:	1"	Sp Gr (Fine) Man. Sand	2.62
Air Content: (%)	2.5%	Absorption (%)	1.50
Unit Weight: pcf	144.7	Fineness Modulus	3.08
Water Cement Ratio:	0.30	Sp Gr (Coarse)	2.59
		Absorption (%)	2.40
Date Samples Cast	11/26/2019		
Lab ID	Scott #5		

Remarks: Aggregate weights shown are for saturated surface dry conditions. Corrections for moisture content in the aggregates were made and the mixing water adjusted accordingly.

11/26/2019

A.4 Asphalt Datasheets

Inserted in the immediately proceeding pages are the asphalt datasheets. These datasheets indicate the materials used to construct the asphalt. The datasheets are broken down into three different categories based on type of dense-graded hot-mix asphalt. The order is Type B, Type C, and Type D, respectively.



Report Number: FB196108-Asphalt
Service Date: 11/14/2019
Report Date: 11/14/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Three samples were prepared using a TxDOT Type B dense-graded hot-mix asphalt. The specific mix design is indicated on the attached pages.

These samples are labeled

B-1

B-2

B-3



TEXAS DEPARTMENT OF TRANSPORTATION

2014 HMACP MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook TX2MXDE14 - File Version: 11/16/16 16:01:04

SAMPLE ID:	Ty B 64-22 R WMA	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEXAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	0341CM0000	MIX TYPE:	341-DG-B
MATERIAL NAME:	Ty B 64-22 R WMA	WMA Additive in Design?	Yes
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT	Target Discharge Temp., °F:	275
AREA ENGINEER:		WMA TECHNOLOGY:	Evotherm (MeadWestvaco)
		WMA RATE:	0.5 UNITS: % by weight of asphalt
COURSE/LIFT:	Base	STATION:	
		DIST. FROM CL:	
		CONTRACTOR DESIGN #:	#76430 PORT B WMA

Maximum Allowable, %	
Frac RAP:	40.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	40.0

Recycled Binder, %	
Bin No.8 :	1.3
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	1.300

Use this value in the CC/QA template>>

Ratio of Recycled to Total Binder, %	
(Based on binder percent (%) entered below in this worksheet)	
Total	31.7

AGGREGATE BIN FRACTIONS										"RECYCLED MATERIALS"		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10		
Source:	Imestone_Dolomit	Imestone_Dolomit	Imestone_Dolomit	Imestone_Dolomit				Fractionated RAP			Material Type	
Pit:	Rio Medina Quarry	Beckmann	Rio Medina Quarry	Beckmann	Poteet Pit						Material Source	
Number:	1516312	1501503	1516312	1501503							RAS Type	
Producer:	Martin Marietta	Martin Marietta	Martin Marietta	Martin Marietta	Martin Marietta			Oldcastle Materials			RAP/RAS Producer	
Sample ID:	57	1/2 X 3/8	Gr. 5	Man. Sand	Washed Sand			Fine 1/2"			Sample ID	

Recycled Asphalt Binder (%)															Combined Gradation		
4.2																	
Hydrated Lime?:															30.0	% of Tot. Mix % of Aggregate	% of Tot. Mix % of Aggregate
Individual Bin (%)	25.0	Percent	13.0	Percent	12.0	Percent	12.0	Percent	8.0	Percent		Percent		Percent	30.0		
Sieve Size:	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing
1-1/2"	100.0	25.0	100.0	13.0	100.0	12.0	100.0	12.0	100.0	8.0			100.0	30.0		100.0	
1"	100.0	25.0	100.0	13.0	100.0	12.0	100.0	12.0	100.0	8.0			100.0	30.0		100.0	
3/4"	91.4	22.9	100.0	13.0	100.0	12.0	100.0	12.0	100.0	8.0			100.0	30.0		97.9	
3/8"	18.1	4.5	62.9	8.2	100.0	12.0	100.0	12.0	100.0	8.0			97.0	29.1		73.8	
No. 4	1.2	0.3	7.6	1.0	70.5	8.5	99.9	12.0	100.0	8.0			75.0	22.5		52.2	
No. 8	1.2	0.3	5.6	0.7	12.6	1.5	87.7	10.5	99.7	8.0			52.9	15.9		36.9	
No. 30	1.1	0.3	2.6	0.3	2.4	0.3	38.9	4.7	80.5	6.4			29.5	8.9		20.9	
No. 50	1.1	0.3	2.0	0.3	2.4	0.3	25.1	3.0	33.5	2.7			22.0	6.6		13.1	
No. 200	1.1	0.3	2.0	0.3	1.9	0.2	8.3	1.0	2.2	0.2			8.0	2.4		4.3	

(Bold Italic) Not within specifications (Bold Italic) Not within specifications- Restricted Zone (Italic) Not cumulative

Lift Thickness, in:	4.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Valero	Binder Percent, (%):	4.1	Asphalt Spec. Grav.:	1.041		
Antistripping Agent:		Percent, (%):					

Remarks:

Combined Gradation

Notes:

Page 1 of 6

11/11/2019

TEXAS DEPARTMENT OF TRANSPORTATION
HMACP MIXTURE DESIGN : MATERIAL PROPERTIES

SAMPLE ID: Ty B 64-22 R WMA		SAMPLE DATE: 11/11/2019	
LOT NUMBER: MIX DESIGN		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY: BEXAR		SPEC YEAR: 2014	
SAMPLED BY: ROBERT RIOS		SPEC ITEM: 341	
SAMPLE LOCATION: PORT SA LAB		SPECIAL PROVISION:	
MATERIAL CODE: DSHCM0000		MIX TYPE: 341-DG-B	
MATERIAL NAME: Ty B 64-22 R WMA			
PRODUCER: OLDCASTLE MATERIALS TEXAS PORT SA PLANT			
AREA ENGINEER:		PROJECT MANAGER:	
COURSE/LIFT: Base		STATION:	
		DIST. FROM CL:	
		CONTRACTOR DESIGN #: 6430 PORT B WM	

		Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7	
Individual Bin (%)		Bin No.1 = 25 %		Bin No.2 = 13 %		Bin No.3 = 12 %		Bin No.4 = 12 %		Bin No.5 = 8 %					
Aggregate Source:		Limestone, Dolomite		Limestone, Dolomite		Limestone, Dolomite		Limestone, Dolomite							
Aggregate Number:		1516312		151503		1516312		151503							
Sample ID:		97		12 X 3/8		Gr. 5		Man Sand		Washed Sand					
Test Name	Site Manager Test Template	Test Method	Spec. Min or Max	Spec. Limit	Modified Spec. Limit	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID
Stockpile															
Decantation	Tx217	Tex-217-F	Max.	1.5		0.20		0.20		0.20					
Deleterious Mat'l	Tx217	Tex-217-F	Max.	1.5		0.10		0.10		0.10					
Surface Aggregate Classification	Tx4AgCIBS	Tex-438-A, Tex-612-J	Min.			B		B		B		NA		NA	
Magnesium Sulfate Soundness	Tx411M	Tex-411-A	Max.	30		15.00		24.00		15.00		NA		NA	
LA Abrasion	Tx410	Tex-410-A	Max.	40		30.00		33.00		30.00		NA		NA	
Crushed Faces Count	Tx460	Tex-460-A	Min.	85		99.00		99.00		99.00		NA		NA	
Flat & Elongated	Tx280	Tex-280-F	Max.	10		1.00		1.00		1.00		NA		NA	
Micro-Deval Abrasion	Tx461	Tex-461-A	Use results to estimate the Mg Sulfate Soundness Loss			19.00		23.00		19.00		NA		NA	
Fine Aggregate															
Bar Linear Shrinkage	Tx107	Tex-107-E	Max.	3						0.00		0.00			
Methylene Blue	-	AASHTO T330	Max.												
Combined Aggregate															
Sand Equivalent	Tx203	Tex-203-F	Min.	45						87.00		75.00			
User Defined Testing															
1															
2															
3															
4															
5															
Recycled Materials															
Deleterious Mat'l	Tx217	Tex-217-F, Part III	Max.	0.5	0.3										
Decantation	Tx406	Tex-406-A, Part I	Max.	5	1.5										
Plasticity Index	Tx104-6	Tex-106-E	Max.	8	0										
User Defined Testing															
Remarks:															

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : Aggregate Classification

SAMPLE ID:	Ty B 64-22 R WMA	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEKAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	0341CM0000	MIX TYPE:	341-DG-B
MATERIAL NAME:	Ty B 64-22 R WMA		
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE/LIFT:	Base	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	176430 PORT B WMA
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Aggregate Classification										
Individual Bin (%)	Bin No.1 = 25 %	Bin No.2 = 13 %	Bin No.3 = 12 %	Bin No.4 = 12 %	Bin No.5 = 8 %	Bin No.6	Bin No.7	Bin No.8 = 30 %	Bin No.9	Bin No.10
Aggregate Source:	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite				Fractionated RAP		
Aggregate Number:	1516312	1501503	1516312	1501503				Fine 1/2"		
Class (A) Rock (Y/N):										
Sieve Size:										
Passing	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Retained										
1-1/2"	0.0	0.0	0.0	0.0	0.0			0.0		
1"	0.0	0.0	0.0	0.0	0.0			0.0		
3/4"	2.2	0.0	0.0	0.0	0.0			0.0		
3/8"	18.3	4.8	0.0	0.0	0.0			0.9		
No. 4	4.2	7.2	3.5	0.0	0.0			6.6		
No. 8	0.0	0.3	6.9	1.5	0.0			6.6		
No. 30	0.0	0.4	1.2	5.9	1.5			7.0		
No. 50	0.0	0.1	0.0	1.7	3.8			2.3		
No. 200	0.0	0.0	0.1	2.0	2.5			4.2		
Pan	0.3	0.3	0.2	1.0	0.2			2.4		
Total:	25.0	13.0	12.0	12.0	8.0			30.0		
Percent of plus No. 4:	24.7	12.0	3.5	0.0	0.0			7.5		

Percent of plus No. 8:	24.7	12.3	10.5	1.5	0.0			14.1		
Percent of plus No. 4 from class (A) Rock:	0.0							0.0		
Total Percent of plus No. 4	47.8							63.1		
Percent of plus No. 4 from class (A) Rock:	0.0							0.0		

Remarks:

HMACP MIXTURE DESIGN : BULK GRAVITY

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TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : SUMMARY SHEET

SAMPLE ID:	Ty B 64-22 R WMA	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEXAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	0341CM0000	MIX TYPE:	341-DG-B
MATERIAL NAME:	Ty B 64-22 R WMA		
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT		
AREA ENGINEER:		PROJECT MANAGER:	
COURSE/LIFT:	Base	STATION:	
		DIST. FROM CL:	
		CONTRACTOR DESIGN #:	6430 PORT B WM

Target Density, %:	96.0
Number of Gyration:	35

Note: This mix design requires an asphalt content of at least 3.3% to meet the Maximum Ratio of Recycled to Total Binder requirement.

TEST SPECIMENS								Mixture Evaluation @ Optimum Asphalt Content			
Asphalt Content (%)	Binder Ratio (%)	Specific Gravity Of Specimen (G _s)	Maximum Specific Gravity (G _m)	Effective Gravity (G _e)	Theo. Max. Specific Gravity (G _t)	Density from G _t (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Hamburg Wheel Tracking Test		Overlay Tester "Min. Number of Cycles"
									Number of cycles	Rut depth (mm)	
3.5	37.1	2.341	2.487	2.619	2.488	94.1	13.8	140	5,000	4.8	
4.0	32.5	2.360	2.469	2.619	2.471	95.5	13.5				
4.5	28.9	2.368	2.456	2.624	2.453	97.3	13.0				

Effective Specific Gravity:	2.621
Optimum Asphalt Content :	4.1
Binder Ratio @ OAC:	31.7
VMA @ Optimum AC:	13.4

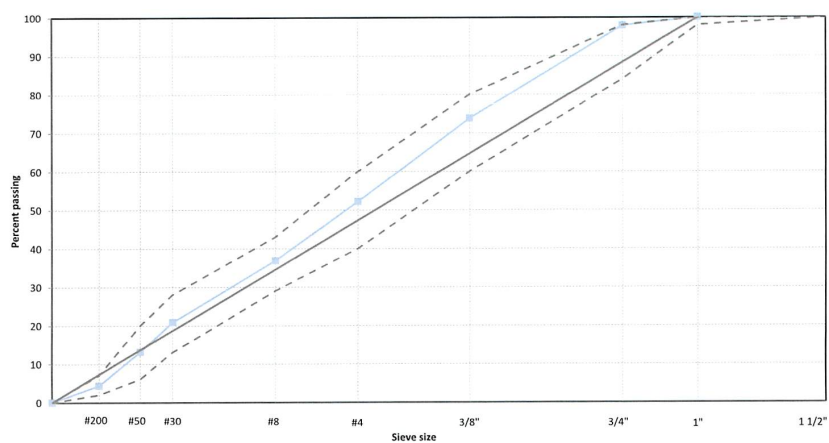
Estimated Percent of Stripping, %:	0
------------------------------------	---

Interpolated Values	
Specific Gravity (G _s):	2.367
Max. Specific Gravity (G _m):	2.466
Theo. Max. Specific Gravity (G _t):	2.466

Mixing Temp, °F:	290
Molding Temp, °F:	250

Remarks:

--



Terracon Asphalt Lab Report

Project: FB196108
 Contractor: _____
 County: _____

Project No.: _____
 Mix Type: B 1-3
 Supplier: _____

Sample Date: _____
 Sample Time: _____
 Sample Temp °F: _____
 Truck No.: _____
 Ticket No.: _____
 Plant No.: _____
 Mix Design No.: _____

Sieve Analysis

Sieve Size	Weight (gr)	Ind. % Ret.	Cum. % Ret.	% Pass	JMF
1 3/4"					
1"					
3/4"					
1/2"					
3/8"					
#4					
#8					
#16					
#30					
#50					
#100					
#200					
Pan					
Total Wt.					

Lab Molded Density

Specimen No.	1	2	3
Specimen Height	116.3	115.5	117.9
Air Weight	4750.3	4750.4	4750.6
Weight in Water	2773.8	2770.3	2759.9
SSD Weight	4772.8	4765.1	4777.8
Bulk Volume CC	1999.0	1994.8	2017.9
Specific Gravity	2.377	2.381	2.354
Unit Weight (pcf)			
% Absorption by Vol.			
% Density	95.5	95.7	94.6
% Air Voids			
% VMA			
% Voids Filled			
Average Bulk Specific Gravity			
Average Lab Density			95.3

Asphalt Content	NA
AC JMF	NA

Rice Gravity

Water Temp: 77
 -3/4
 Wt. of Calibrated Pyc.: 1437.5
 Wt. of Dry Sample in Air: 2051.8
 Wt. of Sample in H₂O: 2665.1
829.2 G: 2.989
 + 3/4 155.3
 Wt. of Calibrated Pyc.: _____
 Wt. of Dry Sample in Air: _____
 Wt. of Sample in H₂O: _____
 G: _____

Technician: TL

Comments: _____

Ignition Oven Method

Basket Weight _____ g
 Sample + Basket Weight _____ g
 Sample Weight _____ g
 Sample + Basket Weight after Ignition _____ g
 Sample Weight Loss _____ g
 AC = (Loss / Orig Sample Weight) x 100 _____ %

AN % = 4.7 %

Stability

Average _____
 Hveem _____
 Marshall Stability _____
 Marshall Flow _____

Specimen	1	2	3
Load (lbs)			
Flow (mm)			
Flow (in)			



Report Number: FB196108-Asphalt
Service Date: 11/14/2019
Report Date: 11/14/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Three samples were prepared using a TxDOT Type C dense-graded hot-mix asphalt. The specific mix design is indicated on the attached pages.

These samples are labeled

- C-1
- C-2
- C-3

TEXAS DEPARTMENT OF TRANSPORTATION

2014 HMACT MIXTURE DESIGN : COMBINED GRADATION

Refresh Worksheet

SAMPLE ID:	Ty C 64-22 R	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEXAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	213010	MIX TYPE:	341-DG-C
MATERIAL NAME:	Ty C 64-22 R	WMA Additive in Design?	No
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT	Target Discharge Temp., °F:	315
AREA ENGINEER:		WMA TECHNOLOGY:	
PROJECT MANAGER:		WMA RATE:	UNITS:
COURSE/LIFT:	Intermediate	STATION:	
DIST. FROM CL:		CONTRACTOR DESIGN #:	1764 PORT C

Maximum Allowable, %	
Frac RAP:	30.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8 :	0.8
Bin No.9 :	0.0
Bin No.10 :	0.0
Total	0.800

Use this value in the QC/QA template>>

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Source:	limestone_Dolomit	limestone_Dolomit	limestone_Dolomit	limestone_Dolomit				Fractionated RAP			Material Type
Pit:	Rio Medina Quarry	Beckmann Quarry	Rio Medina Quarry	Beckmann Quarry	Poteet Pit						Material Source
Number:	1516312	1501503	1516312	1501503							RAS Type
Producer:	Martin Marietta	Martin Marietta	Martin Marietta	Martin Marietta	Martin Marietta			Oldcastle Materials			RAP/RAS Producer
Sample ID:	57	1/2 X 3/8	Gr. 5	Man. Sand	Washed Sand			Fine 1/2"			Sample ID

Ratio of Recycled to Total Binder, %	
(based on binder percent (%) entered below in this worksheet)	
Total	16.3

Recycled Asphalt Binder (%)															Combined Gradation			
4.2															100.0%			
Individual Bin (%)															Total Bin			
13.0 Percent															100.0%			
23.0 Percent															100.0%			
20.0 Percent															100.0%			
17.0 Percent															100.0%			
7.0 Percent															100.0%			
19.9 % of Tot. Mix % of Aggreg.															100.0%			
20.0 % of Tot. Mix % of Aggreg.															100.0%			
Sieve Size:															Sieve Size:			
1"															1"			
3/4"															3/4"			
3/8"															3/8"			
No. 4															No. 4			
No. 8															No. 8			
No. 30															No. 30			
No. 50															No. 50			
No. 200															No. 200			

(Bold Italic) Not within specifications (Bold Italic) Not within specifications- Restricted Zone (Italic) Not cumulative

Lift Thickness, in:	4.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Valero	Binder Percent, (%):	4.9	Asphalt Spec. Grav.:	1.041		
Antistripping Agent:		Percent, (%):					

Remarks:

Combined Gradation

Notes:

Page 1 of 6

11/11/2019

TEXAS DEPARTMENT OF TRANSPORTATION
HMACP MIXTURE DESIGN : MATERIAL PROPERTIES

SAMPLE ID	Ty C 64-22 R	SAMPLE DATE	11/11/2019
LOT NUMBER	MIX DESIGN	LETTING DATE	
SAMPLE STATUS		CONTROLLING CS	
COUNTY	BEXAR	SPEC YEAR	2014
SAMPLED BY	ROBERT RIOS	SPEC ITEM	341
SAMPLE LOCATION	PORT SA LAB	SPECIAL PROVISION	
MATERIAL CODE	213010	MIX TYPE	341-DG-C
MATERIAL NAME	Ty C 64-22 R		
PRODUCER	OLDCASTLE MATERIALS TEXAS PORT SA PLANT		
AREA ENGINEER		PROJECT MANAGER	

COURSE/LIFT	Intermediate	STATION		DIST. FROM CL		CONTRACTOR DESIGN #	1764 PORT C
-------------	--------------	---------	--	---------------	--	---------------------	-------------

		Individual Bin (%)				Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7	
		Aggregate Source				Bin No.1 = 13 %		Bin No.2 = 23 %		Bin No.3 = 20 %		Bin No.4 = 17 %		Bin No.5 = 7 %					
		Aggregate Number				Limestone, Dolomite 1516312		Limestone, Dolomite 100100		Limestone, Dolomite 1516312		Limestone, Dolomite 100100							
		Sample ID				57		1/2 X 3/8		Gr. 5		Man. Sand		Washed Sand					
Test Name	SiteManager Test Template	Test Method	Spec. Min or Max	Spec. Limit	Modified Spec. Limit	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID	Result	Sample ID
Stockpile																			
						Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7	
Decantation	Tx217	Tex-217-F	Max.	1.5		0.20		0.20		0.20									
Deleterious Mat'l	Tx217	Tex-217-F	Max.	1.5		0.10		0.10		0.10									
Surface Aggregate Classification	Tx4AgClas	Tex-435-A, Tex-612-J	Min.			B		B		B		NA		NA					
Magnesium Sulfate Soundness	Tx411M	Tex-411-A	Max.	30		15.00		24.00		15.00		NA		NA					
LA Abrasion	Tx410	Tex-410-A	Max.	40		30.00		33.00		30.00		NA		NA					
Crushed Faces Count	Tx460	Tex-460-A	Min.	85		99.00		99.00		99.00		NA		NA					
Flat & Elongated	Tx280	Tex-280-F	Max.	10		1.00		1.00		1.00		NA		NA					
Micro-Deval Abrasion	Tx461	Tex-461-A	Use results to estimate the Mg Sulfate Soundness Loss			19.00		23.00		19.00		NA		NA					
Fine Aggregate																			
Bar Linear Shrinkage	Tx107	Tex-107-E	Max.	3								0.00		0.00					
Methylene Blue	-	AASHTO T330	Max.																
Combined Aggregate																			
Sand Equivalent	Tx203	Tex-203-F	Min.	45								87.00		75.00					
User Defined Testing																			
Use this area to enter any test methods, specifications & test result that apply to this material(s) but are not listed above.	1																		
	2																		
	3																		
	4																		
	5																		
Recycled Materials																			
Deleterious Mat'l	Tx217	Tex-217-F, Part II	Max.	0.5	0.3														
Decantation	Tx406	Tex-406-A, Part I	Max.	5	1.5														
Plasticity Index	Tx104-6	Tex-106-E	Max.	8	0														
User Defined Testing																			
Remarks:																			

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : Aggregate Classification

SAMPLE ID:	Ty C 64-22 R	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEXAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	213010	MIX TYPE:	341-DG-C
MATERIAL NAME:	Ty C 64-22 R		
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE/LIFT:	Intermed	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	1764 PORT C
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Aggregate Classification											
		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Individual Bin (%)		Bin No.1 = 13 %	Bin No.2 = 23 %	Bin No.3 = 20 %	Bin No.4 = 17 %	Bin No.5 = 7 %			Bin No.8 = 20 %		
Aggregate Source:		Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite				Fractionated RAP		
Aggregate Number:		1516312	1501503	1516312	1501503				Fine 1/2"		
Class (A) Rock (Y/N):											
Sieve Size:											
Passing	Retained	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
-	1"	0.0	0.0	0.0	0.0	0.0			0.0		
1"	3/4"	1.1	0.0	0.0	0.0	0.0			0.0		
3/4"	3/8"	9.5	8.5	0.0	0.0	0.0			0.6		
3/8"	No. 4	2.2	12.7	5.9	0.0	0.0			4.4		
No. 4	No. 8	0.0	0.5	11.6	2.1	0.0			4.4		
No. 8	No. 30	0.0	0.7	2.0	8.4	1.3			4.7		
No. 30	No. 50	0.0	0.1	0.0	2.2	3.3			1.5		
No. 50	No. 200	0.0	0.0	0.1	2.9	2.2			2.8		
No. 200	Pan	0.1	0.5	0.4	1.4	0.2			1.6		
Total:		13.0	23.0	20.0	17.0	7.0			20.0		
Percent of plus No. 4		12.8	21.3	5.9	0.0	0.0			5.0		

Percent of plus No. 8	12.8	21.7	17.5	2.1	0.0				9.4		
Percent of plus No. 4 from class (A) Rock:		0.0							0.0		
Total Percent of plus No. 4		45.0							63.6		
Percent of plus No. 4 from class (A) Rock:		0.0							0.0		

Remarks:

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : BULK GRAVITY

SAMPLE ID: Ty C 64-22 R		SAMPLE DATE: 11/11/2019	
LOT NUMBER: MIX DESIGN		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY: BEXAR		SPEC YEAR: 2014	
SAMPLED BY: ROBERT RIOS		SPEC ITEM: 341	
SAMPLE LOCATION: PORT SA LAB		SPECIAL PROVISION:	
MATERIAL CODE: 213010		MIX TYPE: 341-DG-C	
MATERIAL NAME: Ty C 64-22 R			
PRODUCER: OLDCASTLE MATERIALS TEXAS PORT SA PLANT			
AREA ENGINEER:		PROJECT MANAGER:	

COURSE/LIFT: Intermedi		STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # : 1764 PORT C	
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Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10	
Individual Bin (%)		Bin No.1 = 13 %		Bin No.2 = 23 %		Bin No.3 = 20 %		Bin No.4 = 17 %		Bin No.5 = 7 %				Bin No.8 = 19.9 %					
Aggregate Source:		Limestone_Dolomite		Limestone_Dolomite		Limestone_Dolomite		Limestone_Dolomite						Fractionated RAP					
Aggregate Number:		1516312		1501503		1516312		1501503											
Sample ID:		57		1/2 X 3/8		Gr. 5		Man. Sand		Washed Sand						Fine 1/2"			

Sieve Size:		Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG
Passing	Retained																		
1"	3/4"	8.6	2.572																
3/4"	3/8"	73.3	2.572	37.1	2.565														
3/8"	No. 4	16.9	2.572	55.3	2.565	29.5		0.1	2.420										
No. 4	No. 8			2.0	2.565	57.9	2.541	12.2	2.420	0.3	2.632								
No. 8	No. 30	0.1	2.572	3.0	2.565	10.2	2.541	49.7	2.420	19.2	2.632								
No. 30	No. 50			0.6	2.565			12.9	2.420	47.0	2.632								
No. 50	No. 200					0.5	2.541	16.8	2.420	31.3	2.632								
No. 200	Pan	1.1	2.572	2.0	2.565	1.9	2.541	8.3	2.420	2.2	2.632								
Totals		100.0	2.572	100.0	2.565	100.0	2.541	100.0	2.420	100.0	2.632					100.0	2.539		

Combined Bulk Specific Gravity: 2.535		Specific Gravity of Asphalt: 1.041	
Coarse Agg. Combined BSG:			

Remarks:

TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : SUMMARY SHEET

SAMPLE ID:	Ty C 64-22 R	SAMPLE DATE:	11/11/2019
LOT NUMBER:	MIX DESIGN	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	BEXAR	SPEC YEAR:	2014
SAMPLED BY:	ROBERT RIOS	SPEC ITEM:	341
SAMPLE LOCATION:	PORT SA LAB	SPECIAL PROVISION:	
MATERIAL CODE:	213010	MIX TYPE:	341-DG-C
MATERIAL NAME:	Ty C 64-22 R		
PRODUCER:	OLDCASTLE MATERIALS TEXAS PORT SA PLANT		
AREA ENGINEER:		PROJECT MANAGER:	
COURSE/LIFT:	Intermed	STATION:	
		DIST. FROM CL:	
		CONTRACTOR DESIGN # :	1764 PORT C

Target Density, %:	96.0
Number of Gyration:	40

Note: This mix design requires an asphalt content of at least **4.0%** to meet the Maximum Ratio of Recycled to Total Binder requirement.

TEST SPECIMENS								Mixture Evaluation @ Optimum Asphalt Content			
Asphalt Content (%)	Binder Ratio (%)	Specific Gravity Of Specimen (G _a)	Maximum Specific Gravity (G _r)	Effective Gravity (G _e)	Theo. Max. Specific Gravity (G _t)	Density from Gt (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Hamburg Wheel Tracking Test		Cooper-Fuster Test Number of Cycles
									Number of cycles	Rut depth (mm)	
4.5	17.8	2.358	2.475	2.647	2.483	95.0	15.2	135	5,000	3.3	
5.0	16.0	2.370	2.462	2.653	2.465	96.1	15.3				
5.5	14.3	2.394	2.459	2.671	2.448	97.4	15.2				

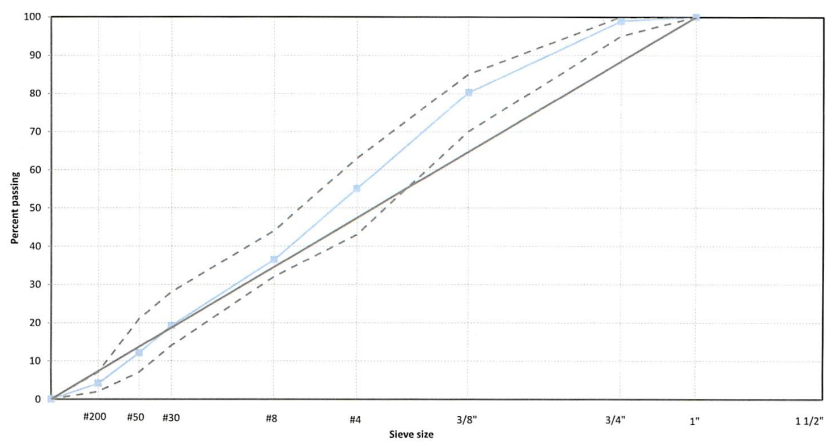
Effective Specific Gravity:	2.657
Optimum Asphalt Content :	4.9
Binder Ratio @ OAC:	16.3
VMA @ Optimum AC:	15.3

Estimated Percent of Stripping, %:	0
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Interpolated Values	
Specific Gravity (G _a):	2.369
Max. Specific Gravity (G _t):	2.463
Theo. Max. Specific Gravity (G _t):	2.467

Mixing Temp, °F:	290
Molding Temp, °F:	250

Remarks:



Terracon Asphalt Lab Report

Project: FB196108
 Contractor: _____
 County: _____

Project No.: _____
 Mix Type: TY C
 Supplier: _____

Sample Date: _____
 Sample Time: _____
 Sample Temp °F: _____
 Truck No.: _____
 Ticket No.: _____
 Plant No.: _____
 Mix Design No.: _____

Sieve Analysis

Sieve Size	Weight (gr)	Ind. % Ret.	Cum. % Ret.	% Pass	JMF
1 3/4"					
1"					
3/4"					
1/2"					
3/8"					
#4					
#8					
#16					
#30					
#50					
#100					
#200					
Pan					
Total Wt.					

Technician: Tid Carlisle (TC)

Comments:

Lab Molded Density

Specimen No.	1	2	3
Specimen Height	116.2	115.1	115.1
Air Weight	4749.1	4747.2	4750.4
Weight in Water	2765.0	2767.4	2773.8
SSD Weight	4759.1	4758.6	4757.0
Bulk Volume CC	1994.1	1991.2	1983.2
Specific Gravity	2.340	2.384	2.340
Unit Weight (pcf)			
% Absorption by Vol.			
% Density	94.9	96.7	94.9
% Air Voids			
% VMA			
% Voids Filled			
Average Bulk Specific Gravity			
Average Lab Density			95.5

Air voids 4.5

Ignition Oven Method

Basket Weight	_____ g
Sample + Basket Weight	_____ g
Sample Weight	_____ g
Sample + Basket Weight after Ignition	_____ g
Sample Weight Loss	_____ g
AC = (Loss / Orig Sample Weight) x 100	_____ %

Asphalt Content

Asphalt Content	.NA
AC JMF	NA

Rice Gravity

Water Temp:	75
-3/4	
Wt. of Calibrated Pyc:	1437.6
Wt. of Dry Sample in Air:	1551.2
Wt. of Sample in H ₂ O:	2359.6
+ 3/4	629.2 G: 296.5
Wt. of Calibrated Pyc:	153.8
Wt. of Dry Sample in Air:	
Wt. of Sample in H ₂ O:	
G _r :	

Stability

Average	
Hveem	
Marshall Stability	
Marshall Flow	

Specimen	1	2	3
Load (lbs)			
Flow (mm)			
Flow (in)			



Report Number: FB196108-Asphalt
Service Date: 11/14/2019
Report Date: 11/14/2019

Client

Glenda Walker
General Dynamics Information Technology, Inc.
101 Station Drive
Westwood, MA 02090

Project

Samples of Construction Materials

Project Number: FB196108

Three samples were prepared using a TxDOT Type D dense-graded hot-mix asphalt. The specific mix design is indicated on the attached pages.

These samples are labeled

D-1

D-2

D-3



TEXAS DEPARTMENT OF TRANSPORTATION
OLDCASTLE MATERIALS-TEXAS S.A.(FORMERLY APAC-SA)
2014 HMAPC MIXTURE DESIGN : COMBINED GRADATION

Refresh Workbook TX2MMXD14 - File Version: 01/19/17 15:32:54

SAMPLE ID:	Ty D 64-22 R	SAMPLE DATE:	5/7/2019
LOT NUMBER:	Mix Design	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	Bexar	SPEC YEAR:	2014
SAMPLED BY:	Robert Rios	SPEC ITEM:	
SAMPLE LOCATION:	Port SA	SPECIAL PROVISION:	
MATERIAL CODE:	0341CM0000	MIX TYPE:	341-DG-D
MATERIAL NAME:	ITEM 341 COMPLETE MIX QC/QA ALL MIX TYPES		
PRODUCER:	OLDCASTLE PORT SA		
AREA ENGINEER:		PROJECT MANAGER:	
COURSE/LIFT:	Surface	STATION:	
		DIST. FROM CL:	
		CONTRACTOR DESIGN #:	1764 PORT D
		WMA Additive in Design?	No
		Target Discharge Temp., °F:	315
		WMA TECHNOLOGY:	
		WMA RATE:	
		UNITS:	

Maximum Allowable, %
Frac RAP: 20.0
Unfrac RAP: 10.0
RAS: 5.0
RB Ratio: 20.0

Recycled Binder, %
Bin No.8 : 0.8
Bin No.9 : 0.0
Bin No.10 : 0.0
Total 0.8

Use this value in the QC/QA template>>

AGGREGATE BIN FRACTIONS								"RECYCLED MATERIALS"		
Aggregate	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Source:	Imestone_Dolomit	Imestone_Dolomit	Imestone_Dolomit					Fractionated RAP		Material Type Material Source RAS Type RAP/RAS Produce Sample ID
Pit:	Beckmann	Rio Medina Quarry	Beckmann	Poteet						
Number:	1501503	1516312	1501503							
Producer:	Martin Marietta	Martin Marietta	Martin Marietta	Martin Marietta				Oldcastle Materials		
Sample ID:	1/2" X 3/8"	Gr. 5	Man Sand	Washed Sand				Fine 1/2"		

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
16.3

Recycled Asphalt Binder (%)															Combined Gradation		
4.2															100.0%		
Hydrated Lime?:															19.8	% of Tot. Mix % of Approved	% of Tot. Mix % of Approved
Individual Bin (%):	33.0	Percent	25.0	Percent	15.0	Percent	7.0	Percent		Percent		Percent		Percent	20.0	% of Tot. Mix % of Approved	% of Tot. Mix % of Approved
Sieve Size:		Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Wtd Cum. %	Cum.% Passing	Cum.% Passing	Wtd Cum. %	Cum.% Passing
3/4"	100.0	33.0	100.0	25.0	100.0	15.0	100.0	7.0							100.0	20.0	100.0
1/2"	99.5	32.8	100.0	25.0	100.0	15.0	100.0	7.0							99.8	19.4	98.0
3/8"	62.9	20.8	100.0	25.0	100.0	15.0	100.0	7.0							97.0	19.4	85.0
No. 4	7.6	2.5	60.0	15.0	99.9	15.0	100.0	7.0							75.0	15.0	54.5
No. 8	5.6	1.8	12.6	3.2	87.7	13.2	99.7	7.0							52.9	10.6	35.7
No. 30	2.6	0.9	2.4	0.6	38.9	5.8	80.5	5.6							29.5	5.9	18.8
No. 50	2.0	0.7	2.4	0.6	25.1	3.8	33.5	2.3							22.0	4.4	11.8
No. 200	2.0	0.7	2.0	0.5	8.3	1.2	2.2	0.2							8.0	1.6	4.2

(Bold Italic) Not within specifications (Bold Italic) Not within specifications- Restricted Zone (Italic) Not cumulative

Lift Thickness, in:	2.00	Binder Substitution?	No	Binder Originally Specified:	PG 64-22	Substitute Binder:	
Asphalt Source:	Valero	Binder Percent, (%):	5.1	Asphalt Spec. Grav.:	1.040		
Antistriping Agent:		Percent, (%):					

Remarks:

Combined Gradation

Notes:

Page 1 of 8

11/11/2019

SAMPLE ID: Ty D 64-22 R		SAMPLE DATE: 5/7/2019	
LOT NUMBER: Mix Design		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY: Bexar		SPEC YEAR: 2014	
SAMPLED BY: Robert Rios		SPEC ITEM:	
SAMPLE LOCATION: Port SA		SPECIAL PROVISION:	
MATERIAL CODE: 0341CM0000		MIX TYPE: 341-DG-D	
MATERIAL NAME: ITEM 341 COMPLETE MIX QCGO ALL MIX TYPES			
PRODUCER: OLDCASTLE PORT SA			
AREA ENGINEER:		PROJECT MANAGER:	

**TEXAS DEPARTMENT OF TRANSPORTATION
OLDCASTLE MATERIALS-TEXAS S.A.(FORMERLY APAC-SA)
HMACP MIXTURE DESIGN : Aggregate Classification**

SAMPLE ID:	Ty D 64-22 R	SAMPLE DATE:	5/7/2019
LOT NUMBER:	Mix Design	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	Bexar	SPEC YEAR:	2014
SAMPLED BY:	Robert Rios	SPEC ITEM:	
SAMPLE LOCATION:	Port SA	SPECIAL PROVISION:	
MATERIAL CODE:	0341CM0000	MIX TYPE:	341-DG-D
MATERIAL NAME:	ITEM 341 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER:	OLDCASTLE PORT SA		
AREA ENGINEER:	PROJECT MANAGER:		

COURSE/LIFT:	Surface	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # :	1764 PORT D
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Aggregate Classification											
		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Individual Bin (%)		Bin No.1 = 33 %	Bin No.2 = 25 %	Bin No.3 = 15 %	Bin No.4 = 7 %				Bin No.8 = 20 %		
Aggregate Source:		Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite					Fractionated RAP		
Aggregate Number:		1501503	1516312	1501503					Fine 1/2"		
Class (A) Rock (Y/N):											
Sieve Size:		Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Passing	Retained										
-	3/4"	0.0	0.0	0.0	0.0				0.0		
3/4"	1/2"	0.2	0.0	0.0	0.0				0.0		
1/2"	3/8"	12.1	0.0	0.0	0.0				0.6		
3/8"	No. 4	18.2	10.0	0.0	0.0				4.4		
No. 4	No. 8	0.7	11.9	1.8	0.0				4.4		
No. 8	No. 30	1.0	2.6	7.3	1.3				4.7		
No. 30	No. 50	0.2	0.0	2.1	3.3				1.5		
No. 50	No. 200	0.0	0.1	2.5	2.2				2.8		
No. 200	Pan	0.7	0.5	1.2	0.2				1.6		
Total:		33.0	25.0	15.0	7.0				20.0		
Percent of plus No. 4		30.5	10.0	0.0	0.0				5.0		

Percent of plus No. 8	31.2	21.9	1.8	0.0	9.4
Percent of plus No. 4 from class (A) Rock:	0.0				
Total Percent of plus No. 4	45.5				
Percent of plus No. 4 from class (A) Rock:	0.0				
Percent of plus No. 8 from class (A) Rock:	0.0				
Total Percent of plus No. 8	64.3				
Percent of plus No. 8 from class (A) Rock:	0.0				

Remarks:

TEXAS DEPARTMENT OF TRANSPORTATION
OLDCASTLE MATERIALS-TEXAS S.A.(FORMERLY APAC-SA)
HMACP MIXTURE DESIGN : BULK GRAVITY

SAMPLE ID: Ty D 64-22 R				SAMPLE DATE: 5/7/2019			
LOT NUMBER: Mix Design				LETTING DATE:			
SAMPLE STATUS:				CONTROLLING CSJ:			
COUNTY: Bexar				SPEC YEAR: 2014			
SAMPLED BY: Robert Rios				SPEC ITEM:			
SAMPLE LOCATION: Port SA				SPECIAL PROVISION:			
MATERIAL CODE: 0341CM0000				MIX TYPE: 341-DG-D			
MATERIAL NAME: ITEM 341 COMPLETE MIX QCQA ALL MIX TYPES							
PRODUCER: OLDCASTLE PORT SA							
AREA ENGINEER:				PROJECT MANAGER:			

COURSE/LIFT: Surface		STATION:		DIST. FROM CL:		CONTRACTOR DESIGN # : 1764 PORT D					
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	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10
Individual Bin (%)	Bin No.1 = 33 %	Bin No.2 = 25 %	Bin No.3 = 15 %	Bin No.4 = 7 %				Bin No.8 = 19.8 %		
Aggregate Source:	Limestone, Dolomite	Limestone, Dolomite	Limestone, Dolomite					Fractionated RAP		
Aggregate Number:	1501503	1516312	1501503							
Sample ID:	1/2" X 3/8"	Gr. 5	Man Sand	Washed Sand				Fine 1/2"		

Sieve Size:		Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG	Individual Ret., %	Bulk SG
Passing	Retained																				
3/4"	3/4"																				
3/4"	1/2"	0.5	2.509																		
1/2"	3/8"	36.6	2.509																		
3/8"	No. 4	55.3	2.509	40.0	2.451	0.1	2.420														
No. 4	No. 8	2.0	2.509	47.4	2.451	12.2	2.420	0.3	2.632												
No. 8	No. 30	3.0	2.509	10.2	2.451	48.8	2.420	19.2	2.632												
No. 30	No. 50	0.6	2.509			13.8	2.420	47.0	2.632												
No. 50	No. 200			0.4	2.451	16.8	2.420	31.3	2.632												
No. 200	Pan	2.0	2.509	2.0	2.451	8.3	2.420	2.2	2.632												
Totals		100.0	2.525	100.0	2.451	100.0	2.420	100.0	2.632												

Combined Bulk Specific Gravity:	3.113	Specific Gravity of Asphalt:	1.040
Coarse Agg. Combined BSG:			

Remarks:

TEXAS DEPARTMENT OF TRANSPORTATION
OLDCASTLE MATERIALS-TEXAS S.A.(FORMERLY APAC-SA)
HMACP MIXTURE DESIGN : SUMMARY SHEET

SAMPLE ID:	Ty D 64-22 R	SAMPLE DATE:	5/7/2019
LOT NUMBER:	Mix Design	LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:	Bexar	SPEC YEAR:	2014
SAMPLED BY:	Robert Rios	SPEC ITEM:	
SAMPLE LOCATION:	Port SA	SPECIAL PROVISION:	
MATERIAL CODE:	03H1CM0000	MIX TYPE:	341-DG-D
MATERIAL NAME:	ITEM 341 COMPLETE MIX QCOA ALL MIX TYPES		
PRODUCER:	OLDCASTLE PORT SA		
AREA ENGINEER:		PROJECT MANAGER:	

COURSE/LIFT:	Surface	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN #:	1764 PORT D
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Target Density, %:	96.0
Number of Gyration:	35

CRM* Content, %

Note: This mix design requires an asphalt content of at least 4.2% to meet the Maximum Ratio of Recycled to Total Binder requirement.

TEST SPECIMENS								Mixture Evaluation @ Optimum Asphalt Content			
Asphalt Content (%)	Binder Ratio (%)	Specific Gravity Of Specimen (G _s)	Maximum Specific Gravity (G _m)	Effective Gravity (G _e)	Theo. Max. Specific Gravity (G _t)	Density from G _t (Percent)	VMA (Percent)	Indirect Tensile Strength (psi)	Hamburg Wheel Tracking Test		Overlay Tester: Min. Number of Cycles
									Number of cycles	Rut depth (mm)	
4.5	18.5	2.322	2.452	2.620	2.459	94.4	15.6	145	5,000	3.1	
5.0	16.6	2.339	2.440	2.626	2.441	95.8	15.4				
5.5	15.1	2.345	2.432	2.637	2.424	96.7	15.7				

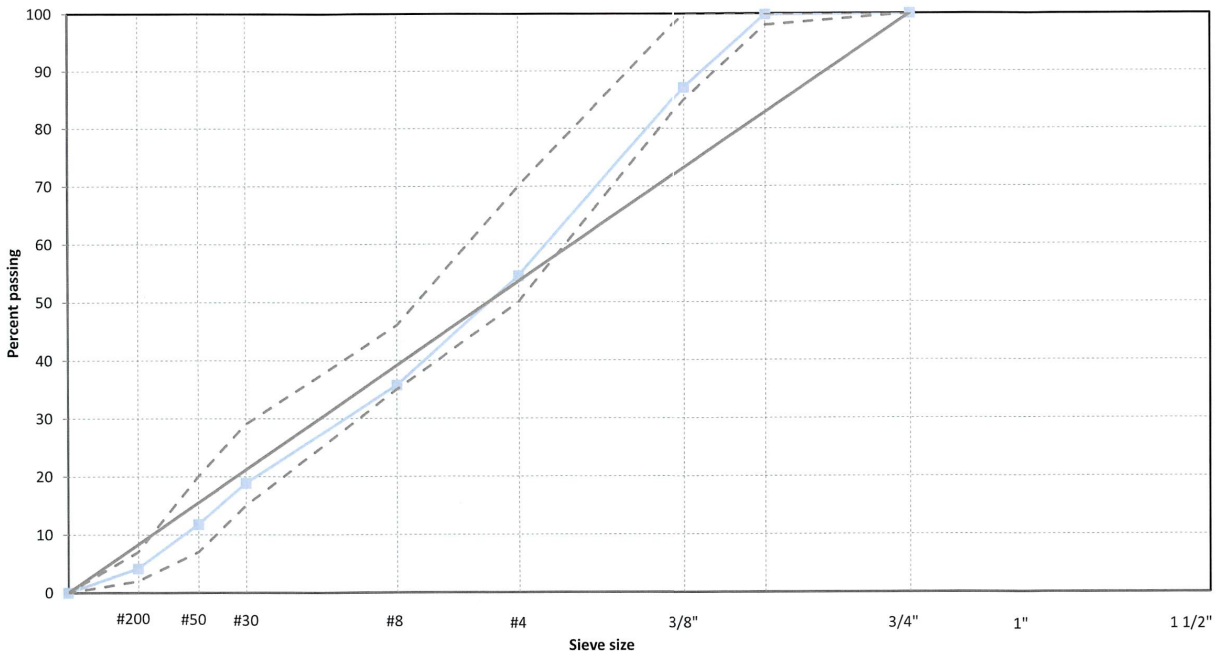
Effective Specific Gravity:	2.628
Optimum Asphalt Content:	5.1
Binder Ratio @ OAC:	16.3
VMA @ Optimum AC:	15.5

Estimated Percent of Stripping, %:

Interpolated Values	
Specific Gravity (G _s):	2.340
Max. Specific Gravity (G _m):	2.438
Theo. Max. Specific Gravity (G _t):	2.438

Mixing Temp., F:	295
Molding Temp., F:	250

Remarks:



Terracon Asphalt Lab Report

Project: FB196108
 Contractor: _____
 County: _____

Project No.: _____
 Mix Type: D A-C
 Supplier: _____

Sample Date: _____
 Sample Time: _____
 Sample Temp °F: _____
 Truck No.: _____
 Ticket No.: _____
 Plant No.: _____
 Mix Design No.: _____

Sieve Analysis

Sieve Size	Weight (gr)	Ind. % Ret.	Cum. % Ret.	% Pass	JMF
1 3/4"					
1"					
3/4"					
1/2"					
3/8"					
#4					
#8					
#16					
#30					
#50					
#100					
#200					
Pan					
Total Wt.					

Lab Molded Density

Specimen No.	1	2	3
Specimen Height	115.4	116.9	116.6
Air Weight	4700.2	4700.9	4701.2
Weight in Water	2716.7	2699.5	2703.9
SSD Weight	4706.7	4714.2	4715.2
Bulk Volume CC	1990.0	2014.7	2011.3
Specific Gravity	2.362	2.333	2.337
Unit Weight (pcf)			
% Absorption by Vol.			
% Density	96.1	95.5	95.6
% Air Voids			
% VMA			
% Voids Filled			
Average Bulk Specific Gravity			
Average Lab Density			95.9

Asphalt Content	NA
AC JMF	NA

Rice Gravity

Water Temp: 77
 -3/4
 Wt. of Calibrated Pyc.: 1437.5
 Wt. of Dry Sample in Air: 1051.8
 Wt. of Sample in H₂O: 2059.0
930.3 G: 2.494
 + 3/4 152.5
 Wt. of Calibrated Pyc.: _____
 Wt. of Dry Sample in Air: _____
 Wt. of Sample in H₂O: _____
 G: _____

Technician: TC

Comments:

Ignition Oven Method

Basket Weight _____ g
 Sample + Basket Weight _____ g
 Sample Weight _____ g
 Sample + Basket Weight after Ignition _____ g
 Sample Weight Loss _____ g
 AC = (Loss / Orig Sample Weight) x 100 _____ %

Stability

Average
 Hveem
 Marshall Stability
 Marshall Flow

Specimen	1	2	3
Load (lbs)			
Flow (mm)			
Flow (in)			

APPENDIX B - NETWORK ANALYZER

The free-space method uses a network analyzer with two antennas pointed at one another with a MUT positioned in-between the antennas. An example free-space method setup is shown in Figure B-1. To measure the dielectric properties at ADT frequencies (~ 95 GHz), a millimeter-wave setup, which operates in the W-band, is used. The setup shown in Figure B-1 consists of a network analyzer (Agilent Technologies N5222A VNA), a millimeter head controller (N5261A), two millimeter-wave extenders (OML Inc. V10VNA2-T/R mm-wave VNA Extender), two horn antennas, and two lenses.

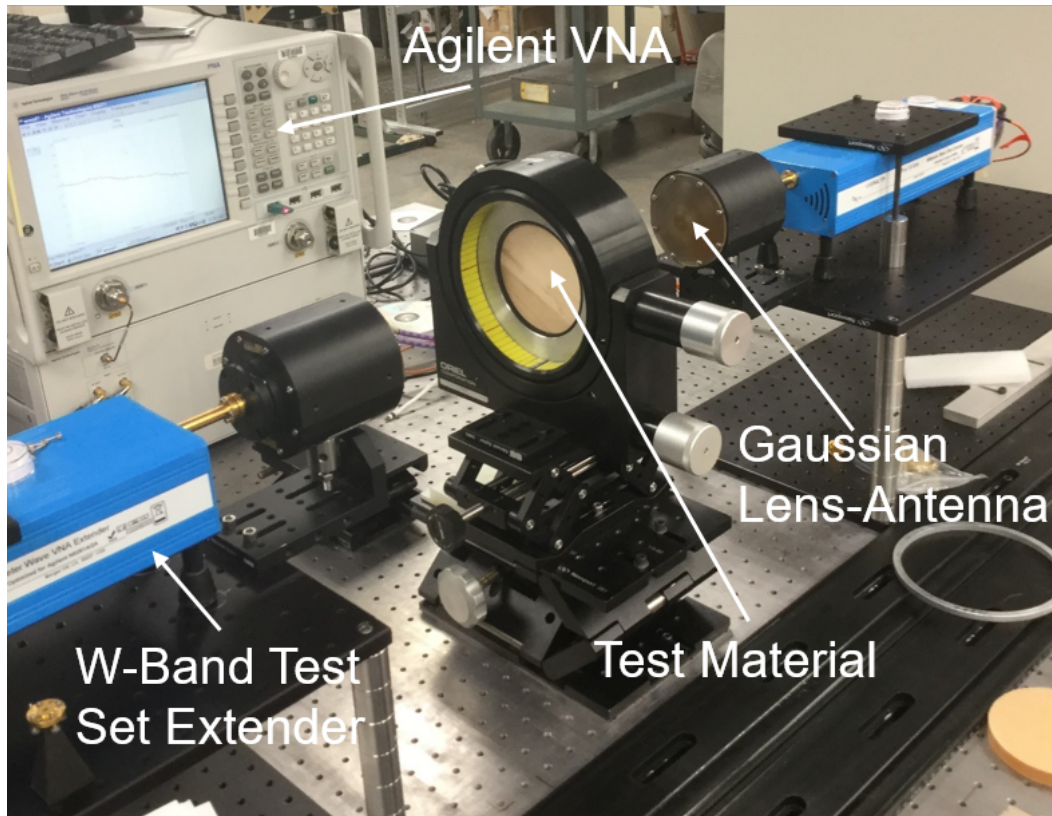


Figure B-1. A picture of the free-space method setup. The VNA (Agilent VNA, Model 5222a, PNA-series) is extended to operate in the W-Band and connected to the two antennas that face one-another with the MUT placed in between the two antennas.

B.1 Network Analyzer Measurements

The network analyzer and space in-between the antennas is a two-port network that can be described by the S-Parameters S_{11} , S_{12} , S_{21} , and S_{22} . These S-Parameters are used to calculate the relative dielectric permittivities for a given material under testing. However, without any calibrations, the S-Parameters contain noise from multiple reflections between the surfaces of the sample and antennas, diffraction at the edges of the sample, and other sources of interference. To reduce these effects, the network is calibrated with the Thru-Reflect-Line (TRL) and Gated-Reflect-Line (GRL) calibrations. The TRL calibration normalizes the measurements and removes

the VNA, cables, W-Band Test Extender, the output waveguides from the measurements. The GRL calibration is performed following the TRL calibration to remove errors due to the lens-antenna and fixtures in the free-space transmission line setup. The full calibration and measurement procedure, which was used as a guide performing measurements, is outlined in the document inserted in subsection B.2. However, the procedure was not always followed exactly (e.g., the lens-antenna setup used to measure the materials is different than the setup mentioned in the procedure). The Millitech CDA-10-990367A (7.5 in. focal length, 0.586 in. spot size) lens-antenna setup was used for every material measurement, except asphalt. For asphalt, the SAGE millimeter SAQ-903017-10-51 (1.7 in. focal length, 0.20 in. spot size) lens-antenna setup was used.

Each sample has been measured multiple times and at different locations to capture variations in the measuring methods and the sample itself. For the samples held in the 4 in. diameter sample holder, the samples have been measured 12 times, where the sample is rotated in-plane in 30° increments between each measurement. (Note: the glass and acrylic samples showed little to no variation from one rotation position to the next position. Hence, limited measurements were performed on these material types.) The network analyzer beam is centered 1 in. away from center of the sample to allow for multiple measurements of the same sample. For homogeneous materials (e.g., acrylic), this should provide the opportunity to see if there are any effects from how normal the beam is to the sample and if there is any effect from the variation in thickness across the sample. For inhomogeneous samples (e.g., asphalt), the variation will also include effects from different material composition at different locations. This method also allows for multiple measurements without having to re-calibrate the network analyzer.

For the materials prepared as rectangular planes (bricks), the sample was measured at 5 different locations with one measurement in the center (p3), 1 in. to the right of center (p1), 0.5 in. to the right of the center (p2), 1 in. to the left of center (p5), 0.5 in. to the right of the center (p4).

B.1.1 Asphalt

The asphalt samples had rougher surfaces than the other materials being measured. To accommodate for the rougher surfaces and the 1 in. thickness, a different antenna and lens combination has been used to perform measurements. The combination resulted in a smaller beam diameter. The smaller beam diameter results in a larger incident power density, which in turn, produces a larger transmission measurement. The smaller diameter was also selected to measure a more uniform surface area than a beam with a larger diameter. Because of the smaller beam diameter, the sample was measured along two different circular paths, an inner and outer path. The beam was radially offset from the center by 1/4 in. and 1/2 in. to form the two paths.

B.1.2 Cinderblock

The cinderblock samples were initially too thick and were trimmed down from ~1 in. thick to ~0.5 in. thick samples. After trimming the samples, one side of each sample was rougher than the other side and striations were formed on the samples. To account for this, each sample was measured in six positions. Four positions where the rough side faced port 2 and two positions where the rough side faced port 1. The four positions with the rough side facing port 2 include two positions where the striations were parallel to the E-field polarization and were displaced from each other by 1 in., and two positions where the striations were perpendicular to the E-field polarization

and displaced from each other by 1 in. The two positions with the rough side facing port 1 include one position where the striations were parallel to the E-field polarization and one position where the striations were perpendicular to the E-field polarization.

B.1.3 Sand

Measuring a loose material such as sand required a modification to the free-space method setup previously used for the other materials. To hold the sand for measurement, two different containers had been used. One container was constructed out of Rexolite® 1422 and the other container was constructed out of Styrofoam. The Rexolite 1422 was selected because of its minimal attenuation of millimeter-wave signals, while the Styrofoam was selected because its permittivity is ~ 1.05 according to Baker-Jarvis et al., 2005.

Two methods have been evaluated to measure the permittivity values of sand. The first method involved an initial GRL calibration without any container in the free-space sample-holder fixture. Then the container is placed in the sample-holder fixture and the sand is poured into the container. The S-parameters of the sand are then measured. The network analyzer's *de-embed* function is applied to the S-parameters to remove the effects of the container while calculating the permittivity. However, the produced S-parameters will still contain the effects of the container. Because the Styrofoam container has permittivity values close to air, its values were only slightly effected. The Rexolite 1422 container has been tested against a known CPVC sample and had good agreement with the known values.

The second method involved an initial GRL calibration with the container in the free-space sample-holder fixture. This de-embeds the container from the S-parameter measurements of the sand. When performed with Rexolite 1422, the calculated ϵ'_r shifted by $\sim 1.5\%$. The Styrofoam being close to air in permittivity, allows for the measured S-parameters to be a cleaner S-parameter measurement than the first method.

For the sand permittivity and reflectivity values presented in this report, the first method was used with a Styrofoam container. The container positioned inside the sample-holder fixture is shown in Figure B-2.

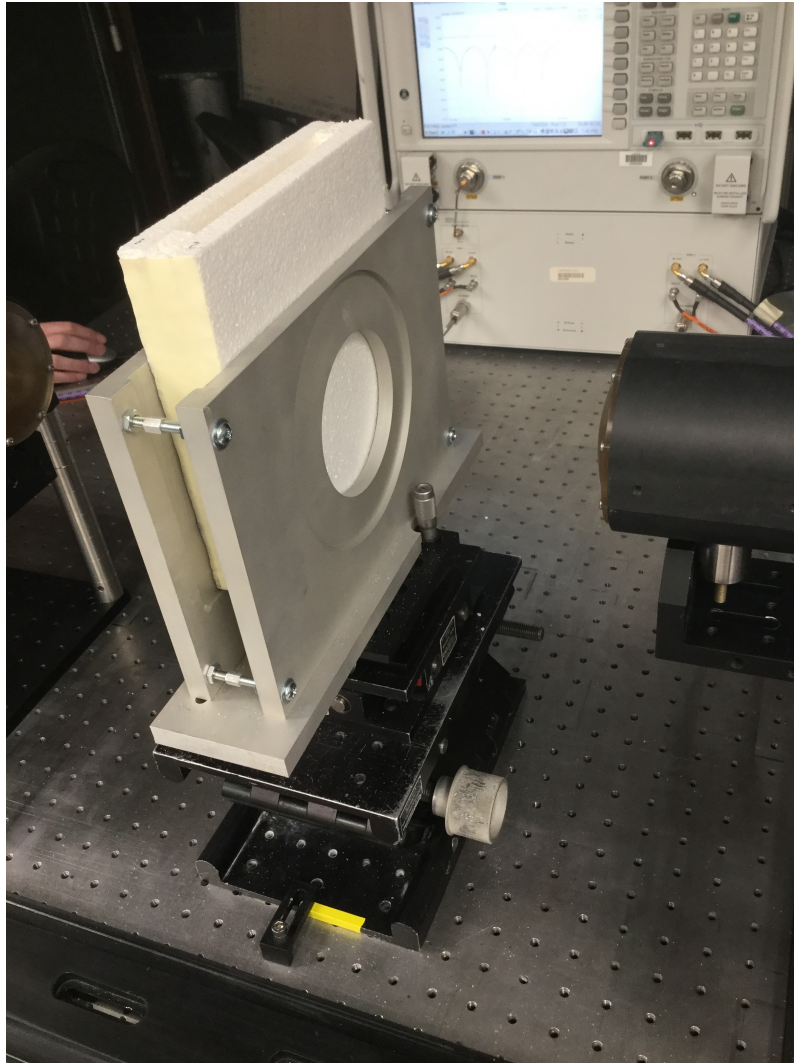


Figure B-2. The Styrofoam container used to hold sand.

B.1.4 Laboratory Conditions

The environmental conditions during measurements are presented in Table B-1. Relative humidity levels have been shown to have an effect on the moisture content on materials measured; in particular, wood and sand. The moisture content will have an effect on the permittivity measurements and has been shown to have an effect on wood in the 0.1-0.6 THz band by Todoruk, Hartley, and Reed, [2012](#). The materials were stored openly in the laboratory. The temperature and relative humidity have been measured with a Traceable Excursion-Trac™ Thermohygrometer with Calibration, Cole-Parmer item #EW-98767-14. The temperature and relative humidity resolution is 0.1 °C and 0.1%, respectively. The temperature and humidity accuracy is ± 0.4 °C and $\pm 0.3\%$ within 5 to 75% relative humidity and 5% otherwise, respectively. Because HERTF is located in a high-altitude desert, the hygrometer needed to be able to measure low relative-humidity values.

Table B-1. Environmental Conditions

Material	Ambient Temperature (°C)	Relative Humidity (%)
Acrylic (1)	22.9	32
Acrylic (2)	22.9	31
Drywall (1)	23	22.3
Drywall (2)	22.9	23.9
Birch Plywood (1)	22.8	27
Birch Plywood (2)	22.8	24.7
Maple Plywood (1)	23.1	32
Maple Plywood (2)	22.9	30
Red Brick (1)	22.8	13.5
Red Brick (2)	22.9	12.4
Gray Brick (1)	22.7	16.0
Gray Brick (2)	22.7	16.0
Cinderblock (1)	22.8	12.5
Cinderblock (2)	22.8	12.5
Asphalt (B1)	25.4	9.3
Asphalt (B2)	25.5	9.5
Asphalt (B3)	25.3	8.9
Asphalt (C1)	25.3	8.9
Asphalt (C2)	25.3	8.8
Asphalt (C3)	25.4	9.1
Asphalt (D1)	24.9	8.6
Asphalt (D2)	25.1	8.6
Asphalt (D3)	25.2	8.7
Concrete (1-1)	22.6	9.1
Concrete (1-2)	22.6	9.1
Concrete (2-1)	22.5	10.1
Concrete (2-2)	22.4	9
Concrete (3-1)	22.6	8.9
Concrete (3-2)	22.6	8.7
Concrete (5-1)	22.7	8.7
Concrete (5-2)	22.8	8.6
Concrete (6-1)	22.8	8.5
Concrete (6-2)	22.8	8.4
Quikrete Fine	22	20.8
Quikrete Medium	22.4	21.2
Sand Express	22.5	21.1
Glass	22.6	15.7

The ambient temperature and relative humidity in the laboratory during the VNA measurements of given material.

B.2 Network Analyzer Calibration Procedures

Inserted in the immediately proceeding pages are the network analyzer methods to calibrate the network. These methods include the TRL and GRL techniques.

N5222A Full Calibration (TRL & GRL) Procedures

Task Description/Scope

These procedures outline the steps required to complete a Thru-Reflect-Line (TRL) and Gated-Reflect-Line (GRL) calibration for the Agilent N5222A Vector Network Analyzer (VNA).

Purpose

To provide instructions/procedures for performing a full two port VNA calibration required for Free Field Measurements.

When to Perform

When performing material S-parameter and permittivity characterizations of materials.

Definitions

GRL	Gated-Reflect-Line
TRL	Through-Reflect-Line
VNA	Vector Network Analyzer

Equipment and Tools

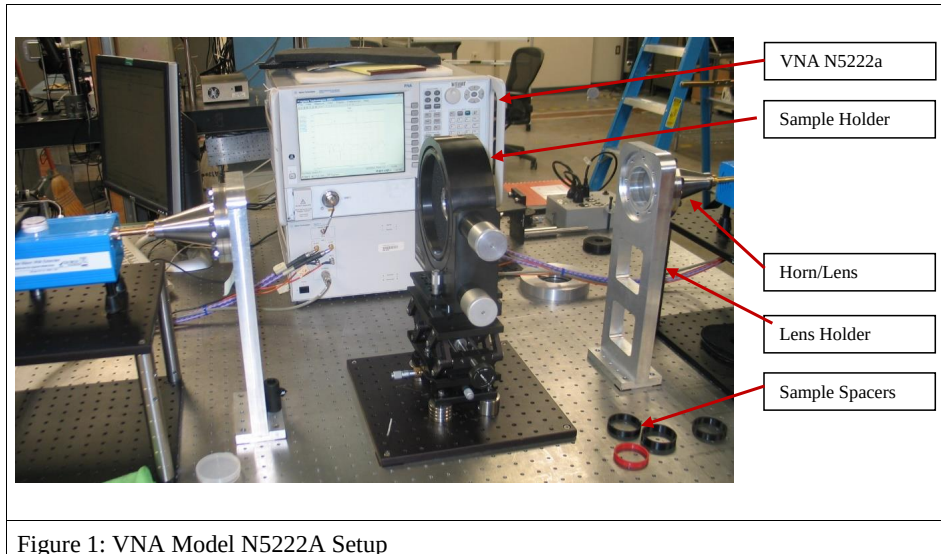
Agilent Technologies N5222A VNA with N5261A Millimeter Head Controller	Aluminum calibration disc, $t = 0.2505''$
Agilent W11644A Cal Kit Including: WR-10 Short Blank disk WR-10 Offset: $\frac{1}{4}$ wavelength spacer (# 00273) Fixed Termination> Matched Load #11643-60076 (S#00333) WR-10 Standard Thru: # 11644-60013 (S# 00662)	Alignment equipment: 4.5" conflat flange (x2) Oriel Corp. 17800 sample holder Laser Tools 540 nm laser ThorLabs DG10-1500-H1-MD
2" precision WR10 waveguides (x2)	Allen Wrenches (.050, 3/32)
OML Inc. V10VNA2-T/R mm-wave VNA Extender (x2)	Mitutoyo CD-8"C caliper
MilliTech GOA-10-120733B horn antennas (x2)	Clips
Software: Agilent Technologies 85071 and PNA-Series Network Analyzer	

Warnings and Precautions

	No Safety Concerns
	Note. When performing a calibration, a Server Busy error will pop-up if the computer mouse isn't moved for three minutes. Click on the Switch To ... button to continue with calibration.
	When removing and installing the calibration disk and samples from the sample always install the item from Port 2 (right) side. <u>Never</u> remove/rotate the Port 1 side threaded ring.

Bold text requires the operator to click on the command
Regular text commands require the operator to hover over the command
Italic Comments, no commands

Procedures



Power up VNA (Vector Network Analyzer)

1. Turn on VNA and millimeter head controller
 - a) Push N5222a power on button
 - b) Toggle on N5261a power switch
2. For accurate results wait 30 minutes (one hour is better) for components to reach thermal equilibrium

Open VNA Software Programs

1. Open PNA-Series Network Analyzer program from Desktop
 - a) Double Click on “**Network Analyzer**” icon. PNA-Series Network Analyzer Program will Launch. Wait for Waveform screen to appear.
 - b) Minimize PNA-Series Network Analyzer Program
 - **File > Minimize Application**
2. Open Agilent 85071 control/setup program
 - a) Double click on “**85071**” icon Polar chart will appear
 - b) Minimize VNA Network Analyzer Smith chart page
 - **File > Minimize Application;** “Agilent Technologies 85071” active waveform page will appear

Set up VNA Sample Holder Freespace Settings. (On “Agilent Technologies 85071” page)

1. **Measure > Define measurement...**
2. Set up the Sample holder Freespace setting



Do not click on the keyboards “Enter” key while perform the calibrations. It accepts it as an OK and goes to next section. Do not click on the pages “OK” button until step d.

- a) **Set Frequency** tab for W-band measurements, Transmission Epsilon Fast (Tran e Fast) Model, Full 2-Port Cal, Sample is multiple of 12 wavelength
 - Start freq: **75 GHz**
 - Stop frequency: **110 GHz**
 - Power: **11 dBm**
 - IFBW: **300 Hz**
 - Num pts: **201**
 - Select **Linear sweep**
- b) **Measurement Model** tab
 - In Measurement Box, select **Tran e Fast**
 - Put check in **Verify Estimate** box
- c) **Sample Holder** tab
 - Select/Check Mark “**Freespace**” in sample holder box located on the right. *Changes test in test setup description*
 - Metal plate thickness (Enter the calibration metal plate thickness): **0.2505**
 - Distance to sample: **0”** (Enter the distance from target sample surface to the calibrated metal plate surface on port 1 side)
 - Sample thickness: **0.25** (Enter thickness of the test sample under test)
 - Select **Inch** in Units box
 - Enter check mark in the **Show when measuring or recalculating** box
- d) Click **OK**. “TR 1 S₂₁ Polar...” polar plot page, “PNA-Series Network Analyzer” program should appear;
 - “**File > Minimize Application**” Agilent Technologies 85071” screen should appear

Select Existing TRL (Thru-Reflection, Line) Calibration If using existing TRL file

Perform all TRL and GRL calibrations with 2” precision WR10 waveguide attached to the W-band Extender heads

1. If you are creating a new TRL file skip to next section “Set up for TRL (...”
2. Select Desired Cal Set
 - a) **Measure > Select Cal Set > Select Cal set pop-up appears**
 - b) Under “Description :GUID” pull down, Select desired TRL file (Ex. 0_TRL201_20180905_Paul)
 - c) Click on **OK** S11... Polar Plot window will pop up
 - d) Click on **File > Minimize Application**
3. Skip to “Mechanically Align Sample Holder” section on Page 5.

Set up for TRL (Thru-Reflection, Line) Calibration (from “Agilent Technologies 85071” page)

1. Set up Freespace calibration parameters
 - a) **Measure** tab > **Freespace calibration** > **Perform a Gated Reflect Line calibration from a cal set (GRL)**
 - b) Click **Cal Wizard** button to begin TRL calibration. “Calibration Wizard: Begin Calibration” page will pop up.
 - c) Select “**UNGUIDED calibration ...**”
 - d) Click on “**Next**” “Select Calibration Type for Mechanical Standard” pop-up will appear
2. Select calibrate type
 - a) Select **TRL** (through-reflect-line)
 - b) Select ports = **1-2**
 - c) Click **View/Select Cal Kit**
Select **W11644A**
 - d) Click on “**OK**”
 - e) Select **Next** “Select Calibration type for Mechanical Standards” pop-up will appear
3. Select Calibration Type

- a) Select **THRU Standard** and **LINE Standard**
- b) Select **Next** Calibration components screen will appear

Perform TRL Calibration Use the Agilent W11644A calibration kit, containing short and line standards

1. Perform calibration on Port 1
 - a) Attach short to Port 1 (the solid metallic disc)
 - b) Finger tighten short screws then torque them using a ¼ turn of the Allen key
 - c) Click **SHORT** under Port 1 *Green check mark will appear above calibration box*
 - d) Trace should be between +/-3 dB
2. Perform calibration on Port 2
 - a) Attach short to Port 2
 - b) Finger tighten short screws then torque them using a ¼ turn of the Allen key
 - c) Click **SHORT** under Port 2 *Green check mark will appear above calibration box*
 - d) Trace should be between +/-3 dB
3. Perform line (1/4 wavelength) calibration
 - a) Remove short and bolt both extender waveguides together with quarter wave line in between (thin metal disc)
 - b) Use long screws (in cal kit) with same torque. 2 vertical from left, 2 horizontal from right
 - c) Click **LINE** “Multiple Standards – Choose to cover....” pop-up menu will appear
 - Click **W-band 1/4 wavelength line** Wait for calibration to finish and check mark in box
 - Click on **OK**
 - d) S₁₁ and S₂₂ should be -20 to -30 dB
4. Perform Thru calibration
 - a) Remove line and attach extender waveguides (using short screws) together
 - b) Click **Thru**
 - c) S₁₁ and S₂₂ should be between -20 and -30 dB
 - d) **Do not disconnect the two extender waveguide flanges from each other until “Save S-Parameter TRL Calibration” section is completed**
5. Skip the Isolation (optional) step
6. Click **Next** > to finish TRL calibration *Save File pop-up box will appear.*
7. Save File
 - a) **Save as User CalSet** with the following name convention:
0_TRL#Points_date_name) e.g. 0_TRL201_20181024_Telmer
 - b) Click on **Save** *Keep thru connection until told to remove. Polar plot will appear*

Note: Calibrations are automatically stored in C:\Program Files\Agilent\Network Analyzer\UserCalSets\

Verify TRL Calibration

1. Adjust Marker so it is at 95 GHz
 - a) Right click on the reference frequency marker on right top of page “>: 92.500 GHz ...” *Marker box will pop up*
 - b) Click on **Marker**
 - c) Click in frequency box and enter **95G**. Verify On is checked *It will fill in the rest.*
 - d) Click on **OK**
2. Change from Polar to Logarithmic Scale
 - a) Right click on **Tr 1 S₂₁ Polar 1.000** > Format > **Log Mag**
 - b) Right click on the **Y-axis** > **Auto Scale**
3. Verify Thru calibration
 - a) To change waveform displayed right click on the displayed traces name > **Measure....**

- b) Click in box adjacent to desired trace
- c) Click on **OK**
S11 and S22: <-50 dB (ex. -55 dB)
S12 and S21: Between -.01 and .01 dB
4. Evaluate error terms
 - a) **Response** > Cal > Manage Cals > **Cal Set Viewer**
 - b) Select the TRL calibration from dropdown menu. (e.g. 0_TRL201_20180530_Paul)
 - c) Check the **Enable** box on right “*TR2 Cross Talk (1,2)....*” will pop-up
5. Select term you would like to compare in right dropdown menu > right click y-axis > **autoscale axis**
 - a) Most important terms:

SourceMatch (1, 1)	right click y-axis > autoscale axis	approximately -30 to -50 dB
SourceMatch (2, 2)	right click y-axis > autoscale axis	approximately -30 to -50 dB
LoadMatch (1, 2)	right click y-axis > autoscale axis	approximately -20 to -30 dB
LoadMatch (2, 1)	right click y-axis > autoscale axis	approximately -20 to -30 dB
TransmissionTracking (1, 2)	right click y-axis > autoscale axis	between -2 and +2 dB
TransmissionTracking (1, 1)	right click y-axis > autoscale axis	between -2 and +2 dB
ReflectionTracking (1, 1)	right click y-axis > autoscale axis	between -4 and +4 dB
ReflectionTracking (2, 2)	right click y-axis > autoscale axis	between -4 and +4 dB
 - b) Compare cal set to previous one, ensuring similarity
 - Double-click **Calset** *CalSet Viewer drop down box appears, turns blue*
 - Select recent calibration you believe is correct
 - Ensure similarity
 - Close out drop down box

Open and Save S-Parameter TRL Calibration

1. Plot S-Parameters to save them *The S-Parameters will be used to create the GRL Calibration files:*
 - a) Make sure ports are still attached in Thru set up
 - b) Scale S21 Y-axis: Select S₂₁ in top menu > right click y-axis > **Autoscale axis**
 - Note: expected values for S₁₂, S₂₁ +/- .01 dB
 - c) Bring S₁₂ on screen
 - Right click anywhere on graph (not on the S₂₁ trace)
 - Click on **New Trace**
 - Select S₁₂
 - Click on “**OK**”
 - Scale S₁₂ Y-axis:
 - Select S₁₂ in top menu > right click y-axis > **Autoscale axis**
 - d) Bring S₁₁ on screen
 - Right click anywhere on graph (not on the current traces)
 - Click on **New Trace**
 - Select S₁₁
 - Click on “**OK**”
 - Scale S₁₁ Y-axis:
 - Select S₁₁ in top menu > right click y-axis > **Autoscale axis**
 - Expected value is less than -65 dB
 - e) Bring S₂₂ on screen
 - Right click anywhere on graph (not on the current traces)
 - Click on **New Trace**

- Select S_{22}
- Click on “OK”
- Scale S_{22} Y-axis:
 - Select S_{22} in top menu > right click y-axis > **Autoscale** axis
- Expected S_{22} less than -65.0 dB
- f) Uncheck **Enable** in CalSet Viewer
- g) Create S-parameters file
 - **File > Save Data As** Enter name
 - > Format: *Date_Name_TRL_S-Par_cal* (e.g. 20180530_Paul_TRL_S-Par_cal)
 - Click on **Save** Select desired format
- h) **File > Print > Print to File** > same naming format as g) (choose JPEG format)

Mechanically Align Sample Holder *If Lens/horns and Sample holder are already mechanically aligned skip to “Perform Free Field GRL (Gated....” on Page 8*

1. Separate the ports and install the horn antennas
 - a) Unscrew ports, leaving 2” waveguide extenders on the extender head
 - b) Unscrew, slide, and bolt extender head baseplates to extender baseplate outline on optical table (Lens approximately 26” apart).
 - c) Attach horn antennas with supports to extender waveguides (ensure transmitter (as labeled) on your left, receiver right) (1/2” Cap screws)
 - d) Install sample holder between horn antennas (5” from antenna’s baseplate to holder’s baseplate, outlined on table)
2. Align laser with horn lenses *Cover VNA screen to reduce area light and turn off room lighting as needed*
 - Attach 4.5” conflat with laser to Port 2 and conflat with ThorLabs opaque/reflector tube to Port 1
 - Plug in laser and align laser beam with middle of opposite center conflat. If laser isn’t centered on Port 1’s opaque disk and the reflection isn’t centered on Port 2’s laser:
 - If close on both or off by relative amounts (Port 2 off by twice Port 1’s distance) adjust laser three point Allen bolts (.05” Allen) located on sides of lasers blue base
 - If far off or isn’t off by a relative amount (ex. Off on Port 1 at top right and the reflection on port two is on bottom right):
 - Loosen all three set screws completely (laser beam should settle on center of Port 1 target)
 - Slowly screw in all screws until they are about to move the internal laser
 - Slowly tighten each screw until tight and beam and its reflection are centered in Port 1 and Port 2
 - Check alignment by rotating laser conflat to the 90 and 180 degree position.
3. Align sample holder
 - Place ThorLabs mirror/opaque disc (DG10-1500-H1-MD) insert into sample holder, holding in place with thin black metal rings (right side) in sample holder
 - Horizontally and Vertically center laser on opaque disc: See Page 8 for sample holder controls
 - Remove opaque disc
 - Use sample holders rotational controls to center reflected beam at laser source
 - Loosen Allen set screw (1/16” Allen wrench) at bottom rotational scale to rotate about “Z” axis
 - Remove mirror/opaque disc (unscrew thin black ring from right side)
4. Remove laser alignment conflat from both port 1 and 2
5. Insert 2505” thick, free field, flat, aluminum, calibration reflector disk into sample holder from Port 2 side.
6. Minimize “PNA-Series Network Analyzer” program
 - a) Click on **File > Minimize Application**
7. Electrically center the aluminum short
 - a) Mechanically position the aluminum calibration disk equal distance as centered between Port A and Port B with Calipers/ruler.

- b) Select Calibration
 - In “Agilent Technologies 85071” program: **Measure > Freespace Calibration... > Perform a gated reflect line calibration from a calset (GRL)**
 - Select desired TRL calibration set from dropdown. Ex: 0_TRL201_Date_Name_TRL1
 - Click on “**Next**” *S11 Polar Plot appears*
- c) Turn on S11 and S22
 - Screen should be displaying “PNA-Series Network Analyzer” program
 - If Trace 1 (TR1) isn’t S11, right click on the S-parameter portion of the trace name. Ex: “**Tr1 S21 Polar 1.000u/ 1.00U**” portion in the trace name.
 - Click **Measure...** > Click in S11 box
 - Click on **OK**
 - Turn on Trace T2 S22
 - Click on **Trace/Chan** > Trace > **New Trace** > Click in “**S22**” box.
 - Click on **OK**
 - Format both TR1 and TR2 to log Mag *If not already in Logmag*
 - Right Click on “**TR1 S11...**”
 - Format > **Log Mag**
 - Right Click on “**TR2 S22...**”
 - Format > **Log Mag**
- d) Convert both S11 and S22 to time domain *From PNA-Series Network Analyzer Program*
 - Click on Trace 1 (**Tr1 S21 Polar 1.000u/ 1.00U/**) heading **TR 1** in trace heading will highlight
 - **Marker/Analysis** > Click on **Transform...** “*Transform*” pop up will appear
 - Verify/Click **Band Pass** box is selected
 - Click in **Transform** box to put check in box
 - Verify Start = 0 ns; Stop = 10 nS; Center = 5; Span = 10 ns
 - Click on **Coupler Settings** “*Trace Coupling Setting*” pop up will appear
 - Verify/Check all **boxes** in both the Transform and Gating Parameter boxes
 - Click on **OK**
 - Click on **OK**
 - Click on Trace 2 (**Tr2 S22 Polar 1.000u/ 1.00U/**) heading **TR 2** in trace heading will highlight
 - **Marker/Analysis** > Click on **Transform...** “*Transform*” pop up will appear
 - Click in Transform **Box**
 - Verify Start = 0 ns; Stop = 10 nS; Span = 10 ns;
 - Click on **Band Pass**
 - Click on **Coupler Settings** “*Trace Coupling Setting*” pop up will appear
 - Verify/Check all boxes
 - Click on **OK**
 - Click on **OK**
 - Right click on vertical scale > **Autoscale All**
 - With mouse draw box around the tallest paired peak approximately 3 ns (36” travel time) from T0
 - Click on **Zoom xy**
 - Adjust sample holder X-axis knob F until peaks align.



Note the time for the sample holder peak (in ns). This value can be used in the “Perform Free Field GRL (Gated, reflection, Line) Calibration” section.

Alignment of the target holder with lenses is complete



When removing and installing the calibration disk and samples from the sample always install the item from Port 2 (right) side. Never remove/rotate the Port 1 side threaded ring.

Reset/Verify Correct TRL Cal Set

1. Set up/verify the TRL
 - a) **File > Minimize Application** “Agilent technologies 85071” program “Set time domain parameters” popup will appear
 - b) Click on **Back Cal Set** Pop-up will appear. The desired cal set should be in the dropdown menu
 - c) Click on **Next** “S11 Polar plot will appear
 - d) Click on **File > Minimize Application** “Set time domain parameters” popup will reappear

Set up Time Domain Parameters

1. Set up the “Time domain parameters” *The time domain parameters determine the gating time window used to eliminate the non-sample reflections*

If using the standard configuration described in the warning box above, skip to 2.b,

 - a) If using the standard setup described in note above, enter the following time domain parameters else skip to b):
 - Search Start Time = 3.0 ns > Search Stop Time = 3.2 ns *The VNA will search for the peak in this time window*
 - Gate Span is .6 ns *The gate span will be +- .3 ns around the peak in the time window*
 - Gate Shape = Minimum
 - Click **Next**
 - Skip to step 3
 - b) Determine Time Domain Parameters (If you already know them (see standard setup above) skip to Step 3)
 - a) Delete all traces
 - b) New trace > check S11, S22 > OK
 - c) Marker/analysis > transform... > check transform > OK (for both S11 and S22) (20 ns span)
 - d) Right click y-axis > scale coupling > check ‘all’ > Right click y-axis > Autoscale
 - e) Stimulus > trigger > continuous
 - f) Right click S11 > Add marker
 - Find large peak
 - To calculate where the actual peak is approximately = two way travel distance (in) / 12 (in) in ns
 - Draw box around peak > zoom xy (repeat as necessary)
 - Center marker on peak > right click marker > search > max
 - g) Repeat (f) for S22
 - h) Adjust sample holder (using x-axis translation) until both peaks completely overlap
 - i) Right click marker > search > bandwidth (repeat for S11 and S22)
 - j) Compare bandwidth values (should be within 2 dB), take picture of values
 - k) File > Minimize
2. Enter time domain parameters in 85071
 - a) Note: you may have to click back > next > (should plot polar graph of S11)
 - b) File > Minimize (return to 85071)
 - c) Enter time domain found in PNA Network Analyzer (limits are ± 0.3 ns from peak max)
 - d) Enter “Search START Time” (Current standard setup = 3.0 ns)
 - e) Enter “Search Stop Time” (Current standard setup = 3.2 ns)
 - f) Enter “Gate Span” (Current standard setup = .6 ns)
 - g) Gate shape: Minimum
 - h) Click Next “Measure Plate” window will appear

3. Measure free field reflector
 - a) Enter cal plate thickness (.2505" for standard calibration plate)
 - b) Click **Measure** (or Re-Measure) "Measure Empty Fixture" pop-up will appear
 4. Measure Empty Fixture
 - a) Remove Aluminum calibration disk from Port 2 side
 - b) Install, .2505 spacer, spacer ring, and capture ring.
 - c) Click on **Measure** "Description" pop-up box will appear
 5. Save and activate the GRL calibration
 - d) For calibration description use name format Date_Name_GRL_cal (e.g. 20180530_Paul_GRL_cal)
 - e) Click **Finish** "Calculating Coefficients" followed by "Gated resp/isol" pop-up's will appear
 - f) Select **Yes** to the "Do you want to apply the gated response isolation cal to your measurement?" question.
- Note: Calibrations are automatically stored in C:/Program Files\Agilent\Network\ Analyzer\UserCalSets\



Gating can be disable/enable from the **Measure > Free-space calibration** menu

If using Existing GRL (Gated, Reflection, Line) Calibration *If desire to create new GRL Calibration skip to "Perform Free Field GRL (Gated, Reflection, Line) Calibration" next section*

1. Select TRL file
 - a) **Measure > Select Cal Set > Select Cal set pop-up appears**
 - b) Under "Description :GUID" pull down, Select desired TRL file (Ex. 0_TRL201_20180905_Paul)
 - c) Click on **OK** S11... Polar Plot window will pop up
 - d) Click on **File > Minimize Application**
2. Select GRL file
 - a) **Measure > Select Cal Set > Select Cal set pop-up appears**
 - b) Under "Description :GUID" pull down, Select desired GRL file (Ex. 20180905_Paul_GRL_cal)
 - c) Click on **OK** S11... Polar Plot window will pop up
 - d) Click on **File > Minimize Application**
 - e) Skip to "Set up Time Domain Parameters" section below"

Perform Free Field GRL (Gated, Reflection, Line) Calibration



When removing and installing the calibration disk and samples from the sample holder, always install the item from the Port 2 (right) side. Never remove/rotate the Port 1 side threaded ring.



The Standard freespace configuration is 26" between Millitech horn/lens (lens to lens) with the sample holder centered between the lenses, and the .2505" thick aluminum calibration disk.

1. If the "Set time domain parameters" pop up window is on the screen skip to step (#2) else Select the **TRL Cal Set** From "Agilent Technologies 85071" program
 - a) **Measure > Freespace calibration > click on Perform a gated reflect line calibration from a calset (GRL).**
 - If the sample holder Freespace info isn't in memory, "Agilent Technologies 85071" Freespace warning pop-up box will appear. Set up the Freespace data.
 - Click on **"OK"**
 - **Measure > Click on Define Measurement...** "Agilent Technologies 85071" active waveform page will appear.
 - Set up VNA Sample Holder Freespace Settings, as describe on Page 2
 - b) **Re-enter Measure > Freespace calibration > click on Perform a gated reflect line calibration from a**

- calset (GRL).** “Cal Set” pop-up “description GUID” box should pop-up.
- c) In the “Cal Set” pop-up, “Description GUID” box, select the most recent TRL calibration (Ex. Date-0_TRL201_Date_Name)
 - Click on **Next** (opens VNA Network Analyzer Smith Chart)
- d) File > **Minimize Application** “Set time domain parameters” window will pop up.

Turn on the S Parameters and Markers

1. Turn on S parameters
 - a) Right click on the **chart > New Trace > Measurements...**
 - b) Click on the plus sign adjacent to Two-port measurement and **Measure S-Parameters**
 - c) Click on box next to **S11 > OK**
 - d) Repeat above steps for S22, S21, S12 in order one at a time
2. Set up markers
 - a) Click on **Display > Markers**
 - Set up frequency in MHz (Ex. **95000**)
 - **OK**

Verify GRL Calibration in “Agilent Technologies 85071” Screen (Starting with empty fixture)

3. Enter/Verify sample/test parameters
 - a) **Measure > Trigger measurement** “Measure Description” window will appear.
4. Set up/verify “Set Frequency”, “Measurement Model”, and “Sample Holder” tab information is correct

 Do not click on the keyboards “Enter” key while entering data. It accepts it as an **OK** and skips to next the next pop-up screen. Do not click on the pages “OK” button until done with all tabs).

 - a) Set “Frequency” tab for W-band measurements (transmission Epsilon Fast Model), Full 2-Port Cal, Sample is multiple of 12 wavelength)
 - Start freq: **75 GHz**
 - Stop frequency: **110 GHz**
 - Power: **11 dBm**
 - IFBW: **300 Hz**
 - Num pts: **201**
 - Select **Linear sweep**
 - b) Enter/verify “Measurement Model” tab settings
 - In Measurement Box, select **Transmission Fast**
 - Put check in **Verify Estimate** box
 - c) Enter/Verify “Sample Holder” tab settings
 - Check Mark “**Freespace**” in sample holder box located on the right. *Changes test in test setup description*
 - Metal plate thickness (Enter the calibration metal plate thickness): **0.2505**
 - Distance to sample: **0”** (Enter the Port 1’s distance from target samples surface to the calibrated metal plate surface. Since we always insert/remove sample pieces/calibration disk from the Port 2 side, this should always be 0.)
 - Sample thickness: **0.25** (Enter thickness of the test sample under test)
 - Select **Inch** in Units box
 - Enter check mark in the **Show when measuring or recalculating** box
 - Click on **OK**. The “Verify Estimate” pop-up should appear
 - d) Make initial guess (Approximately 0.99 – j0 for air) > Click on **OK**
 - e) Verify calibration parameters
 - Verify free space air Permittivity (ϵ') errors are acceptable
 - Right click on ϵ' trace call out on left side of screen

-
- Click on **Autoscale**
 - Verify Permittivity (ϵ') = $1.0 \pm .02$ across all frequencies
 - Verify free space air permittivity imaginary part (ϵ'') errors are acceptable
 - Right click on ϵ' trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (ϵ'') = $0 \pm 100 \mu\text{dB}$ across all frequencies
 - Verify free space air S11 errors are acceptable
 - Right click on S11 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S11) = $< -65 \text{ dB } (.00003\%)$ across all frequencies
 - Verify free space air S22 errors are acceptable
 - Right click on S22 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S22) = $< -65 \text{ dB } (.00003\%)$ across all frequencies
 - Verify free space air S12 errors are acceptable
 - Right click on S12 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S21) = $10\text{m dB} < S12 < -10\text{m dB } (< 0.1\%)$ across all frequencies
 - Verify free space air S21 errors are acceptable
 - Right click on S21 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S21) = $-10\text{m dB} < S21 < 10\text{m dB } (< 0.1\%)$ across all frequencies
5. Set up/verify the sample holder freespace aluminum calibration disk measurements
- a) Insert aluminum calibration disk in sample holder
 - b) Click on **Measure > Trigger measurement** “Measure Description window” will appear.
 - c) Verify “Set Frequency”, “Measurement Model”, and “Sample Holder” tab information is correct (Especially sample thickness). See previous section verifying air.
 - Click **OK**. “TR 1 S₂₁ Polar...” polar plot page, “PNA-Series Network Analyzer” program should appear;
 - d) Make initial guess (Since the permittivity of metal is undefined, accept whatever is suggested).
 - Verify Aluminum Calibration Disk free space Permittivity (ϵ' and ϵ'') errors are acceptable
 - Undefined across all frequencies
 - Verify Aluminum Calibration Disk S11 errors are acceptable
 - Right click on S11 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S11) = $-.05 \text{ dB} < S11 < .05 \text{ dB } (< .3\%)$ across all frequencies
 - Verify Aluminum Calibration Disk S22 errors are acceptable
 - Right click on S22 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S22) = $-.05 \text{ dB} < S22 < .05 \text{ dB } (< .3\%)$ across all frequencies
 - Verify Aluminum Calibration Disk S12 errors are acceptable
 - Right click on S12 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S12) = $-50 \text{ dB } (< .01 \%)$ across all frequencies
 - Verify Aluminum Calibration Disk S21 errors are acceptable
 - Right click on S21 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S21) = $-50 \text{ dB } (< -.01\%)$ across all frequencies
- Verify
-

6. Set up/Verify freespace calibration with SiC standard sample
 - a) Insert SiC standard target in sample holder
 - b) Click on **Measure > Trigger measurement** “Measure Description window” will appear.
 - c) Verify “Set Frequency”, “Measure Model”, and “Sample Holder” tab information is correct (Especially sample thickness). See previous section verifying air.
 - d) Click **OK**. “TR 1 S_{21} Polar...” polar plot page, “PNA-Series Network Analyzer” program should appear;
 - e) Make initial guess (Approximately 2.4 for the standard SiC target).
 - Verify free space air Permittivity (ϵ') errors are acceptable
 - Right click on ϵ' trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (ϵ') = 13.72
 - Verify free space air S11 errors are acceptable
 - Right click on S11 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S11) = -5.5 dB < S11 < -3.7 dB (< 1.0%) across all frequencies
 - Verify free space air S22 errors are acceptable
 - Right click on S22 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S22) = -5.5 dB < S22 < -3.7 dB (< 1.0%) across all frequencies
 - Verify free space air S12 errors are acceptable
 - Right click on S12 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S12) = -17.7 dB < S12 < -14 dB across all frequencies
 - Verify free space air S21 errors are acceptable
 - Right click on S21 trace call out on left side of screen
 - Click on **Autoscale**
 - Verify Permittivity (S21) = -17.7 dB < S21 < -14.0 dB across all frequencies

Calibration is complete

To turn on Markers

1. Display > “Marker”
2. In Properties box, set the desired frequency you want to monitor in MHz.

Determine Permittivity

1. Determine Rough Real Permittivity Component
 - a) Click on **e'** in screen banner
 - b) Click on Measure > “**Trigger Measure**” Description *Always use Trigger Measure for first measurement on a new sample or when the previous scan was suspect.*
 - c) Verify “Set Frequency”, “Measure Model” (Start with Tran-e Fast), and “Sample Holder” tab information is correct (especially sample thickness)
 - Click on “**Ok**” when done. “*Verify Estimate*” will pop-up
 - d) Enter and note the estimate you chose
 - Click on “**Ok**”
 - e) View Data
 - Right Click on the Tr1 Data box (left side of screen)
 - Autoscale
 - If the Tr 1 Data slopes upward the estimate is to low
 - If the Tr 1 Data slopes downward the estimate is to high
 - If the Tr 1 Data oscillates around the value you chose the data is close
 - f) If the data is close, note the permittivity value the data oscillates around and skip to Step 2. Else repeat this step
2. Determine Real Permittivity Component
 - a) Click on “Measure > **Recalculate...**” Use “Recalculate” when you want to recalculate permittivity with a different Estimate or use a different Model on a previously “Trigger Measured” sample.
 - b) Verify “Set Frequency”, “Measure Model” (**Switch to Polly Tran e and set Polynomial Options to 3**), and “Sample Holder” tab information is correct
 - c) Click on “**Ok**” “*Verify Estimate*” will pop-up
 - d) Enter and note the estimate you chose in the permittivity box
 - Click on “**Ok**” “*Measurement Statistics*” box will appear
 - e) Select Measurement Statistics
 - Select “**Transmission Measurement to Data**”
 - Click on “**Ok**”
 - f) Right Click on the Tr1 Data box (left side of screen)
 - Click on **Autoscale**
 - If permittivity has a wide data range, note average value of first half of the pulse.
 - If the Tr 1 Data has a straight line around a value this is the real part
 - g) If you have determined the real part skip to Step 3 else repeat this step using the average value of the first half of the pulse.
3. Determine Imaginary Permittivity Component
 - a) Click on **e''** in screen banner
 - Note the e'' value in first half of pulse
 - b) Click on “Measure > **Recalculate...**”
 - c) Verify “Set Frequency”, “Measurement Model” (**Switch to Poly Tran e**), and “Sample Holder” tab information is correct
 - d) Click on “**Ok**” “*Verify Estimate*” will pop-up
 - e) Enter the real part determined in previous step and an estimate of the imaginary (e'') part (divided by 1000

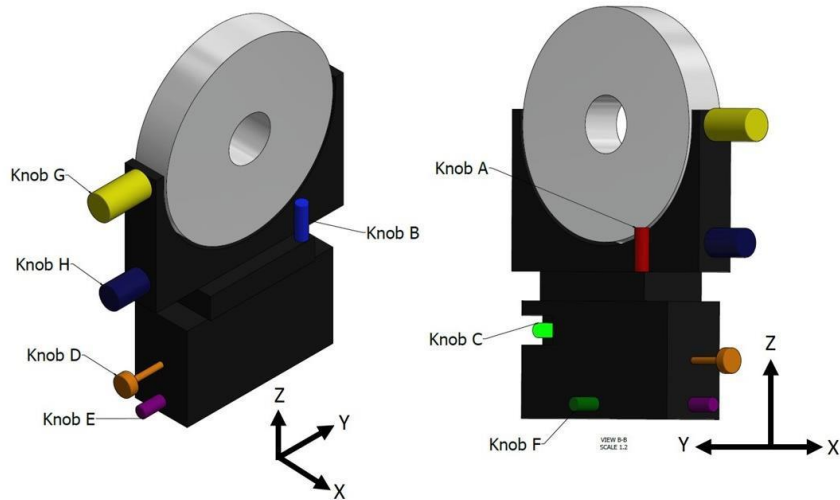
because the e'' is displayed in mils.)

- Click on “**Ok**”

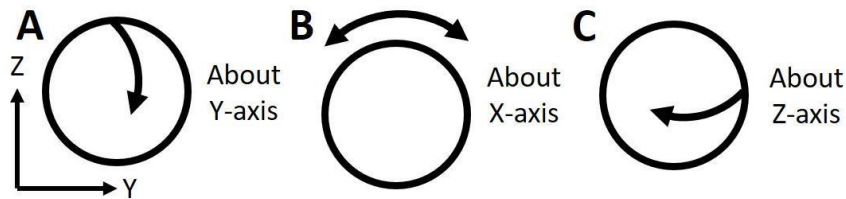
f) Right Click on the Tr1 Data box (left side of screen)

- Click on **Autoscale**
- Note the e'' value average in the first half of the pulse
- If the Tr 1 Data has a reasonably straight line around a value this is the imaginary part, Note value at 95GHz.

g) If the imaginary line isn't a reasonably straight line repeat this step



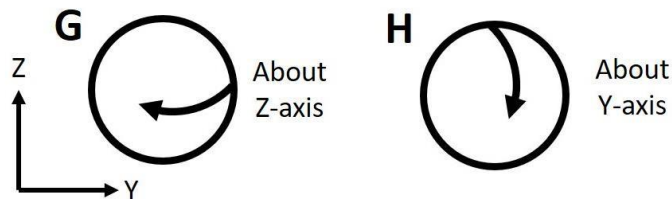
Rotation (Coarse)



Translation (Fine)



Rotation (Fine)



APPENDIX C - RELATIVE COMPLEX PERMITTIVITY MEASUREMENTS IN THE W-BAND

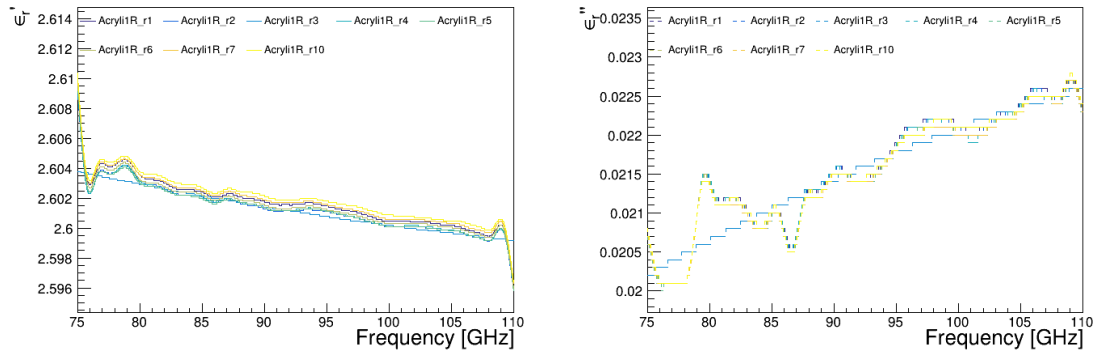


Figure C-1. Relative Complex Permittivity Measurements for Acrylic Sample #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position is at 0° and each subsequent rotation is at 30° , 60° , 90° , 120° , 150° , 180° , and 270° in the clockwise direction, respectively. For acrylic, fewer than 12 measurements were made per sample.

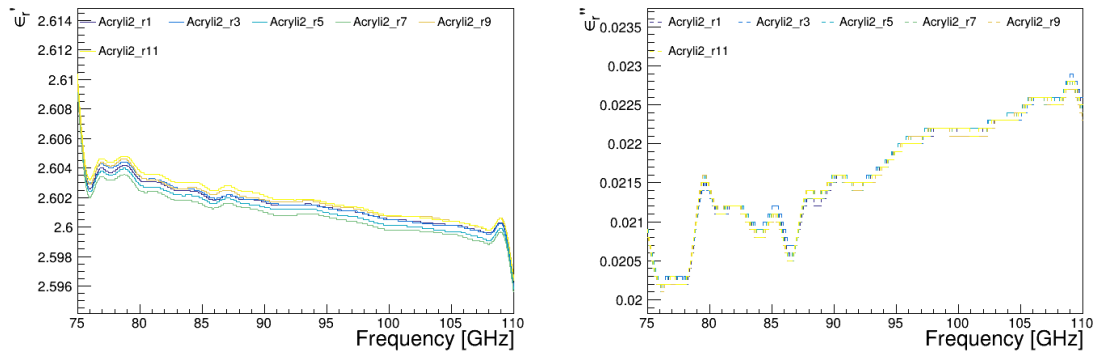


Figure C-2. Relative Complex Permittivity Measurements for Acrylic Sample #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position is at 0° and each subsequent rotation is at 60° , 120° , 180° , 240° , and 300° in the clockwise direction, respectively. For acrylic, fewer than 12 measurements were made per sample.

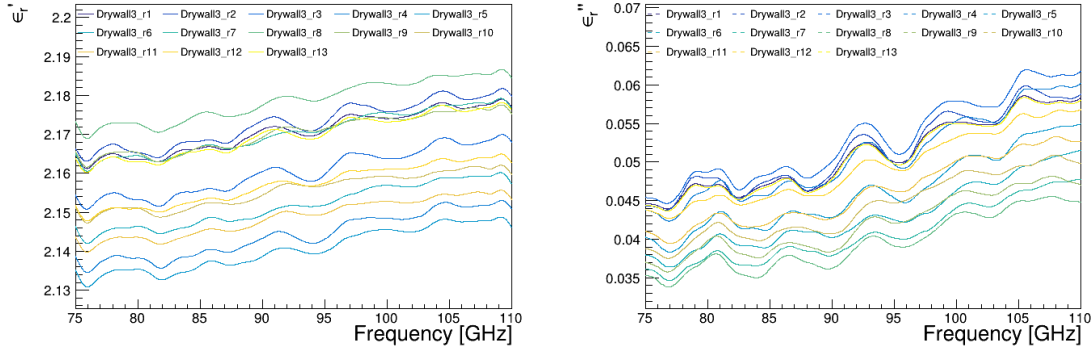


Figure C-3. Relative Complex Permittivity Measurements for Gypsum Drywall Sample #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction. The 13th position is the same location as the 1st position.

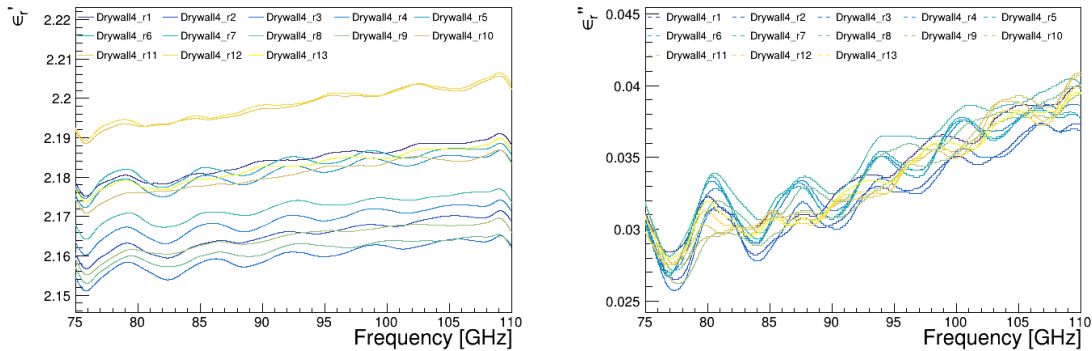


Figure C-4. Relative Complex Permittivity Measurements for Gypsum Drywall Sample #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction. The 13th position is the same location as the 1st position.

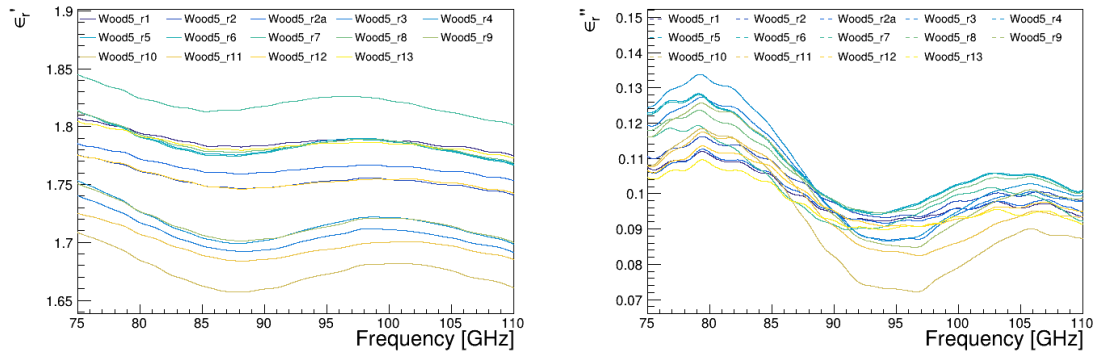


Figure C-5. Relative Complex Permittivity Measurements for Birch Plywood Sample #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction. The 13th position is the same location as the 1st position.

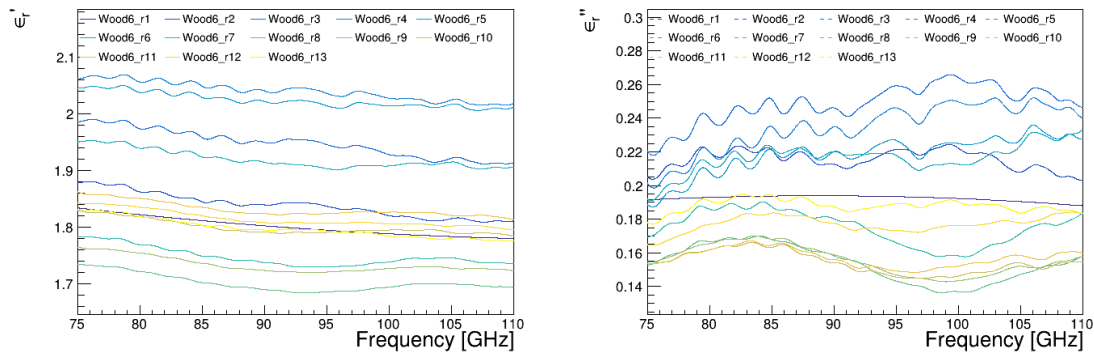


Figure C-6. Relative Complex Permittivity Measurements for Birch Plywood Sample #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction. The 13th position is the same location as the 1st position.

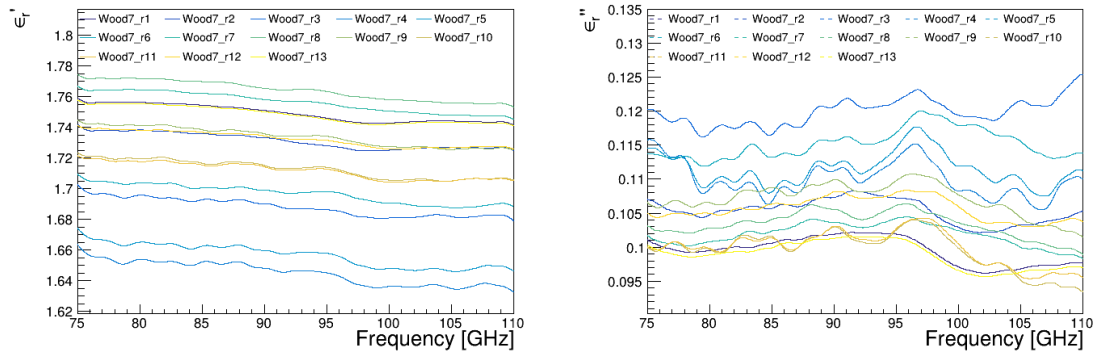


Figure C-7. Relative Complex Permittivity Measurements for Maple Plywood Sample #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction. The 13th position is the same location as the 1st position.

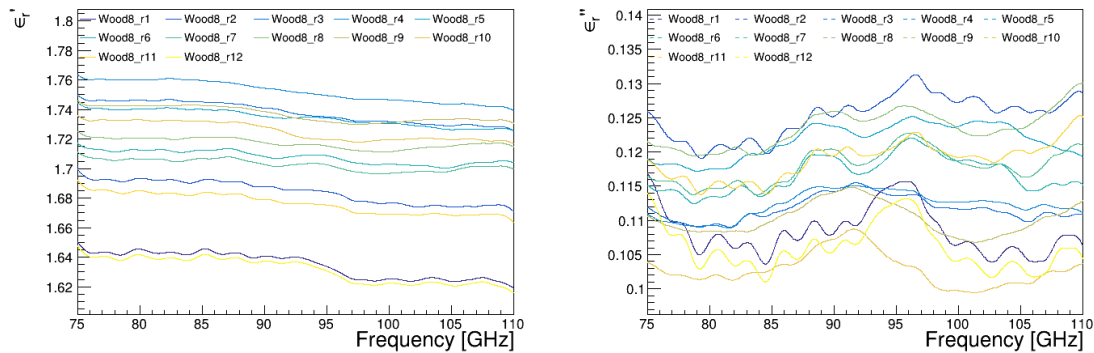


Figure C-8. Relative Complex Permittivity Measurements for Maple Plywood Sample #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where r1 is the first position and each subsequent rotation is 30° in the clockwise direction.

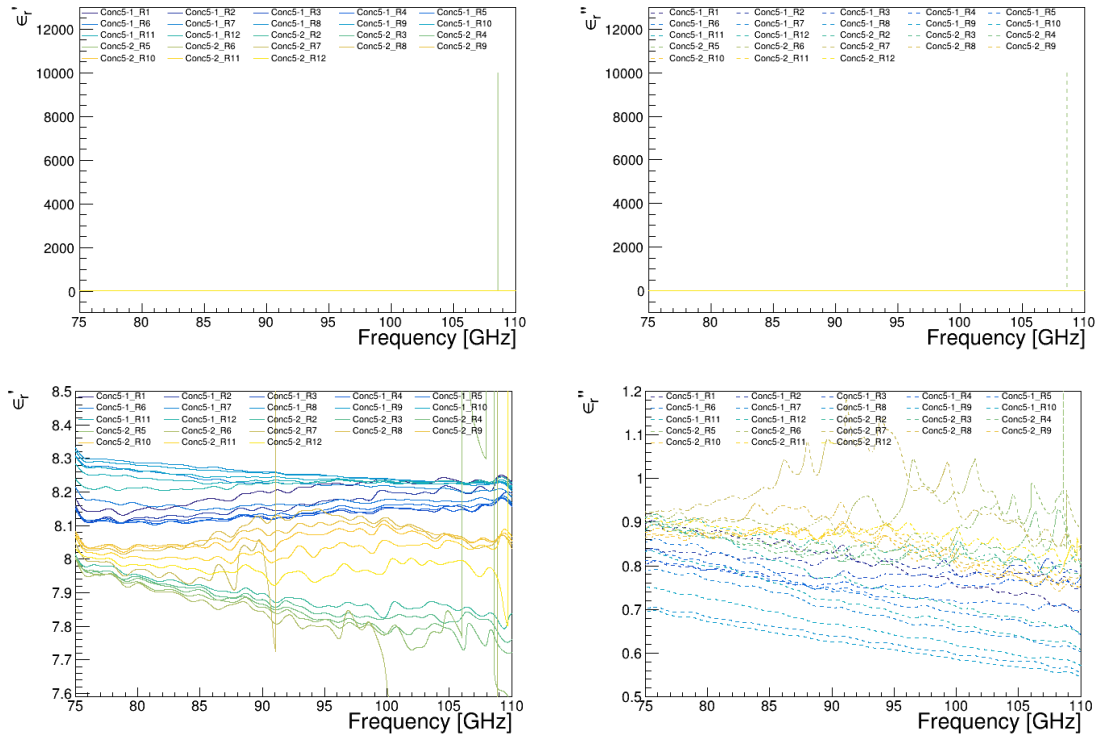


Figure C-9. Relative Complex Permittivity Measurements for Concrete (w/c=0.30). Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. Top, all of the measurements are shown. Bottom, a zoomed-in view of the measurements. In the legend, the trailing number represents the rotation position of the sample during measurement, where R1 is the first position and each subsequent rotation is 30° in the clockwise direction. There were two samples of the concrete measured, Conc5-1 and Conc5-2. During the measurements of Conc5-2, the network analyzer reported low transmission results. The permittivity results for Conc5-2 are suspect.

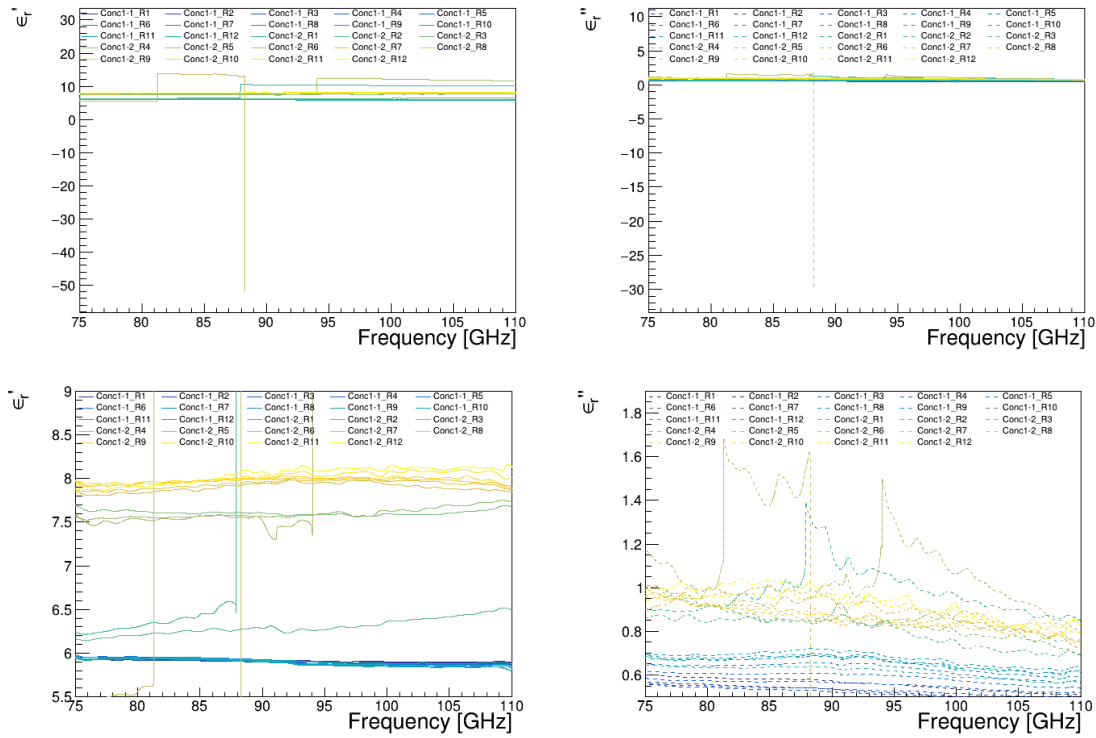


Figure C-10. Relative Complex Permittivity Measurements for Concrete (w/c=0.35). Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. Top, all of the measurements are shown. Bottom, a zoomed-in view of the measurements. In the legend, the trailing number represents the rotation position of the sample during measurement, where R1 is the first position and each subsequent rotation is 30° in the clockwise direction. There were two samples of the concrete measured, Conc1-1 and Conc1-2. During the measurements of Conc1-2, the network analyzer reported low transmission results. The permittivity results for Conc1-2 are suspect.

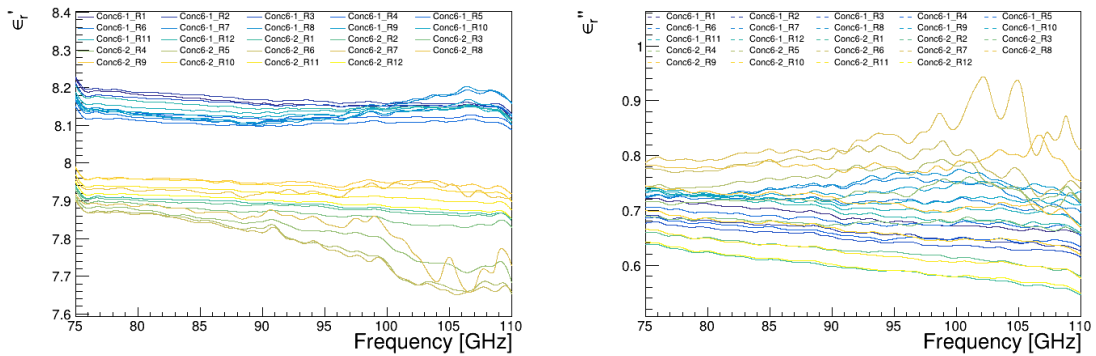


Figure C-11. Relative Complex Permittivity Measurements for Concrete (w/c=0.40). Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where R1 is the first position and each subsequent rotation is 30° in the clockwise direction. There were two samples of the concrete measured, Conc6-1 and Conc6-2.

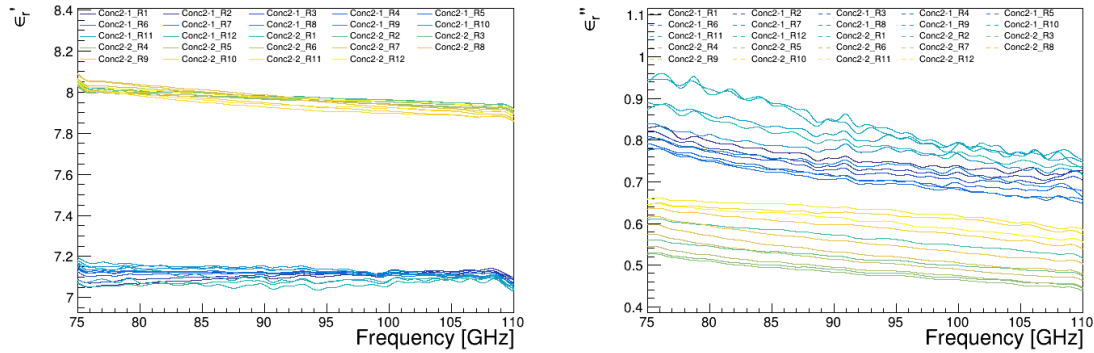


Figure C-12. Relative Complex Permittivity Measurements for Concrete (w/c=0.50). Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where R1 is the first position and each subsequent rotation is 30° in the clockwise direction. There were two samples of the concrete measured, Conc2-1 and Conc2-2.

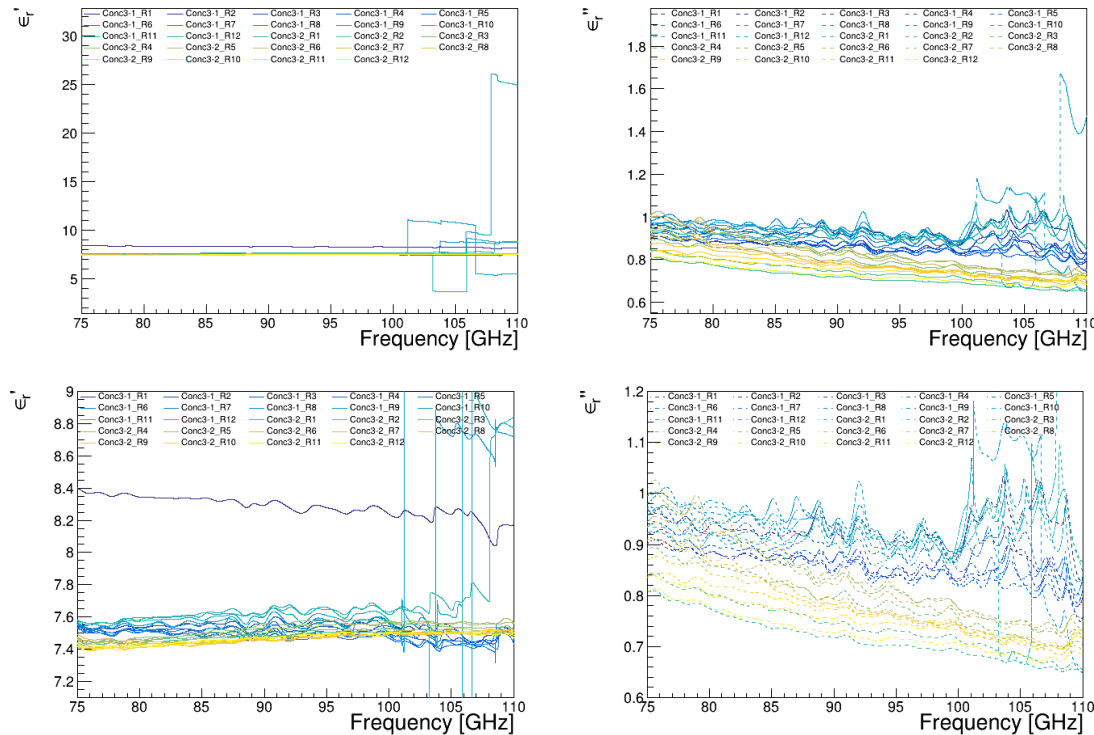


Figure C-13. Relative Complex Permittivity Measurements for Concrete (w/c=0.60). Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. Top, all of the measurements are shown. Bottom, a zoomed-in view of the measurements. In the legend, the trailing number represents the rotation position of the sample during measurement, where R1 is the first position and each subsequent rotation is 30° in the clockwise direction. There were two samples of the concrete measured, Conc3-1 and Conc3-2. During the measurements of Conc3-2, the network analyzer reported low transmission results. The permittivity results for Conc3-1 are suspect.

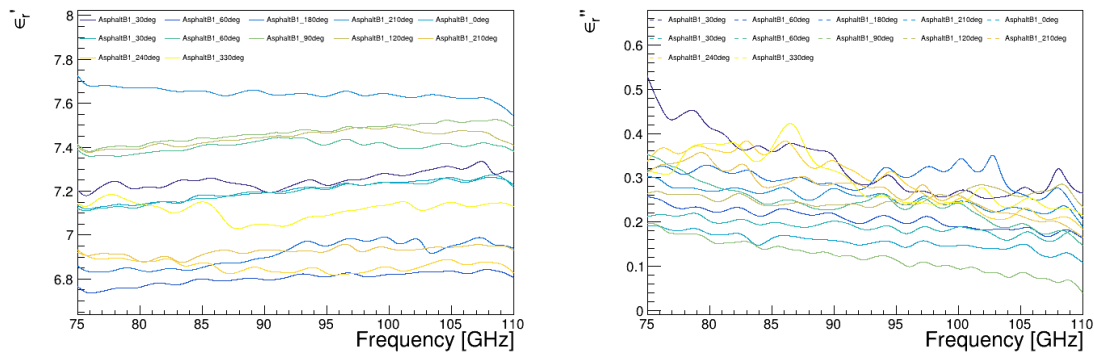


Figure C-14. Relative Complex Permittivity Measurements for Type B Asphalt #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (30°, 60°, 180°, and 210°) from the outer circular pattern is listed first in the legend.

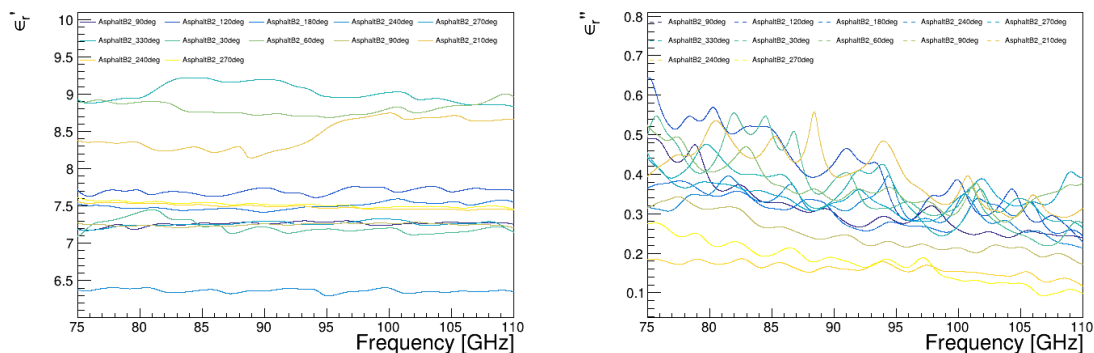


Figure C-15. Relative Complex Permittivity Measurements for Type B Asphalt #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (90°, 120°, 180°, 240°, 270°, and 330°) from the outer circular pattern is listed first in the legend.

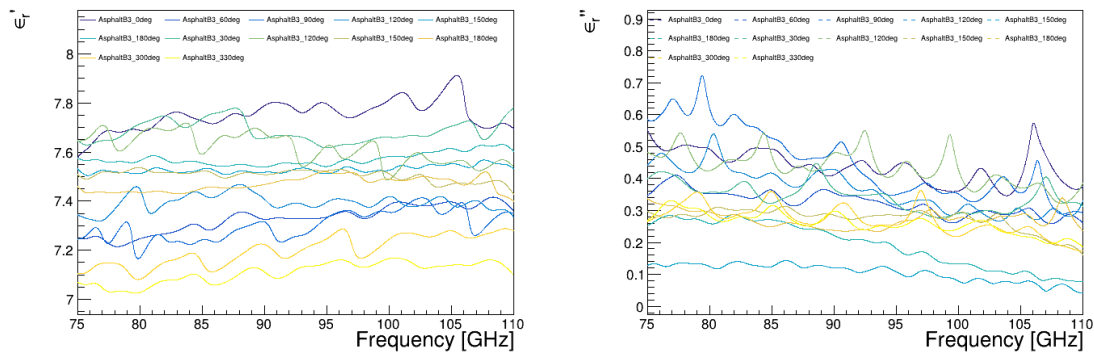


Figure C-16. Relative Complex Permittivity Measurements for Type B Asphalt #3. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (0° , 60° , 90° , 120° , 150° , and 180°) from the outer circular pattern is listed first in the legend.

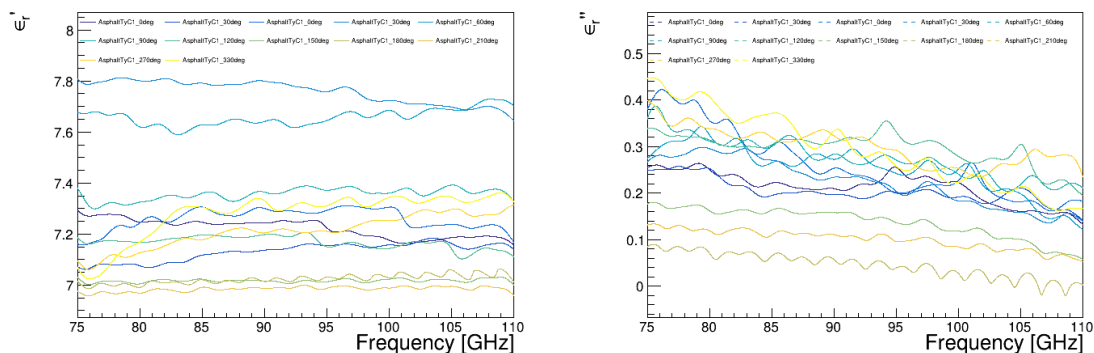


Figure C-17. Relative Complex Permittivity Measurements for Type C Asphalt #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (0° and 30°) from the outer circular pattern is listed first in the legend.

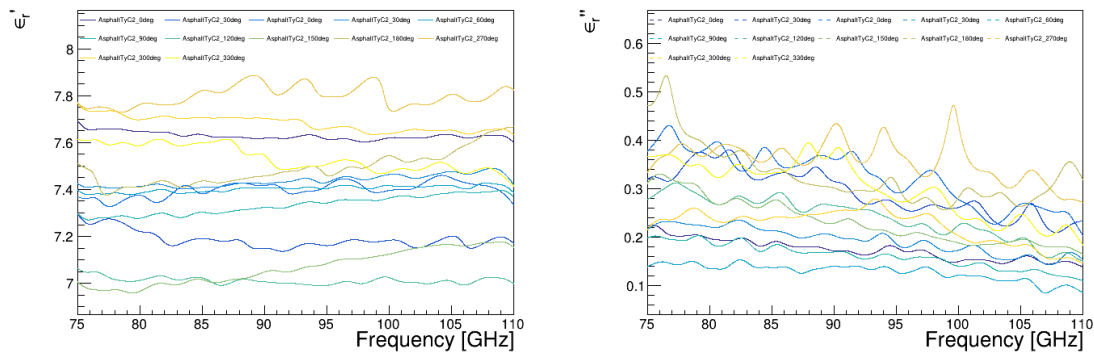


Figure C-18. Relative Complex Permittivity Measurements for Type C Asphalt #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (0° and 30°) from the outer circular pattern is listed first in the legend.

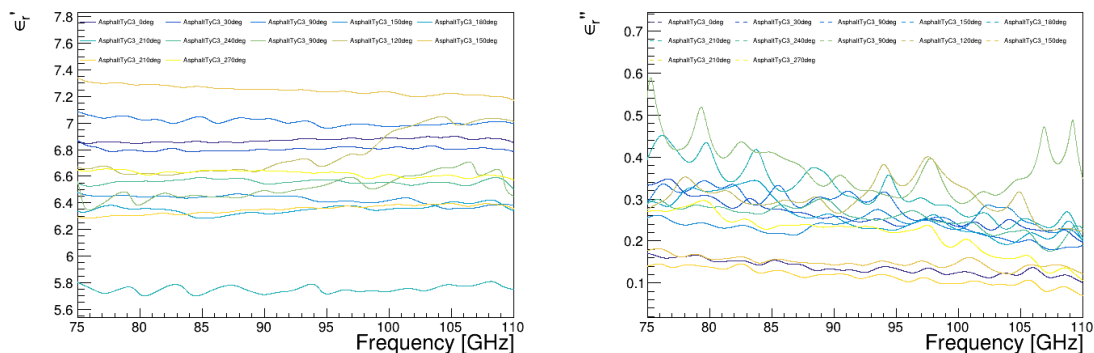


Figure C-19. Relative Complex Permittivity Measurements for Type C Asphalt #3. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The sample was measured in an inner, a 1/4 in. displacement from center, and outer, a 1/2 in. displacement from center, circular pattern with a smaller beam profile. The set of measurements (0° , 30° , 90° , 150° , 180° , 210° , and 240°) from the outer circular pattern is listed first in the legend.

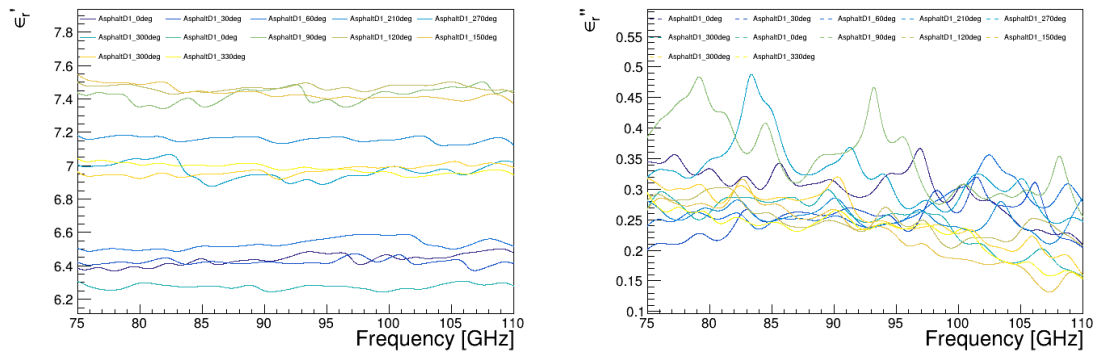


Figure C-20. Relative Complex Permittivity Measurements for Type D Asphalt #1. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The set of measurements (0°, 30°, 60°, 210°, 270°, and 300°) from the outer circular pattern is listed first in the legend.

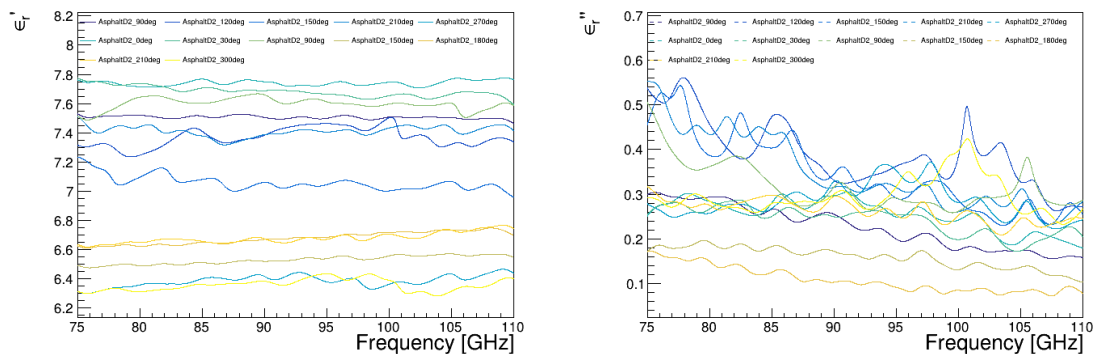


Figure C-21. Relative Complex Permittivity Measurements for Type D Asphalt #2. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The set of measurements (90°, 120°, 150°, 210°, and 270°) from the outer circular pattern is listed first in the legend.

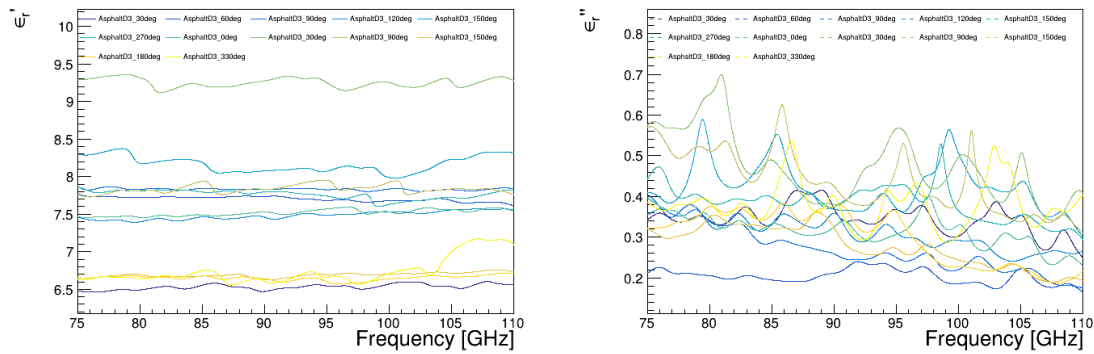


Figure C-22. Relative Complex Permittivity Measurements for Type D Asphalt #3. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement. The set of measurements (30°, 60°, 90°, 120°, 150°, and 270°) from the outer circular pattern is listed first in the legend.

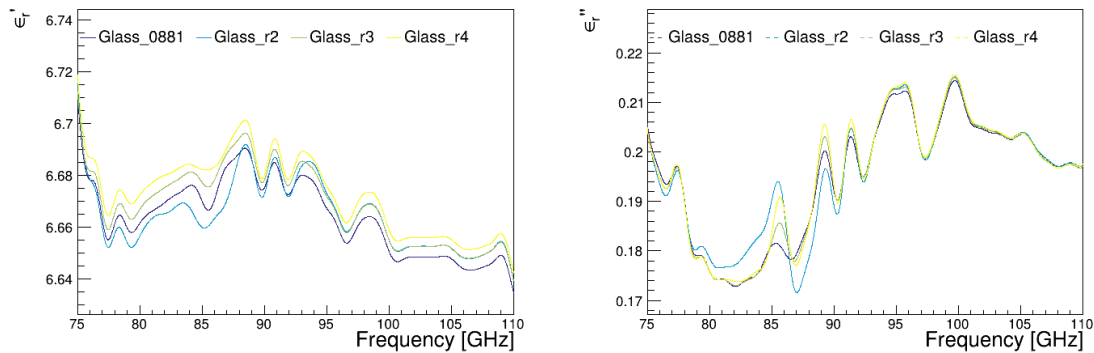


Figure C-23. Relative Complex Permittivity Measurements for Glass. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the rotation position of the sample during measurement, where 0881 is the first position at 0°, and each subsequent position was rotated 90° in the clockwise direction. Only four measurements were made.

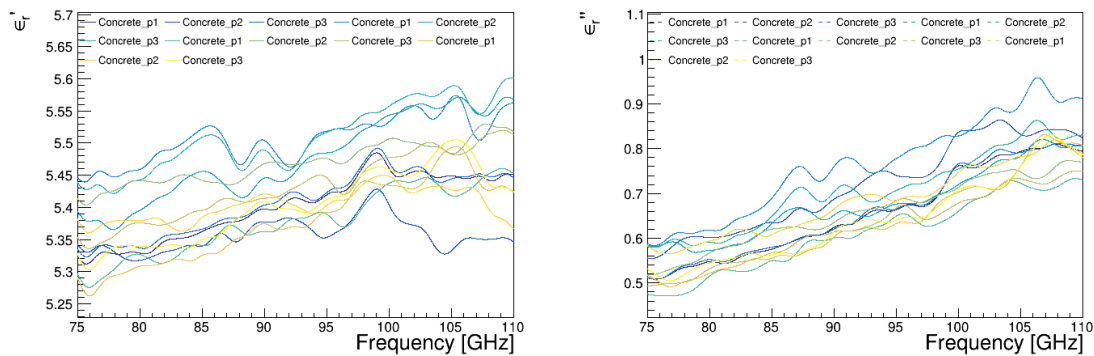


Figure C-24. Relative Complex Permittivity Measurements for Cinderblock. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. Two cinderblock samples measurements are presented. In the legend, the first six items belong to one sample and the next six items belong to the other sample. The first and third sets of Concrete_1, Concrete_2, and Concrete_rough had the striations perpendicular to the RF E-field polarization, where the second and fourth sets had the striations parallel to the RF E-field polarization. Concrete_1 and Concrete_2 indicate that the rough side was facing port 2 and the two measurements were displaced from each other by 1 in. Concrete_rough indicates that the rough side was facing port 1.

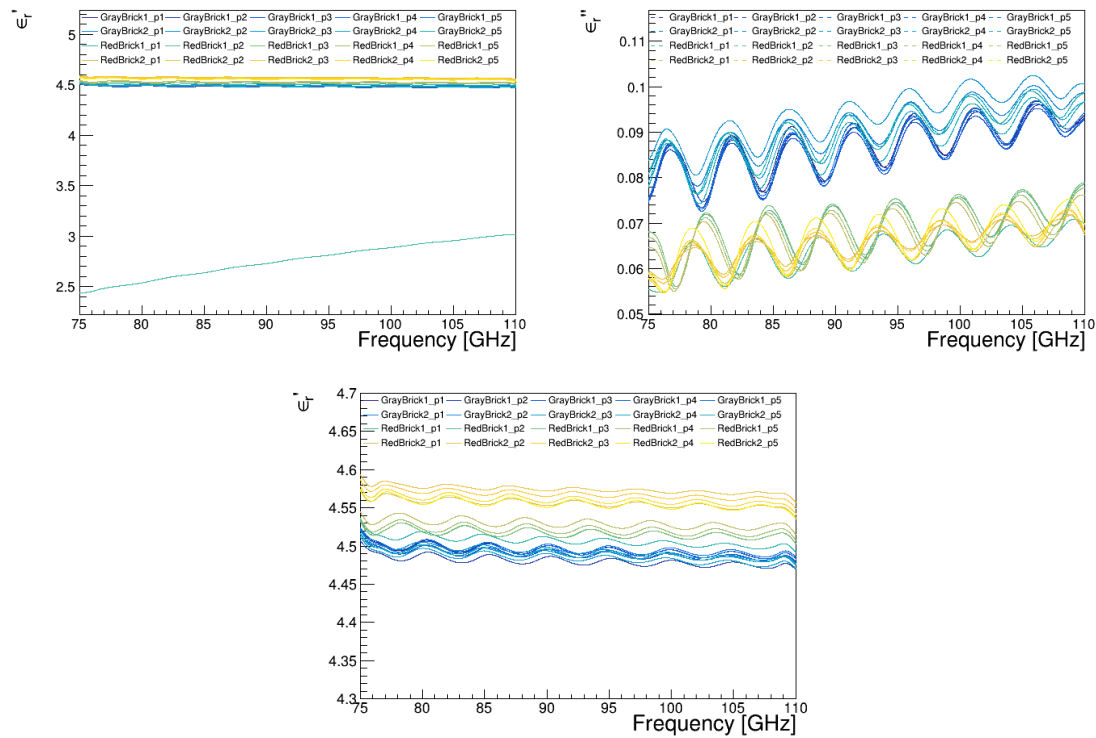


Figure C-25. Relative Complex Permittivity Measurements for Clay Brick. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. Top, the entire set of measurements. Bottom, a zoomed-in view of ϵ'_r as a function of frequency. In the legend, the trailing number represents the position of the sample during measurement. The GrayBrick represents the two Academy Gray samples and RedBrick represents the two Plantation Red samples. One of the measurements were an outlier. Re-measurements of the brick produced permittivity results consistent with previous measurements without the outlier.

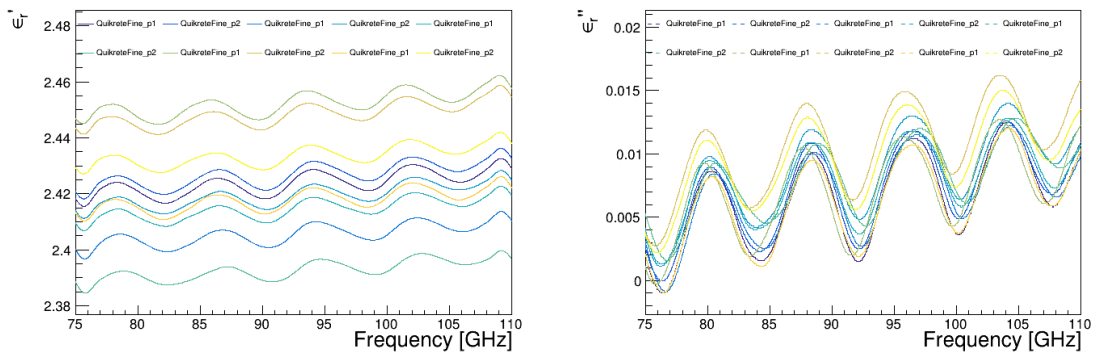


Figure C-26. Relative Complex Permittivity Measurements for Fine Sand. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the position of the sample during measurement.

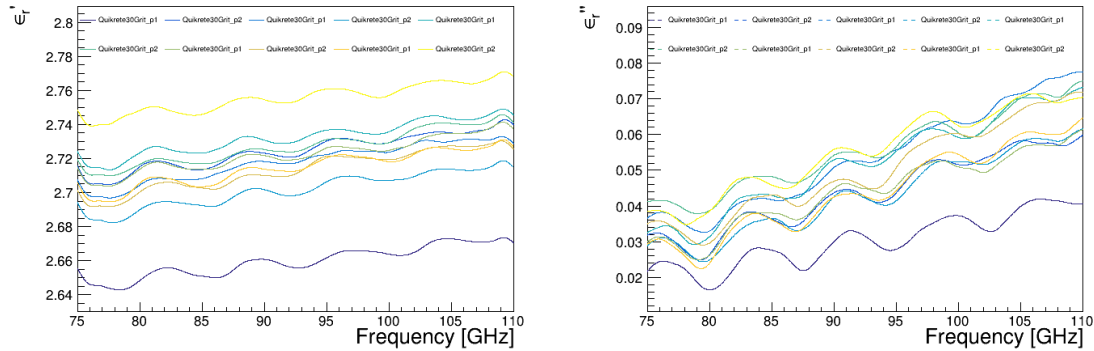


Figure C-27. Relative Complex Permittivity Measurements for Medium Sand. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the position of the sample during measurement.

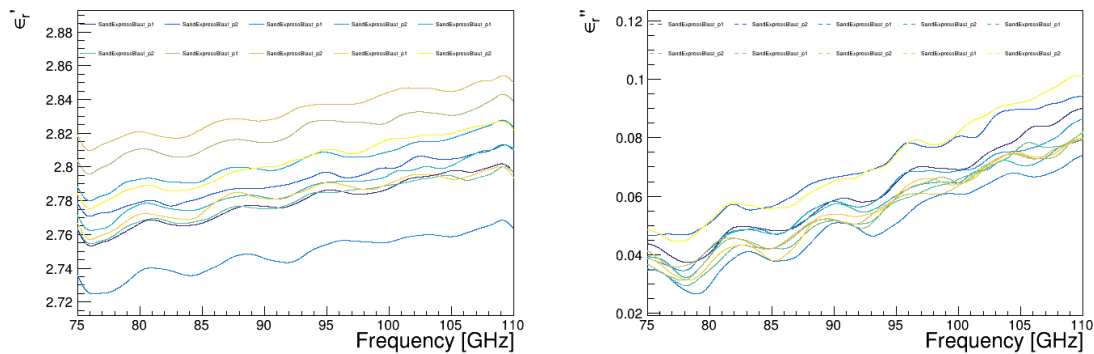


Figure C-28. Relative Complex Permittivity Measurements for Coarse Sand. Left, the real part of the relative complex permittivity ϵ'_r as a function of frequency. Right, the imaginary part of the relative complex permittivity ϵ''_r as a function of frequency. In the legend, the trailing number represents the position of the sample during measurement.

APPENDIX D - REFLECTIVITY COEFFICIENTS AT 95 GHZ

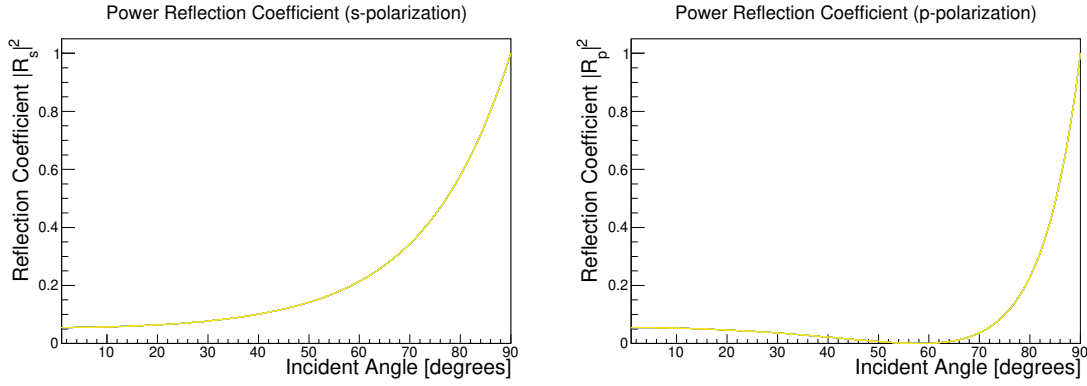


Figure D-1. Reflectivity Coefficients for Acrylic. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

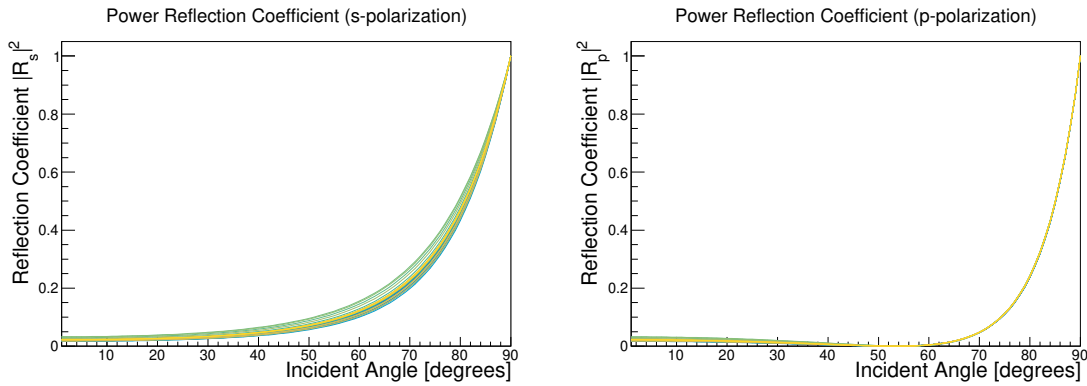


Figure D-2. Reflectivity Coefficients for Birch Plywood. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

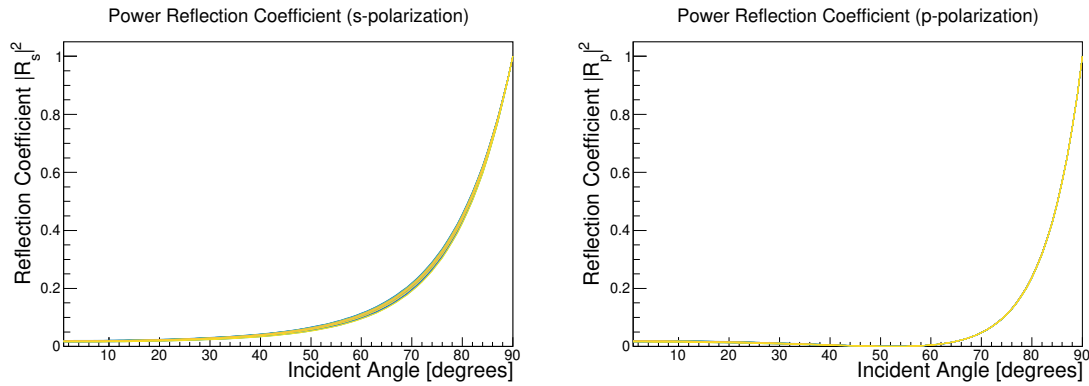


Figure D-3. Reflectivity Coefficients for Maple Plywood. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

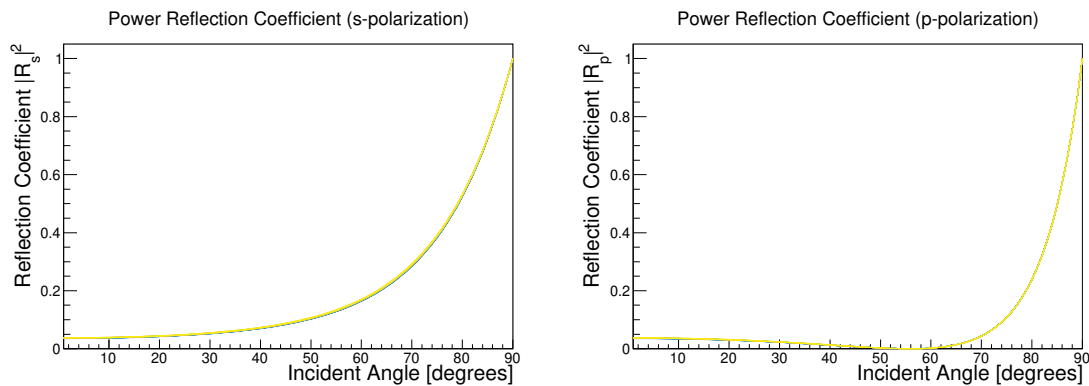


Figure D-4. Reflectivity Coefficients for Gypsum Drywall. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

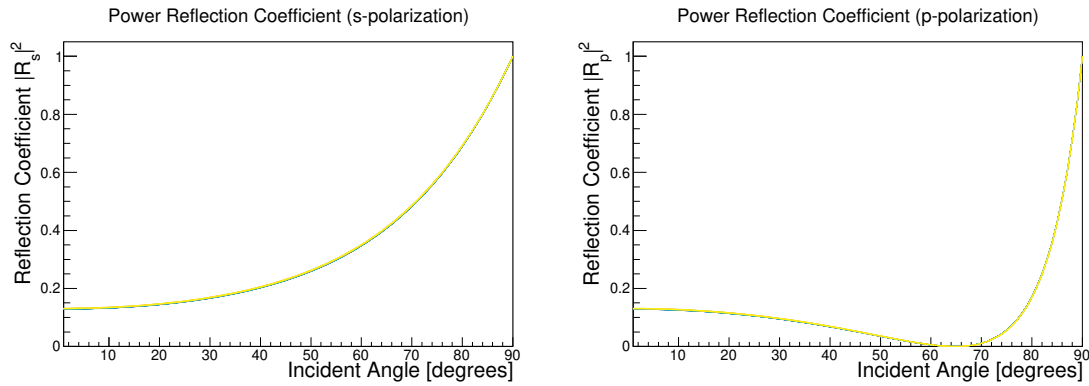


Figure D-5. Reflectivity Coefficients for Clay Brick. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

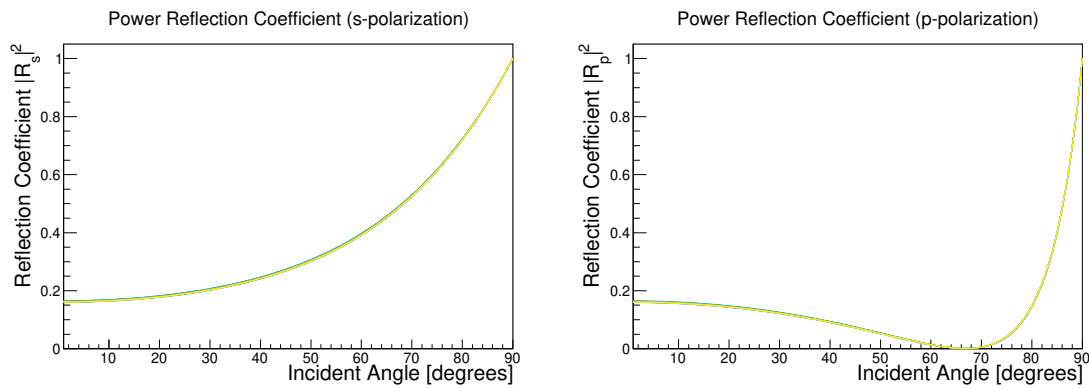


Figure D-6. Reflectivity Coefficients for Cinderblock. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

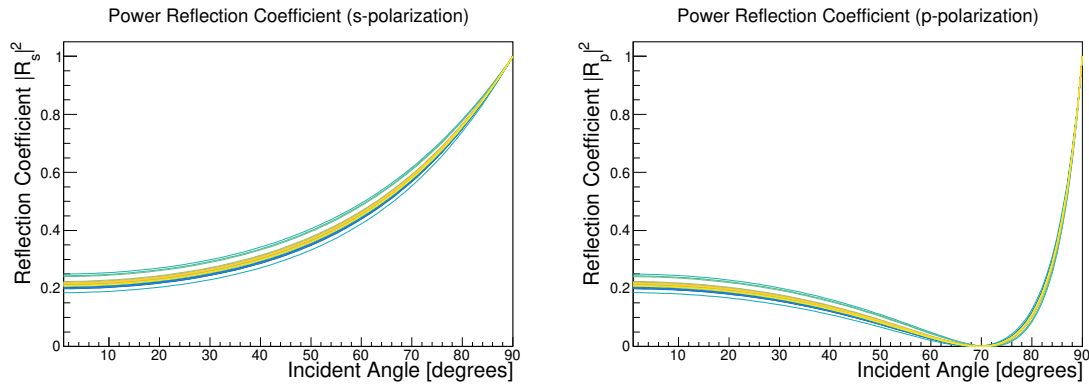


Figure D-7. Reflectivity Coefficients for TxDOT Type B Asphalt. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

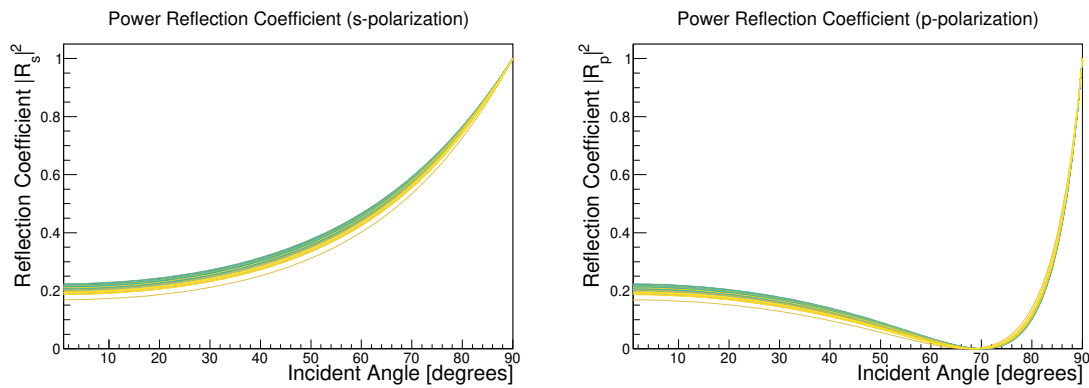


Figure D-8. Reflectivity Coefficients for TxDOT Type C Asphalt. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

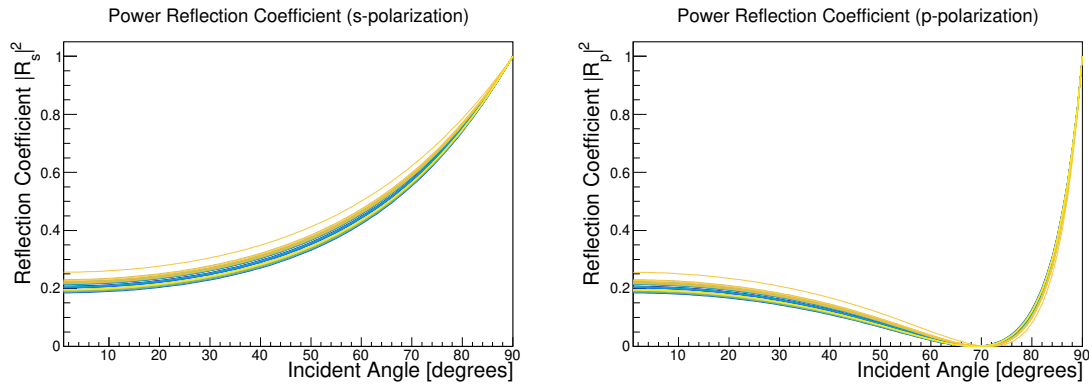


Figure D-9. Reflectivity Coefficients for TxDoT Type D Asphalt. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

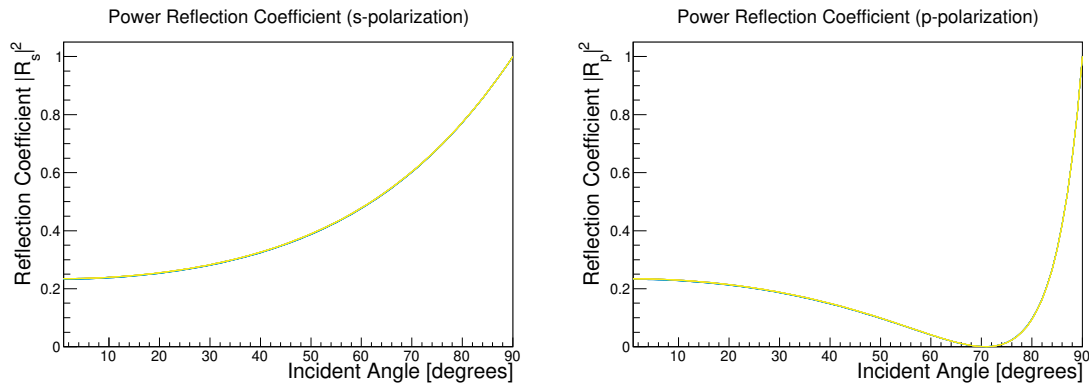


Figure D-10. Reflectivity Coefficients for Concrete, w/c = 0.30. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

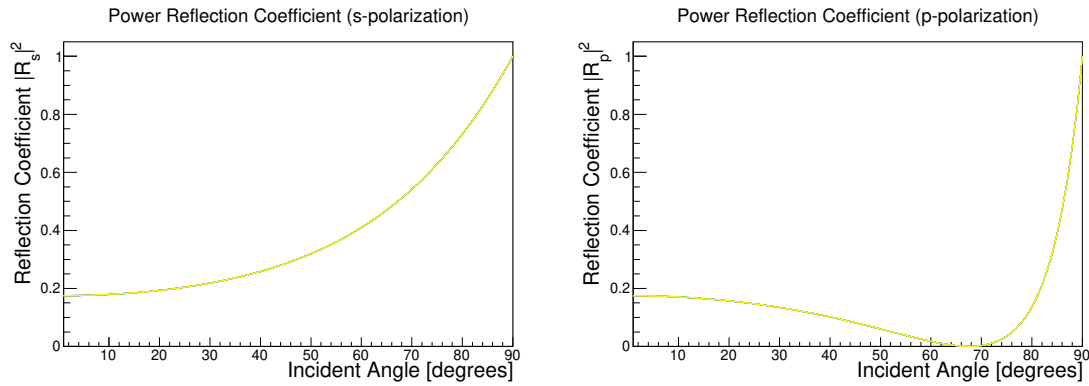


Figure D-11. Reflectivity Coefficients for Concrete, $w/c = 0.35$. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

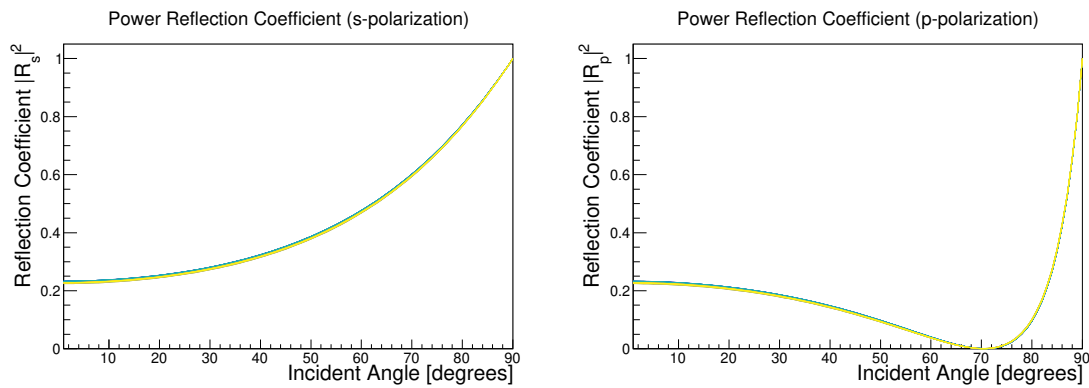


Figure D-12. Reflectivity Coefficients for Concrete, $w/c = 0.40$. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

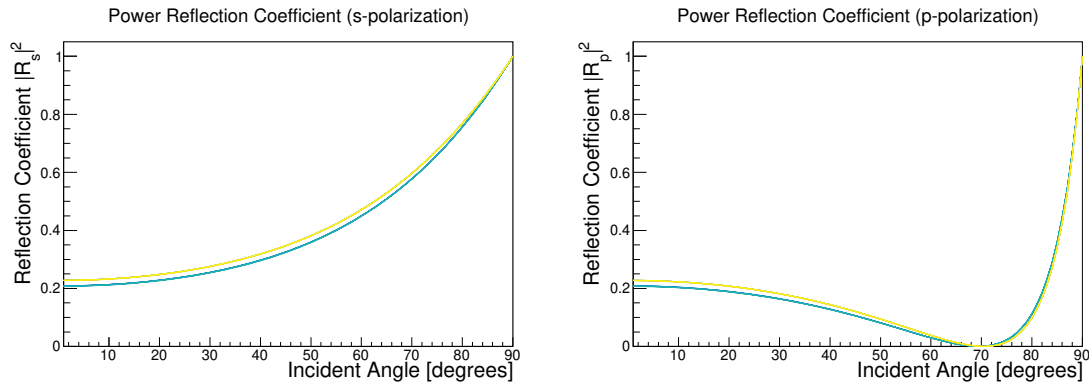


Figure D-13. Reflectivity Coefficients for Concrete, $w/c = 0.50$. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

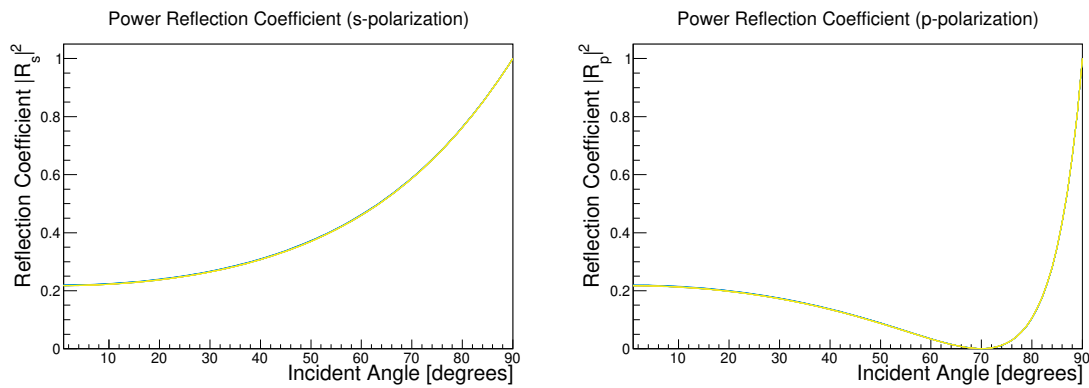


Figure D-14. Reflectivity Coefficients for Concrete, $w/c = 0.60$. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

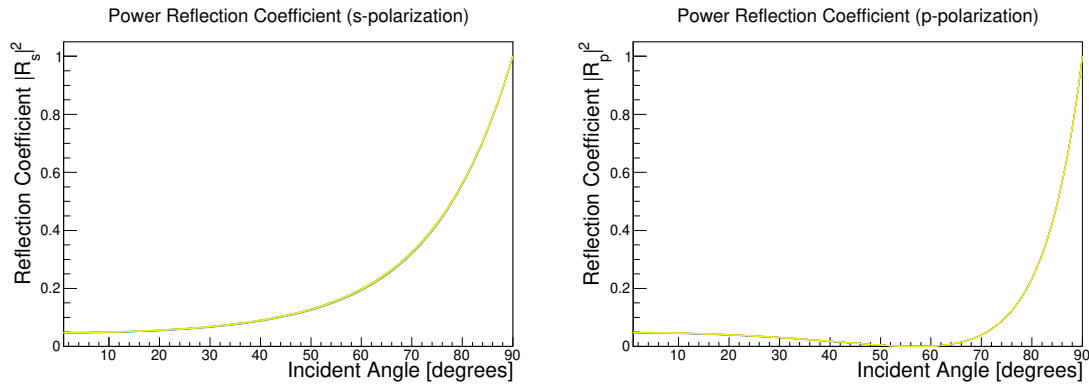


Figure D-15. Reflectivity Coefficients for Sand (Quikrete Fine). Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

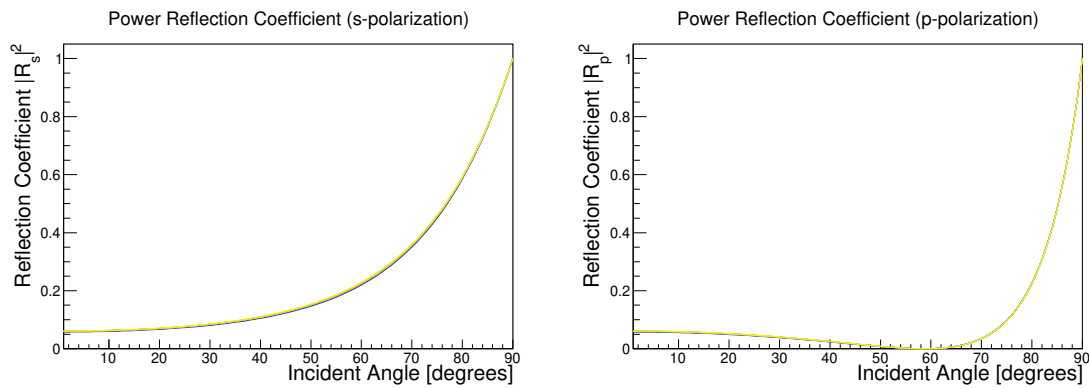


Figure D-16. Reflectivity Coefficients for Sand (Quikrete Medium #30 Grit). Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

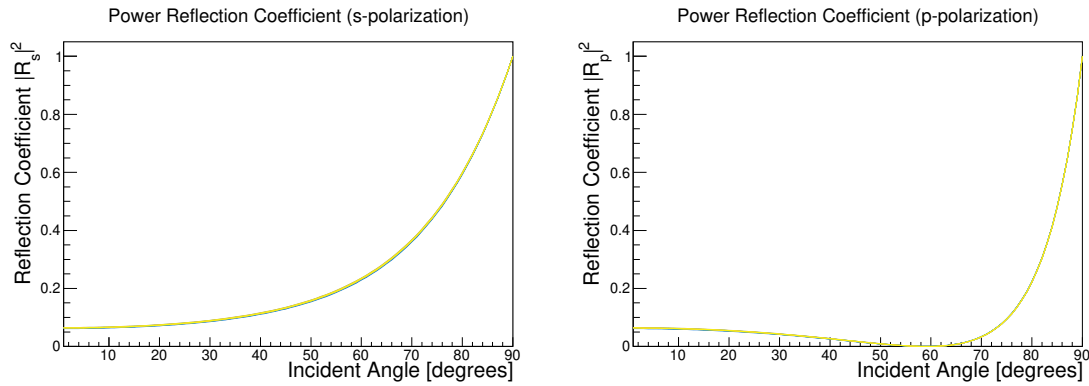


Figure D-17. Reflectivity Coefficients for Sand (SandExpress Blast Medium). Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.

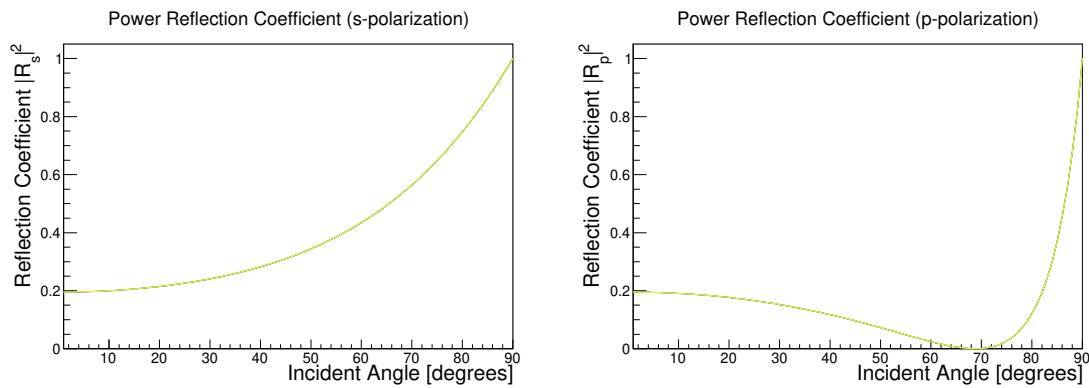


Figure D-18. Reflectivity Coefficients for Glass. Left, the power reflectivity coefficient for s-polarized waves $|R_s|^2$ as a function of incident angle. Right, the power reflectivity coefficient for p-polarized waves $|R_p|^2$ as a function of incident angle. The curves are calculated using Fresnel's equations, Equation 1, with the measured permittivity values at 95 GHz.