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Research Record

Properties of Asphalt Mixtures Containing RAP

Final Report

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16. Abstract

A typical NHDOT Hot Mix Asphalt (HMA) concrete mixture contains at least 15% Reclaimed Asphalt Pavement (RAP). The increasing cost of virgin asphalt and aggregate has increased the interest in using higher percentages of RAP in HMA mixtures. The purpose of this research project was to gain a better understanding of how the addition of RAP affects the properties of HMA. The effects of RAP on a particular mixture were evaluated by comparing the dynamic modulus, strength, and volumetric properties of a series of specimens with similar mix designs and materials but containing different percentages of RAP. Additionally, the Mechanistic-Empirical Pavement Design Guide (MEPDG) software was used to evaluate the predicted performance of the mixtures in a pavement surface course.

Two sites were selected for this study. The cores from the first site were taken from the pavement prior to milling and tested to determine the properties of the RAP. Mixtures were designed and tested in the lab with various RAP contents (0%, 15%, 25%, and 40%) using the milled material. A second site was selected where loose plant mix and field cores from the overlay were collected and tested. This provided comparisons of plant mixed – laboratory compacted, and plant mixed – field compacted mixtures at one RAP percentage.

Overall, this research project showed that the percentage of RAP affects the overall properties of the mixture with respect to volumetrics, dynamic modulus, and strength. However, a statistically significant difference from the virgin mixture was only seen at the 40% RAP level. Laboratory compacted specimens were found to have a significantly higher dynamic modulus and strength than field compacted specimens. Using the MEPDG analysis, the predicted performance of the RAP mixtures in a surface course was equivalent to, or better than the virgin mixture with respect to longitudinal cracking, alligator cracking, and rutting.

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Properties of Asphalt Mixtures Containing RAP

FINAL RESEARCH REPORT

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EXECUTIVE SUMMARY

A typical NHDOT Hot Mix Asphalt (HMA) concrete mixture contains at least 15% Reclaimed Asphalt Pavement (RAP). The increasing cost of virgin asphalt and aggregate has increased the interest in using higher percentages of RAP in HMA mixtures. The purpose of this research project was to gain a better understanding of how the addition of RAP affects the properties of HMA. The effects of RAP on a particular mixture were evaluated by comparing the dynamic modulus, strength, and volumetric properties of a series of specimens with similar mix designs and materials but containing different percentages of RAP. Additionally, the Mechanistic-Empirical Pavement Design Guide (MEPDG) software was used to evaluate the predicted performance of the mixtures in a pavement surface course.

Two sites were selected for this study. The cores from the first site were taken from the pavement prior to milling and tested to determine the properties of the RAP. Mixtures were designed and tested in the lab with various RAP contents (0%, 15%, 25%, and 40%) using the milled material. A second site was selected where loose plant mix and field cores from the overlay were collected and tested. This provided comparisons of plant mixed – laboratory compacted, and plant mixed – field compacted mixtures at one RAP percentage.

Overall, this research project showed that the percentage of RAP affects the overall properties of the mixture with respect to volumetrics, dynamic modulus, and strength. However, a statistically significant difference from the virgin mixture was only seen at the 40% RAP level. Laboratory compacted specimens were found to have a significantly higher dynamic modulus and strength than field compacted specimens. Using the MEPDG analysis, the predicted performance of the RAP mixtures in a surface course was equivalent to, or better than the virgin mixture with respect to longitudinal cracking, alligator cracking, and rutting.

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1.0 INTRODUCTION

1.1 PROJECT OBJECTIVES

The purpose of this research is to gain a better understanding of how the addition of Reclaimed Asphalt Pavement (RAP) affects the properties of asphalt concrete mixtures. The effects of RAP on a particular mixture are evaluated by comparing the dynamic modulus, strength, and volumetric properties of a series of specimens with similar mix designs and materials but containing different percentages of RAP. The primary objectives of this study are to:

- Determine the relationship between RAP content and volumetric properties for one RAP source
- Determine the relationship between RAP content and dynamic modulus for one RAP source
- Determine the relationship between RAP content and strength characteristics for one RAP source
- Investigate differences in plant mixed – laboratory compacted, and plant mixed – field compacted mixtures at one RAP percentage

1.2 LITERATURE REVIEW

Recycling has become more prevalent in the pavement industry due to the dwindling supply of virgin materials, increasing costs, and a shortage of landfill space to dispose of old materials. Different state agencies allow varied amounts of RAP to be used in different pavement layers depending on pavement configuration, intended layer and type of mixing plant (1). Due to issues in quality control during asphalt concrete mixing, a higher percentage of RAP is allowed in base courses than surface layers (2).

Previously, recycled asphalt concrete mix design relied mostly on experience and actual field performance. Due to the implicit empiricism in such a procedure, any predictions were restricted to site specific conditions. However, Superpave (3) and the MEPDG guidelines (4) consider fundamental material properties in the design procedure and material performance can be predicted more accurately.

One approach to study the effect of RAP in an asphalt concrete mix is by separating the binder and aggregates (5). Here, the effect of binder is studied by mixing aged and virgin binder at different proportions and measuring the response. Also, this approach assumes complete blending between the aged and virgin asphalt during mixing, when in actuality partial blending most likely occurs (6). A study by Abdulshafi et al. (7) found that binders become stiffer with the addition of reclaimed binder, but the rate at which the reclaimed binder increases the overall binder stiffness decreases as the percentage of reclaimed binder increases. This indicates that there is a possible optimal reclaimed binder content, and that the binder properties don't combine with a simple mass balance equation. Even though such an approach gives better control over the binders, effects of the interaction between aggregate and binders are neglected (7).

Another approach is to study the overall behavior of the material. In such an approach, different constituents are mixed at various proportions and the macroscopic response of the mixture is observed. Using the overall response, a model can be developed incorporating interaction effects. Such an approach (in principle) has been used in recycled mix design for a while. Different overall properties that have been modeled are fatigue performance, rutting, dynamic modulus, and strength under different models of loading. While there is consensus among published research that the amount of RAP in mixtures affects overall properties, conflicting conclusions regarding the optimum or maximum percentage of RAP to be used have been drawn by researchers. One of the reasons for such a wide range of conclusions is mixture specific properties. The following paragraphs give a brief description of some studies that have been conducted.

A study by Hajj et al. (8) indicated that mixes with 15% RAP show an increased resistance to rutting when compared to a control mix. The same study also reports that the rutting resistance of a mix decreased with an increase in RAP beyond 15 percent. A study by Pereira et al. (9) considered the effect of binder percentage (while keeping the same proportion between aged and new binder same) using the Marshal mix design method. The results of the study showed that all reclaimed specimens performed better than the control (0% recycled material) in permanent deformation testing. A study by Lee et al. (10) to find the effect of mode of loading (static vs dynamic) and RAP percentage on rutting performance indicates that mixtures with 30 percent RAP were more resistant to deformation in dynamic mode as opposed to static mode. However, some studies have indicated that there is no significant difference between recycled and fresh mixes (11).

Some studies have reported that with an increase in RAP content, resistance to thermal cracking increased (8). Lee et al. (10) found that the 30 percent RAP mixture offered the highest resistance to thermal cracking, thus they consider 30 percent RAP as a threshold value.

With an increase in RAP content, the stiffness of the mix increases. Such an increase in stiffness may decrease fatigue resistance. This has been confirmed by several studies (8, 9), and refuted by others (11).

Li et al. (7) found that the percentage of RAP affected the high temperature (low frequency) dynamic modulus significantly when compared to the dynamic modulus at low temperatures (high frequency). The same study also found that mixtures with RAP had higher limiting dynamic modulus (at low temperature/higher frequencies) than mixtures without RAP, and that a stiffer binder also increased the dynamic modulus regardless of whether or not the mixture had RAP. It has been found that the nominal maximum aggregate size had significant effect on limiting dynamic modulus; at higher temperatures the dynamic modulus showed increased values when RAP was combined with large aggregates (12). Another study indicated significant difference in dynamic modulus values at high testing temperatures (13).

Increased tensile strength for moisture susceptibility with increased percentage use of RAP has been reported by Watson et al. (14). Similar conclusions regarding increased strength have been reported by Lee et al. (10). Also at lower temperature, brittleness was observed while the fracture occurred.

A study done at North Carolina State University looked at 42 different mixtures, with varying aggregate sources and gradations, varying binder sources, grades and contents, and varying dynamic modulus testing setups (Indirect Tension vs. Uniaxial Compression). Changes in the binder properties were found to affect the dynamic modulus more than changes in the aggregate properties. For 80% of the time, there was no significant difference between the Indirect Tension (IDT) or Uniaxial Compression tests, although it was found that as the nominal maximum aggregate size increased, so did the variability between tested samples (15,16). While proposing a new mix design procedure for cold in-place recycling (CIR) using foamed asphalt (CIR-foam), Kim and Lee (17) found that for high temperature dynamic modulus testing, it is the binder contributed by the RAP that is most influential, while at low temperatures the fines play a much larger role in the dynamic modulus.

One study related to field performance and actual cost benefits found there were minimal (statistically insignificant) cost savings when the projects were put out to bid, but when "value engineering proposals" (not publicly advertised) were studied, they did show some cost savings when the RAP percentage was over 20% (11).

From published literature it appears that there is consensus among various researchers about the existence of a threshold limit on the percentage of RAP above which the properties of the recycled mixture are significantly different than a virgin mix. Typical threshold values range from 15% (14, 18) to 20% (19,20). It is clear that there is a percentage of RAP that optimizes the material property under consideration and this optimal value can change depending on project specific needs (8) and material availability under local conditions.

Several studies using materials specific to the New England region were carried out by Daniel et al. (21, 22, 23). These studies found that the addition of a processed RAP significantly increased the VMA of the mixture at RAP contents of 25% and 40%. This increase in VMA offset the increase in stiffness from the higher RAP content when the dynamic modulus of the mixtures was measured. The dynamic modulus values of the 25% and 40% RAP mixtures were similar to that for a control mixture with no RAP and fell below the curve for 15% RAP, as shown in Figure 1.1. The likely explanation for this behavior is that the RAP does not completely breakdown and blend with the virgin materials and behaves more like a "black rock". In this condition, the gradation of the mixture becomes coarser and the VMA increases.

The ratios of the virgin stockpiles were kept constant for the different RAP mixtures in this study. Therefore, the higher RAP mixtures were forced to have coarser gradations to maintain the virgin stockpile ratios. Additionally, the design asphalt content for the 25% RAP mixture was 0.5% higher than the other mixtures. Both of these have an effect on the dynamic modulus of a mixture, so it is difficult to isolate the effect of the RAP itself.

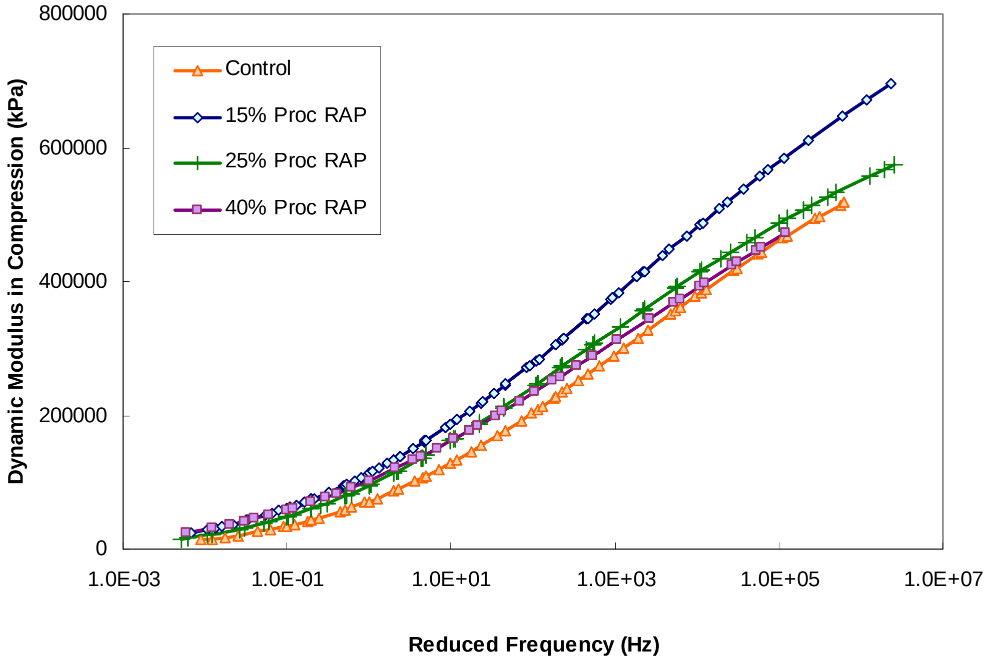


Figure 1.1: Dynamic Modulus Master Curves for RAP Mixtures (22)

2.0 MATERIALS AND TESTING PROGRAM

This chapter presents the materials, the testing equipment, and methods used for the testing of HMA as well as the data analysis methods.

2.1 MATERIALS

2.1.1 Virgin Aggregates

The virgin aggregate for this project was obtained from Hooksett Crushed Stone in Hooksett, New Hampshire, a division of Pike Industries. Material was obtained from the Fillmore natural washed sand, baghouse fines, and the 12.5mm, 9.5mm, washed machine sand (WMS), and dust blast rock stockpiles. The stockpile gradations for these materials are shown in Table 2.1.

Table 2.1: Virgin Aggregate Stockpile Gradations

Sieve Size	Percentage Passing				
	WMS	Dust	9.5 mm	12.5 mm	Fillmore
¾”	100	100	100	100	100
½”	100	100	100	96	100
3/8”	100	100	99	48	100
#4	99	99	32	5	100
#8	73	80	6	3	89
#16	46	58	4	3	71
#30	29	42	3	2	47
#50	17	29	3	2	21
#100	6	18	2	2	4.9
#200	4	10	2	1	1.4

2.1.2 Asphalt Binder

The virgin binder used was a PG 64-28 from Pike Industries in Portsmouth, NH. The mixing and compaction temperature ranges for this binder were 155-162 ^{o}C and 143-148 ^{o}C, respectively. The specific gravity of the binder was 1.035.

2.1.3 Recycled Asphalt Pavement (RAP)

The RAP for this project was obtained from the millings off Rt. 4 between Epsom and Northwood, NH. Five 5-gallon buckets of millings were gathered, three from the westbound lane and two from the eastbound lane. This RAP source included recycled asphalt concrete, sealers, patches, as well as any surface treatments or painted linage. There were also small amounts of organic material and plastics that were removed by hand.

The millings were processed through a small crusher in the lab so that the final “black rock”, or as-is gradation of the RAP was close to a typical RAP stockpile processed at a plant.

The 'black rock' gradation was measured by performing a sieve analysis on the RAP material directly. From binder extraction testing, asphalt content in RAP was determined to be 6.04%. The extracted gradation was measured by performing a sieve analysis on the recovered RAP aggregates after the binder was extracted. The "black rock" and extracted gradations of the RAP are shown in Table 2.2.

Table 2.2: Extracted and Black Rock Gradations for RAP

Sieve Size	Percentage Passing	
	Extracted	"Black Rock"
¾"	100	100
½"	100	99.5
3/8"	99.8	93.8
#4	84.6	43.6
#8	65.4	22.1
#16	51.0	11.6
#30	37.4	5.9
#50	22.9	2.6
#100	12.8	1.0
#200	7.4	0.4

2.1.4 Plant Mix

Approximately 200 pounds of loose 12.5 mm surface course mixture with PG 64-28 binder was obtained from the Portsmouth Pike plant for compaction in the lab.

2.1.5 Field Cores

Field cores were obtained from two different locations in this project. Seven surface cores were taken prior to milling along the Rt. 4 project. Approximate locations of these cores are shown in Figure 2.1. These cores represent a 100% RAP condition.

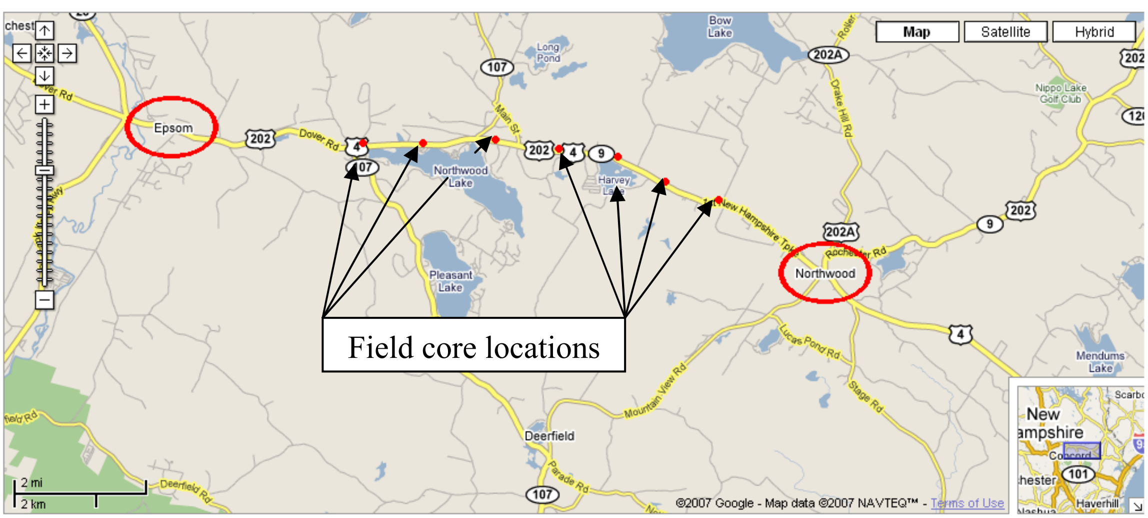


Figure 2.1: Approximate Locations of Field Cores from Rt. 4

Twelve field cores were taken from a newly placed 12.5 mm surface mixture on Route 9/202 between Hillsborough and Henniker, NH. The mixture for this pavement is similar to the mixture from which loose plant mixture was obtained.

2.2 SPECIMEN FABRICATION

Virgin aggregates were batched by individual sieve size and heated at the mixing temperature for a minimum of 4 hours prior to mixing. RAP was batched as a stockpile and heated at the mixing temperature for 2 hours prior to mixing. The asphalt, aggregates, and RAP were mixed in a bucket mixer and then compacted using a Superpave Gyratory Compactor (SGC). The loose plant mix was reheated for approximately 40 minutes at 130^{o}C, run through a splitter to obtain the appropriate sample size, then heated to compaction temperature and compacted using the SGC. After compaction, specimens were cut to the final testing size (150 mm diameter, 35 mm thickness) using a diamond blade wet saw. Figure 2.2 shows an SGC compacted sample marked for cutting. The specific gravity of all specimens were measured using a Corelok Vacuum Sealing System.

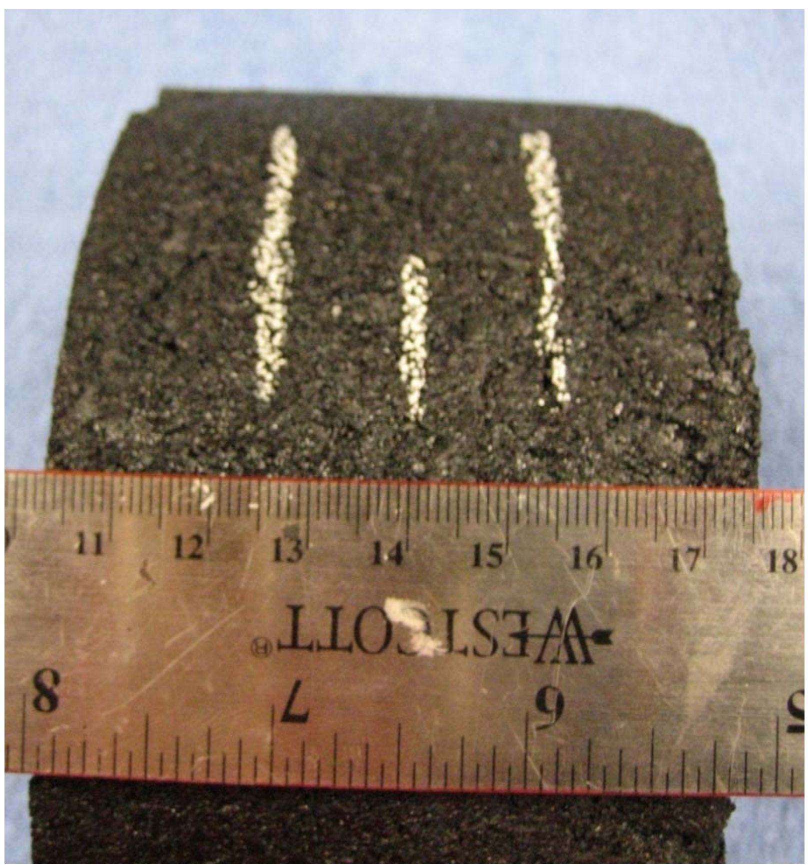


Figure 2.2: Gyratory Compacted Sample Marked for Cutting

2.3 MIX DESIGNS

An existing Superpave 12.5mm surface course mix containing 15% RAP, provided by Pike Industries (mix design #S36-05H), was used as a starting point for the mixtures in this research. Mixes were then designed with 0%, 25%, and 40% RAP. The gradations for each RAP percentage were adjusted to be as close as possible to the target gradation of the 15% RAP mixture by varying the virgin stockpile percentages. The gradations for all four mixtures are shown in Table 2.3 and Figure 2.3.

Table 2.3: Gradations for RAP Mixtures

Sieve Size	Percentage Passing			
	0% RAP	15% RAP	25% RAP	40% RAP
¾"	100	100	100	100
½"	99.1	99.1	99.1	99.1
3/8"	87.8	87.8	87.8	87.8
#4	58.8	58.8	58.1	58.1
#8	42.7	42.6	41.9	41.9
#16	31.8	32.1	31.8	31.8
#30	21.9	22.2	22.2	22.2
#50	13.2	13.2	13.2	13.2
#100	6.6	6.6	6.6	6.6
#200	3.9	3.9	3.9	3.9

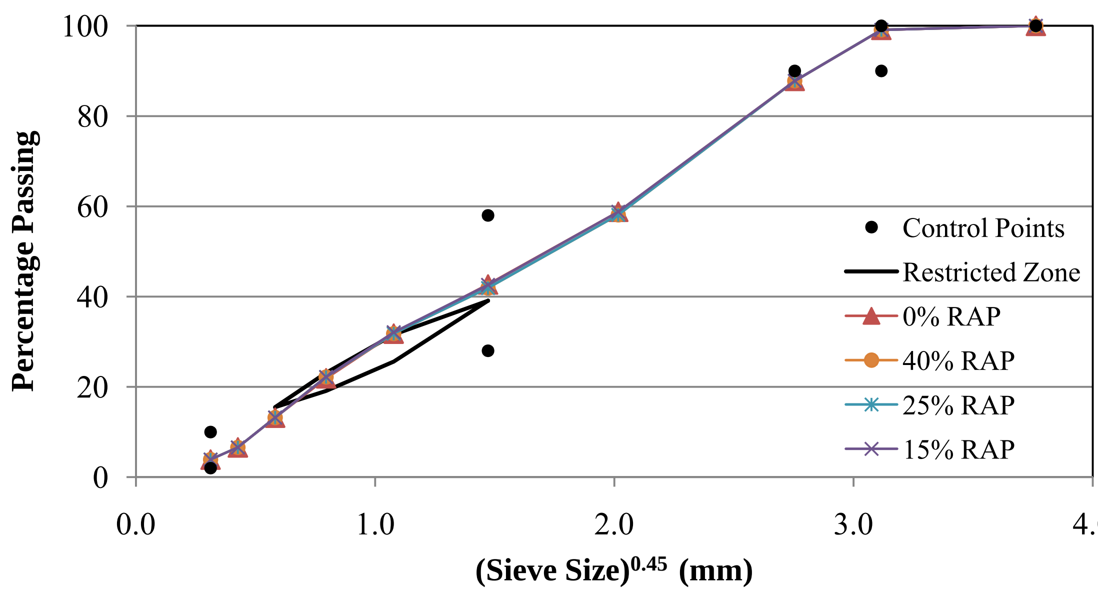


Figure 2.3: RAP Mixture Gradations

Table 2.4 shows a summary of the mix design parameters for each of the RAP contents. The asphalt contents are consistent among the different RAP percentages. The VMA increases with the higher RAP contents.

Table 2.4: Summary of Mix Design Parameters

Parameter	0% RAP	15% RAP	25% RAP	40% RAP	Specifications
Asphalt Content (%)	5.9	5.7	5.9	5.7	--
VMA (%)	15.7	15.6	16.1	16.3	Min 14.0
VFA (%)	74.4	74.5	77.1	75.4	70-80
Percentage G_{mm} @ N_{ini}	89.6	90.1	87.6	89.8	≤ 90.5
Dust Proportion	0.76	0.77	0.71	0.72	0.6-1.2

2.4 TESTING SETUP AND EQUIPMENT

The dynamic modulus and strength testing for this project was performed using a closed-loop servo-hydraulic system, manufactured by Instron®. The testing apparatus included the loading frame (Model 8800), a 20,000 pound hydraulic actuator (Model IST 3690 Series 100KN Pedestal Mounted Actuator), a 5,000 pound load cell, control tower (Model 8500) and control panel (Model 8500 plus), environmental chamber (Model 3119-407), testing sample guide (Interlaken Technology Corporation (ITC), Indirect Tensile (IDT) Fixture), and personal computers running Instron's Fast Track 2 software (actuator control), LabVIEW 7.1 and Matlab 7 (data acquisition and analysis).

The ITC IDT load fixture was used to isolate the loading strips on the sample. This greatly reduces any lateral or rotational loading of the samples caused by misalignments. Figure 2.4 shows the IDT fixture in the environmental chamber prior to testing.

The Envirotherm® environmental chamber controlled the temperature to within + 0.1°C, and the range of -10°C to 30°C was used for these tests. Low pressure liquid nitrogen was used for cooling. Figure 2.5 shows the environmental chamber with liquid nitrogen hose.

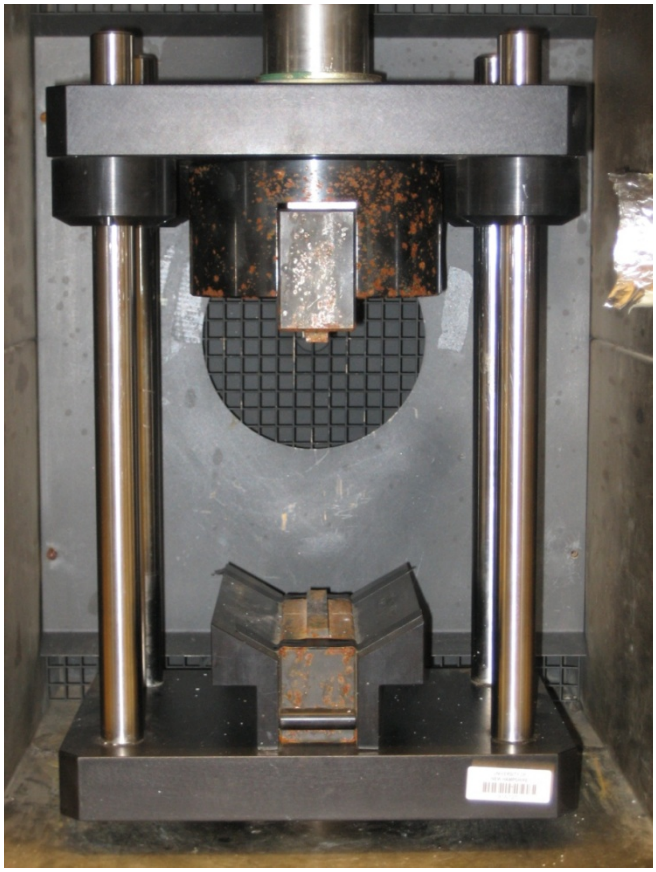


Figure 2.4: IDT Load Fixture Inside Environmental Chamber

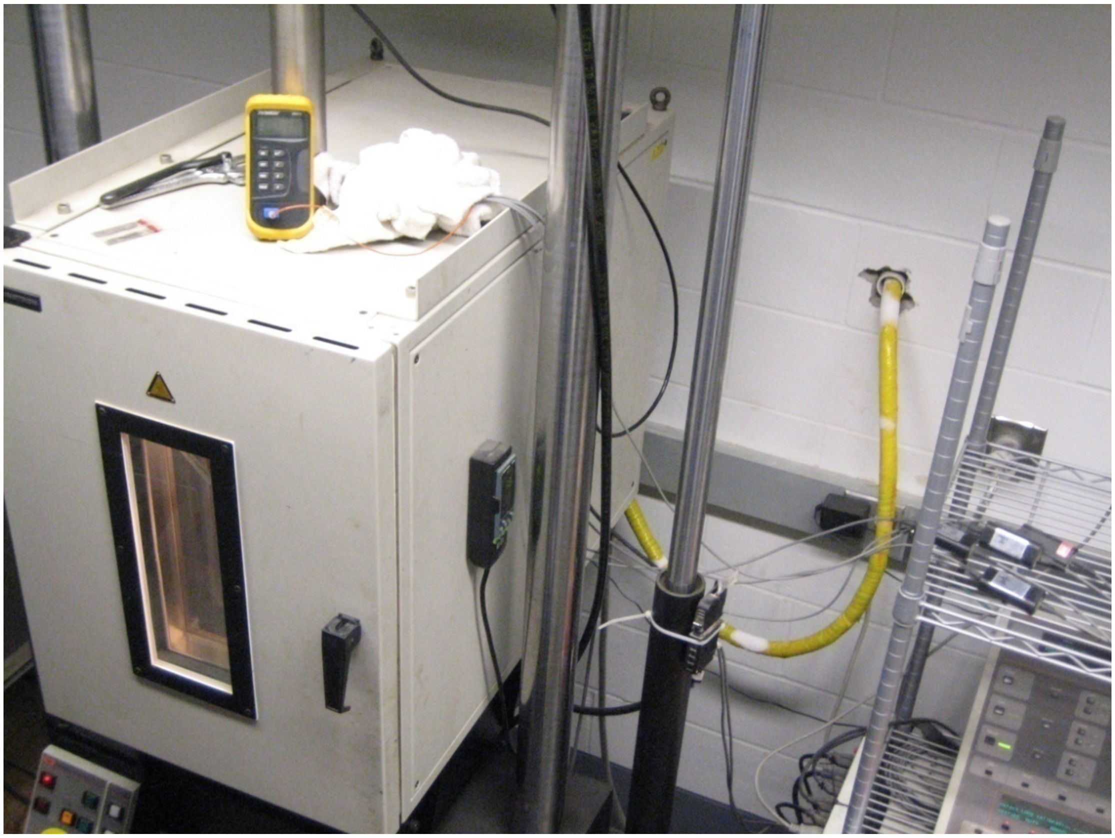


Figure 2.5: Environmental Chamber

2.5 SPECIMEN INSTRUMENTATION

Indirect tensile dynamic modulus testing requires that both the vertical and horizontal strains be measured. This is achieved by two pairs of linearly variable differential transformers (LVDTs), one pair on each face of the specimen. The cut samples are marked with a 50 mm gap using the metal marking stencil, seen in Figure 2.6. Brass targets are attached to L-brackets and an aluminum rod is used to keep each pair of L-bracket and brass target at a fixed distance of 50 mm during the gluing process. The targets and attached brackets are glued to each cut face of the sample at right angles to each other, corresponding to the markings made earlier with the metal marking stencil. Figure 2.7 shows a pair of L-bracket and brass targets connected to an aluminum rod ready to be glued to a sample. Figures 2.8 and Figure 2.9 show a specimen being fitted with LVDT brackets. Figure 2.10 shows the LVDTs in place, and Figure 2.11 shows a fully instrumented sample ready for testing in the IDT load frame.

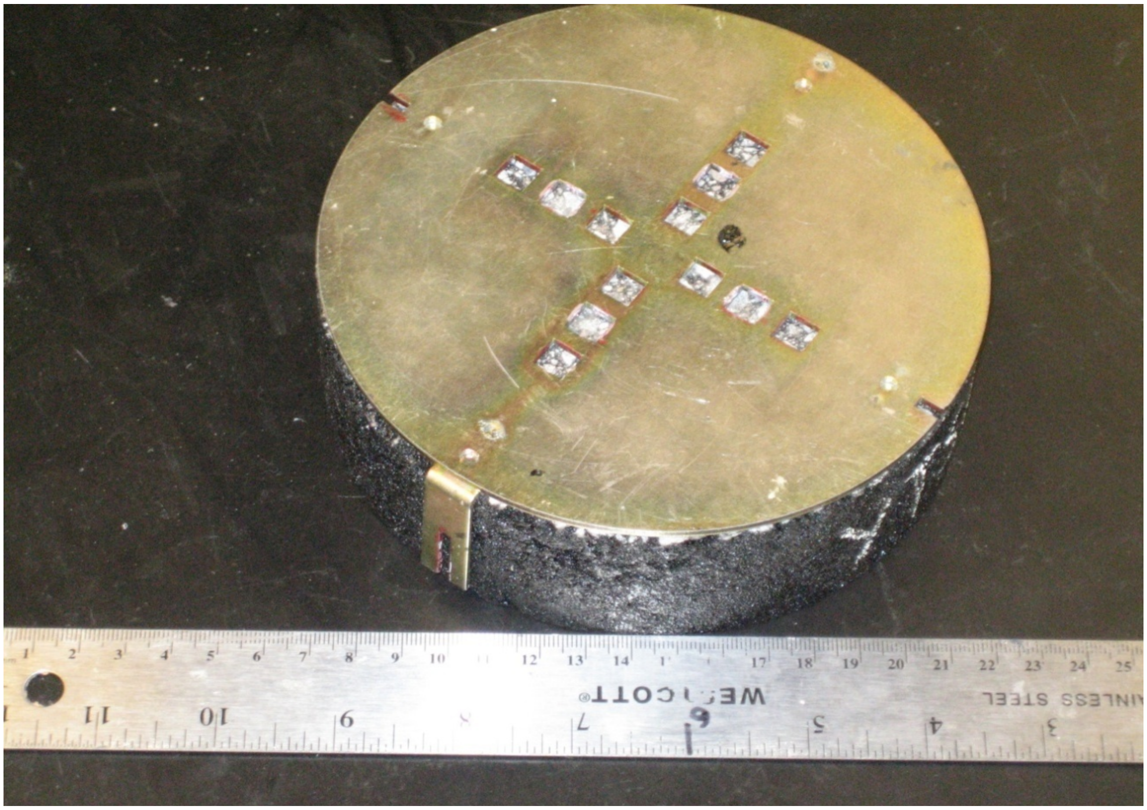


Figure 2.6: Metal Gluing Guide Used to Mark on a Sample

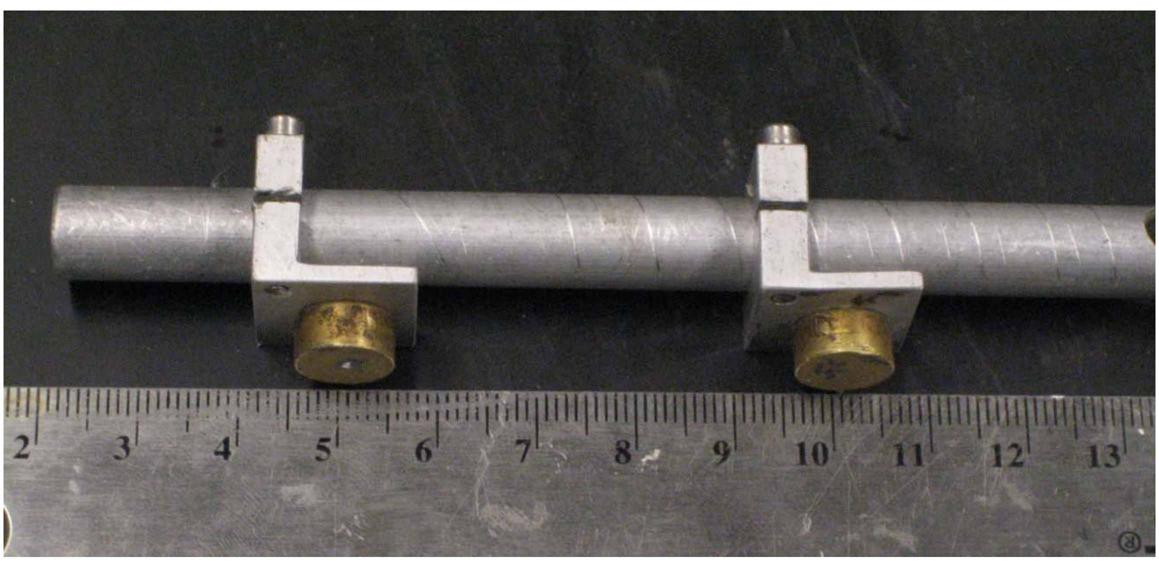


Figure 2.7: L-Bracket and Brass Targets Connected to an Aluminum Rod at 50mm Gauge Length

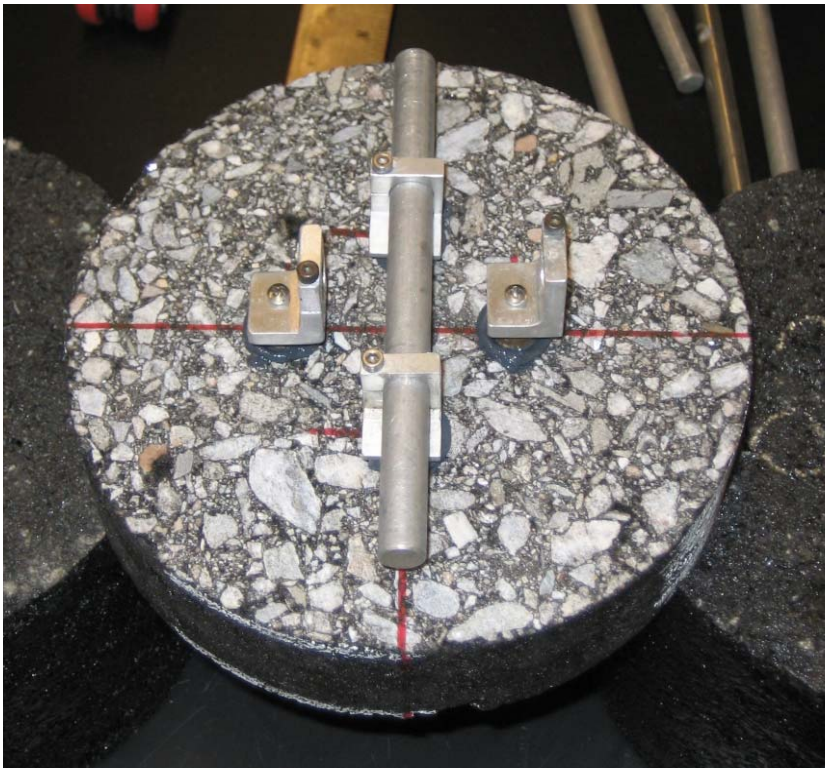


Figure 2.8: LVDT Brackets Positioned at 90º with Gluing Rod

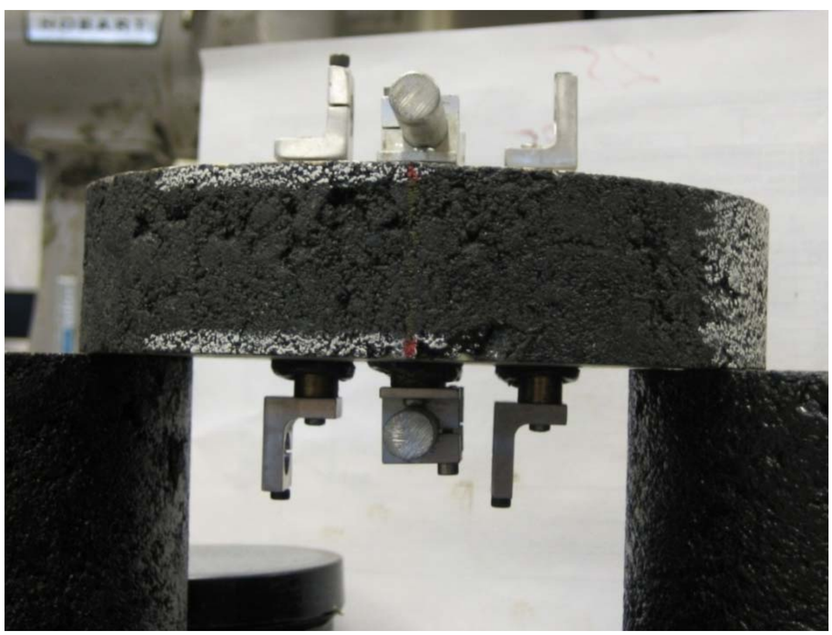


Figure 2.9: LVDT Brackets on Both Faces of the Sample

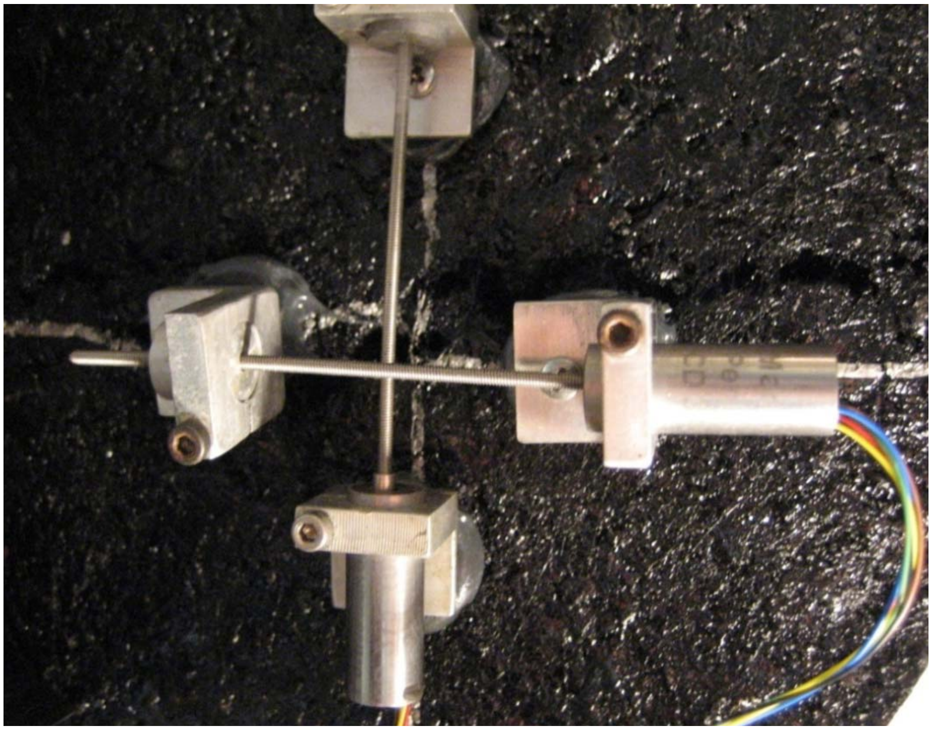


Figure 2.10: Close-Up of L-Bracket and LVDTs Glued on a Sample

Figure 2.11: Sample and LVDTs in Place and Ready for Testing

2.6 DYNAMIC MODULUS

Dynamic modulus testing in this research was performed in the indirect tensile (IDT) mode. The relationship developed by North Carolina State (15, 16) is used to calculate the dynamic modulus from the measured load, horizontal and vertical displacements, as shown in equation 2.1 below.

$$|E^*| = \left| \frac{2P_0}{\pi a d} \times \frac{\beta_1\gamma_2 - \beta_2\gamma_1}{\gamma_2 V_0 - \beta_2 U_0} \right| \tag{2.1}$$

where, P_0 = applied load

a = loading strip width

d = thickness of specimen

U_0 = horizontal displacement amplitude

V_0 = vertical displacement amplitude

$\beta_1, \beta_2, \gamma_1, \gamma_2$ = geometric constants

(-0.0134, -0.0042, 0.0037, 0.0116 respectively)

Frequency and temperature sweeps were performed to obtain dynamic modulus values that were then used to construct the dynamic modulus master curves using the time temperature superposition principle. Frequencies of 0.1Hz, 0.2Hz, 0.5 Hz, 1.0 Hz, 2.0 Hz, 5.0 Hz, 10.0 Hz, and 20.0 Hz and temperatures of -10°C, 0°C, 10°C, 20°C, and 30°C, were used in this study. To accurately estimate the internal temperature of the sample during testing, a dummy sample was embedded with a temperature gauge and subjected to the same temperature changes as the sample being tested. A typical set of dynamic modulus data obtained from the frequency sweep test is shown in Figure 2.12.

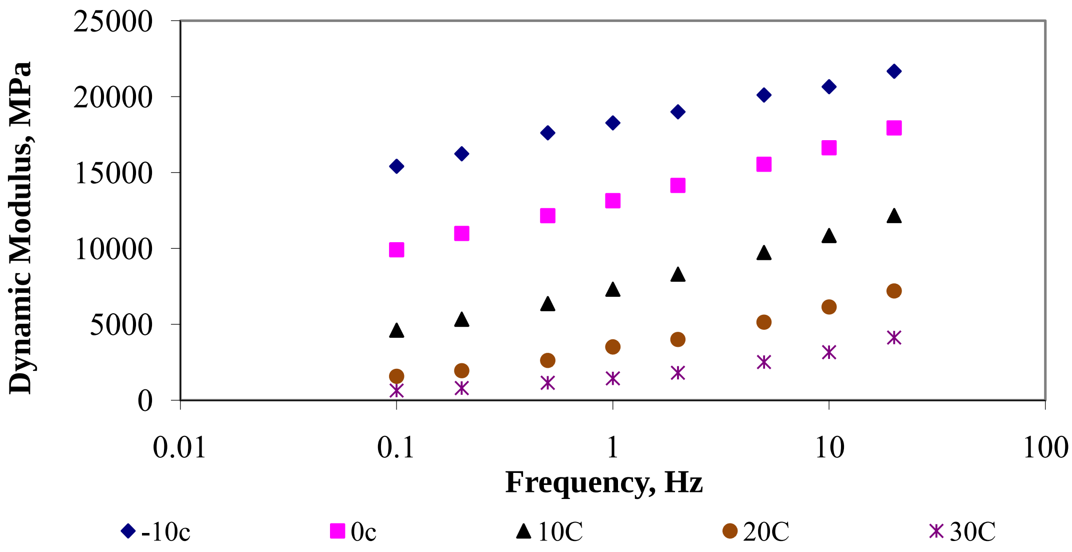


Figure 2.12: Dynamic Modulus with Testing Frequency and Temperature

The individual isotherm curves are then shifted horizontally along the frequency axis to form a master curve at a reference temperature of 20°C. The master curve is fit with a sigmoidal function as shown in equation 2.2.

$$Log|E^*| = a + \frac{b}{1 + \frac{1}{e^{(c + d*\log(\gamma))}}} \tag{2.2}$$

$$\gamma = fa_T \tag{2.3}$$

where, γ = reduced frequency

f = frequency

α_T = time-temperature shift factor

$|E^*|$ = Dynamic Modulus

$a, b, c, d =$ regression coefficients

A typical master curve is shown in Figure 2.13 and the associated temperature shift factors are shown in Figure 2.14.

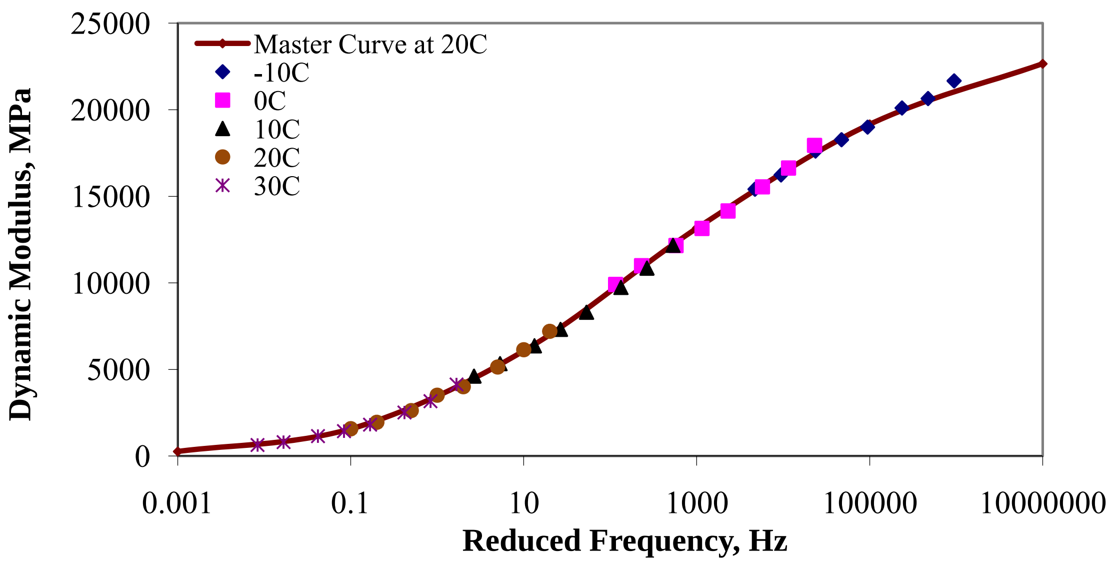


Figure 2.13: Typical Dynamic Modulus Master Curve

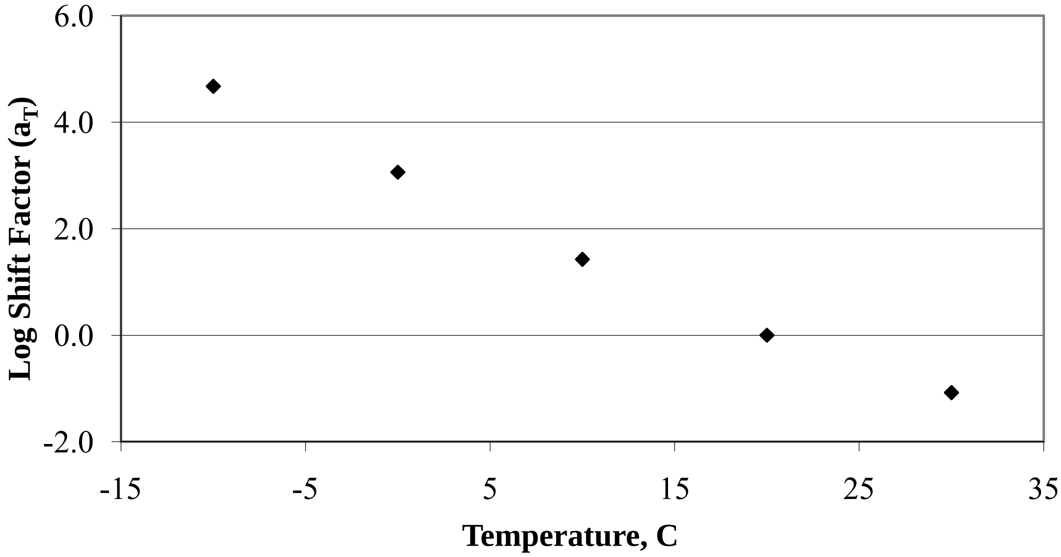


Figure 2.14: Temperature Shift Factors Obtained from Dynamic Modulus Master Curve

2.7 STRENGTH TESTING

Strength testing was performed on the samples after the dynamic modulus testing was completed. The samples were crushed under a constant deformation rate of 2 inches per minute at a temperature of 25ºC. A typical load curve for a strength test is shown in Figure 2.15. The strength of the specimen is calculated using Equation 2.4:

$$S_t = \frac{2}{\pi}\frac{P_f}{bD} \tag{2.4}$$

where, S_t = strength of sample

P_f = maximum load

b = average thickness of sample

D = average diameter of sample

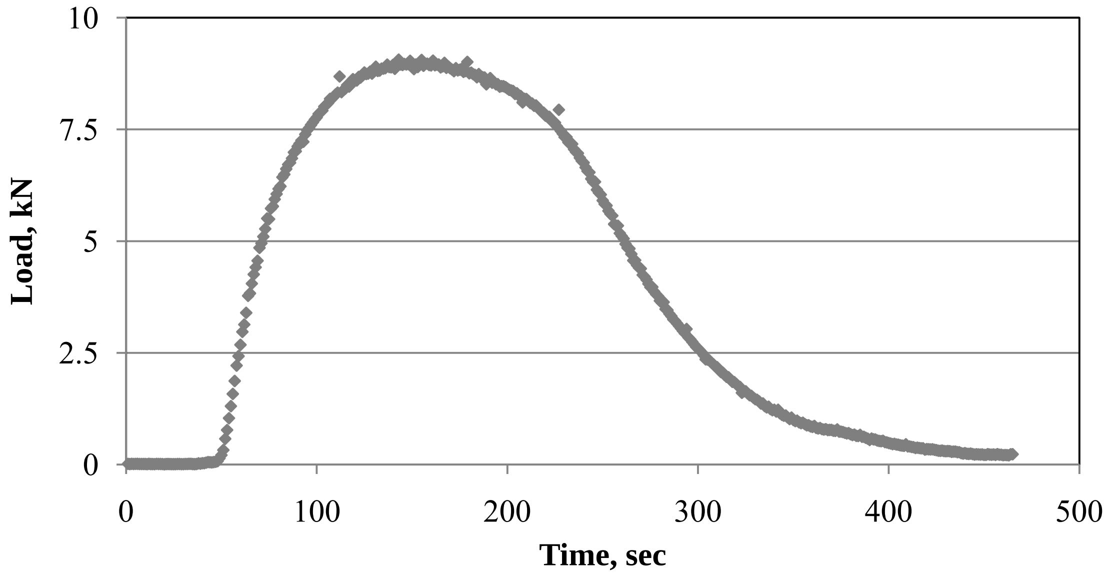


Figure 2.15: Typical Load versus Time Plot for IDT Strength Test

2.8 STATISTICAL ANALYSIS

Statistical analysis was performed to determine if the various dynamic modulus master curves were significantly different from one another. Two methods were used. In the first method, the individual dynamic modulus values at specific frequency intervals were compared. This assumed that if the majority of these dynamic modulus values were different then the overall curves were significantly different. This also showed which frequency areas were most affected by the addition of RAP. The second method compared the mean value of the dynamic modulus for different mixtures. The advantage of this method is that there is a very large sample, which increases the accuracy of the confidence intervals.

The Student's t-test was used for both methods to determine if the sample sets were significantly different. The Student's t-test is a procedure which determines the probability that the mean from one sample set is different from another. This probability is known as the p-value and when it is less than the chosen confidence interval (alpha, $\alpha = 0.05$) the hypothesis, or assumption, that both sample sets are equal, is rejected; and thus the sample sets are deemed significantly different. Along with the p-value, the Student's t-test computes 95% confidence intervals, for which the operator is 95% confident that the true mean of the population falls between.

3.0 RESULTS

This chapter presents the results of the dynamic modulus testing, strength testing, and statistical findings for all laboratory specimens and field cores. Additionally, pavement performance is evaluated using the Mechanistic Empirical Pavement Design Guide (MEPDG) Version 1.0 software.

3.1 DYNAMIC MODULUS

3.1.1 Millings RAP Specimens

The sample identification and air void contents for the specimens containing the millings RAP are shown in Table 3.1. All laboratory specimens were fabricated to a target air void content of 4.0 ± 0.5%. All field cores had air void content above 10%, so direct comparisons cannot be made between the laboratory specimens and the field cores.

Table 3.1: Air Voids and RAP Content of Millings RAP Test Samples

Sample Name	Percentage RAP	Air Voids (%)
WTSA	0	3.9
WTSB	0	4.3
XTSC	15	4.1
XTSD	15	4.0
YTSA	25	3.8
YTSD	25	3.9
YTSMX	25	3.7
ZTSA	40	4.5
ZTSB	40	4.3
ZTSF	40	4.3
FC1	100	10.6
FC2	100	12.2
FC3	100	10.2
FC4	100	10.2
FC5	100	12.8
FC6	100	12.6
FC7	100	10.7

The dynamic modulus master curves for the mixes containing 0%, 15%, 25%, and 40% RAP are shown in Figures 3.1 through 3.4, respectively. Figure 3.5 shows the 100% RAP (field cores), and Figure 3.6 shows the average master curves for the different RAP contents plotted on one single graph. The mean square error for the master curve fit is shown on each figure.

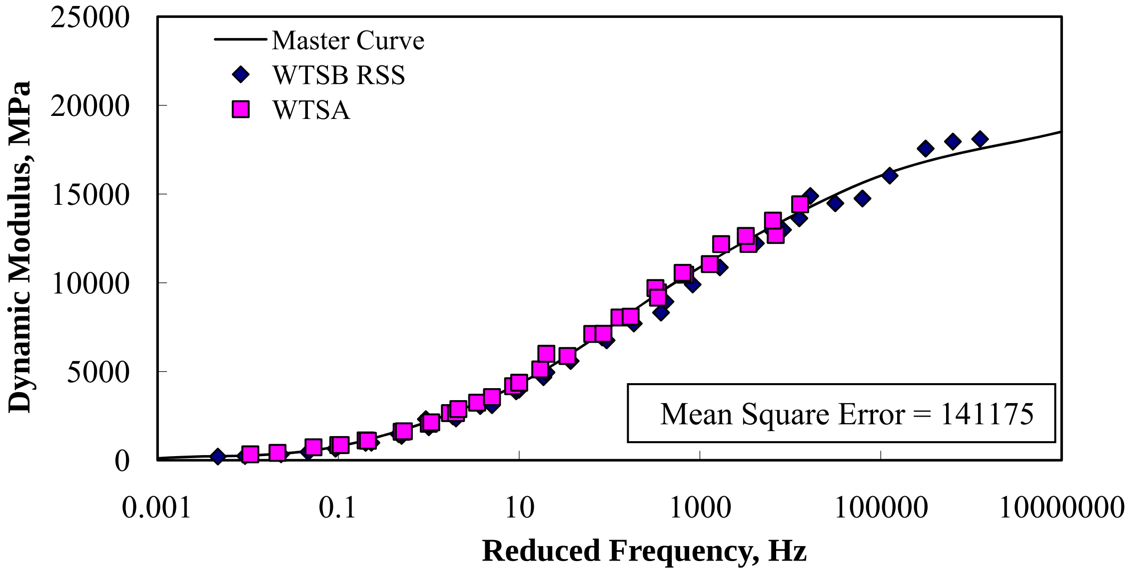


Figure 3.1: Dynamic Modulus Master Curve for 0% RAP Mixture

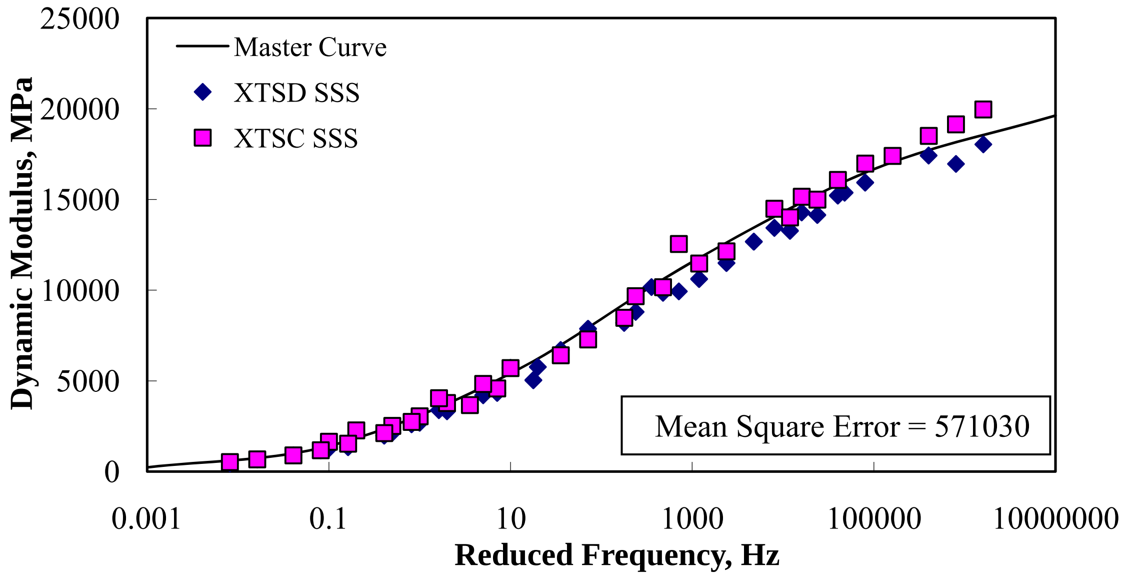


Figure 3.2: Dynamic Modulus Master Curve for 15% RAP Mixture

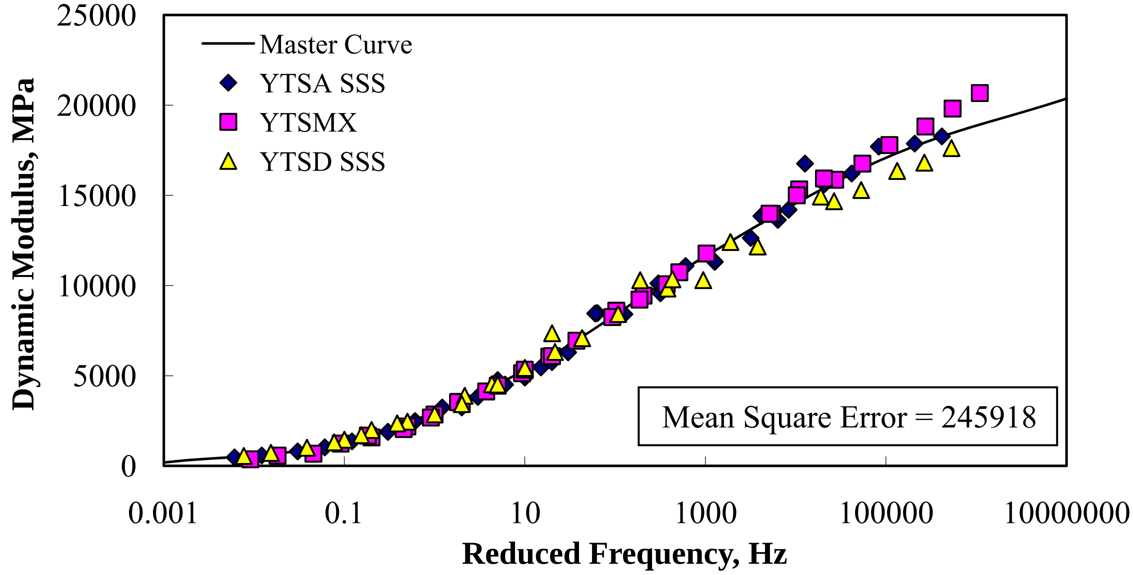


Figure 3.3: Dynamic Modulus Master Curve for 25% RAP Mixture

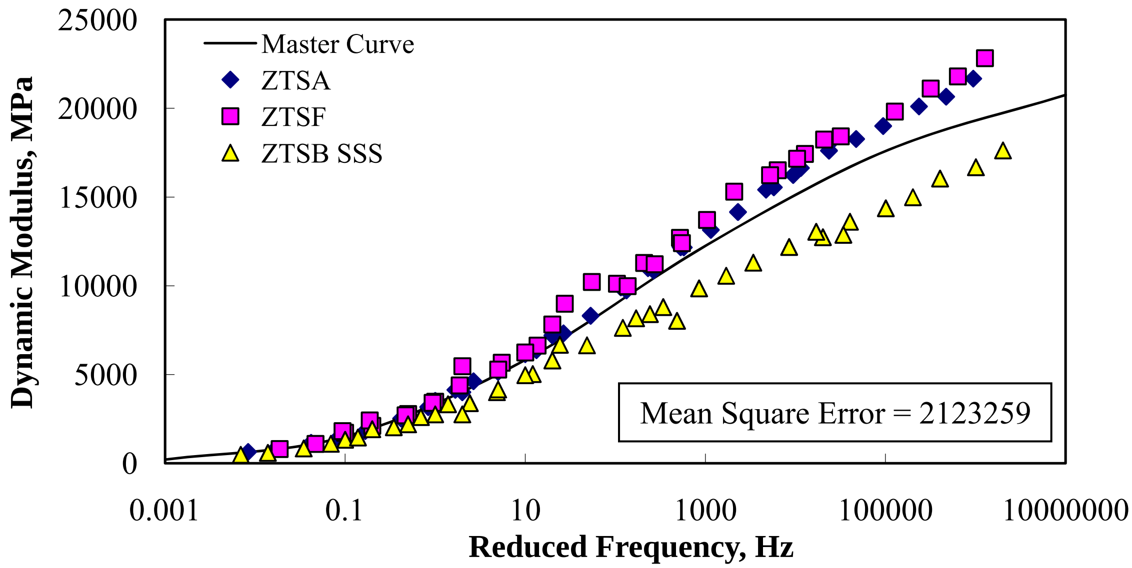


Figure 3.4: Dynamic Modulus Master Curve for 40% RAP Mixture

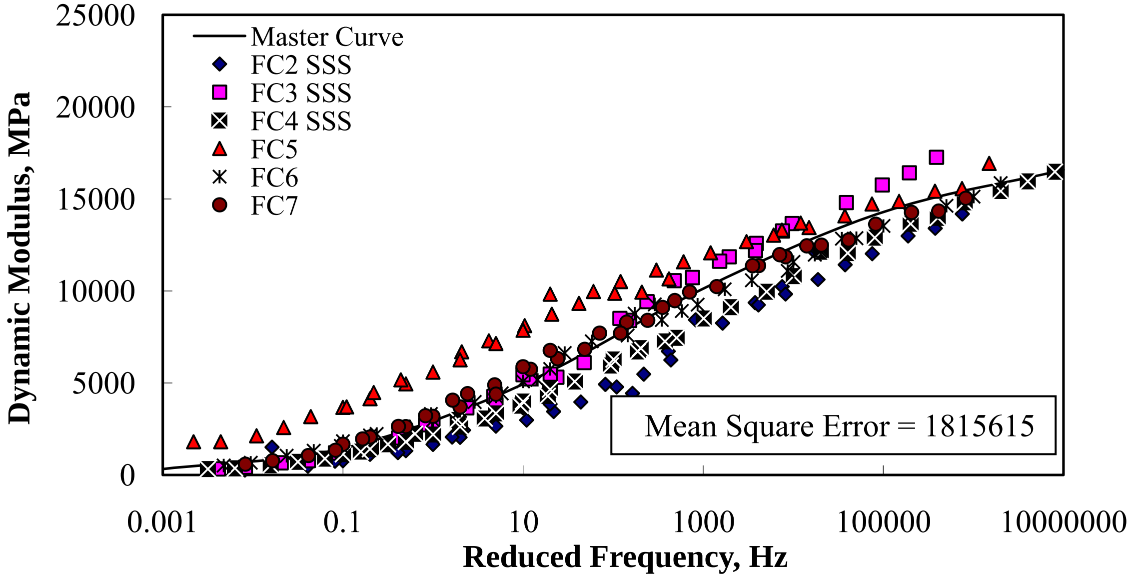


Figure 3.5: Dynamic Modulus Master Curve for the Field Cores (100% RAP)

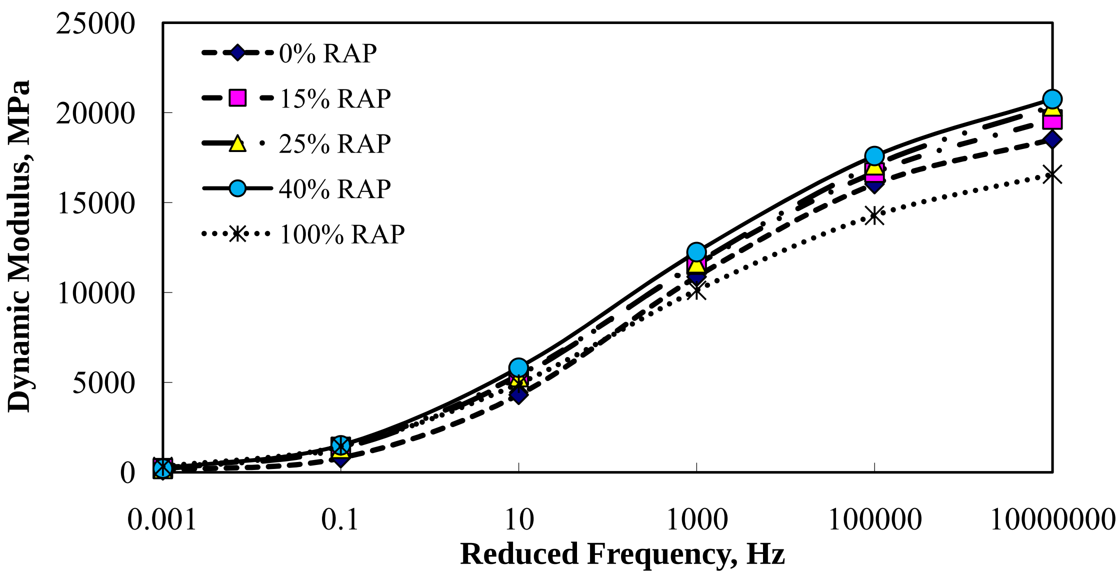


Figure 3.6: Average Dynamic Modulus Master Curves for All Millings RAP Mixtures and Field Cores

The dynamic modulus of the mixture increases as the RAP percentage increases. The mean square error term also increases with increasing RAP percentage (except 15% RAP mixture), indicating that there is more variability with the increased RAP. The field cores have a lower dynamic modulus than the laboratory specimens due to the higher air void content.

Statistical Analysis

The dynamic modulus values at specific frequencies were compared using the t-test to determine if there is a significant difference between various mixtures. Tables 3.2 and 3.3 show the p-value results from this analysis. A p-value below 5% indicates a significant difference at that particular frequency. In Table 3.2, the 25% and 40% RAP mixtures show a significant difference from the control mixture at lower frequencies, but there are not significant differences at the higher frequencies or between other mixtures. Table 3.3 shows that the 25% RAP mixture is significantly different than the field cores at higher frequencies.

Table 3.2: Dynamic Modulus Statistical Results for Lab Mixtures Containing RAP

Frequency (Hz)	0% RAP - 15% RAP	0% RAP - 25% RAP	0% RAP - 40% RAP	15% RAP - 25% RAP	15% RAP - 40% RAP	25% RAP - 40% RAP
0.001	39%	21%	8%	94%	92%	81%
0.01	17%	6%	**1%**	71%	77%	36%
0.1	8%	**2%**	**1%**	56%	60%	19%
1	11%	**3%**	**3%**	67%	58%	29%
10	21%	6%	8%	86%	61%	42%
100	38%	15%	17%	99%	63%	53%
1000	59%	26%	33%	95%	64%	61%
10000	76%	51%	47%	93%	65%	65%
100000	82%	74%	55%	96%	66%	66%
1000000	77%	81%	57%	94%	68%	66%
10000000	68%	82%	56%	80%	71%	64%

In Figure 3.4, it is apparent that specimen ZTSB is different than the other two 40% RAP specimens. The statistical analysis was also performed omitting this sample and is summarized in Table 3.4. There are more frequencies where the 40% RAP mixture is different than the control and field cores with the ZTSB specimen omitted.

Table 3.3: Dynamic Modulus Statistical Results Comparing Lab Specimens and Field Cores

Frequency (Hz)	100% (FC) - 0% Control	100% (FC) - 15% RAP	100% (FC) - 25% RAP	100% (FC) - 40% RAP
0.001	19%	35%	33%	36%
0.01	12%	40%	33%	45%
0.1	9%	56%	41%	70%
1	10%	88%	69%	84%
10	25%	71%	76%	42%
100	88%	43%	24%	21%
1000	25%	29%	**4%**	15%
10000	8%	20%	**1%**	14%
100000	10%	12%	**1%**	13%
1000000	14%	**3%**	**2%**	12%
10000000	17%	**0%**	**3%**	12%

Table 3.4: Dynamic Modulus Statistical Results for Mixtures Containing RAP*

Frequency (Hz)	0% RAP - 40% RAP	15% RAP - 40% RAP	25% RAP - 40% RAP	100% (FC) - 40% RAP
0.001	25%	80%	57%	40%
0.01	**2%**	57%	26%	51%
0.1	**1%**	86%	**3%**	87%
1	**2%**	27%	15%	54%
10	**3%**	28%	14%	14%
100	**3%**	29%	12%	**2%**
1000	**4%**	28%	10%	**0%**
10000	7%	24%	8%	**0%**
100000	12%	17%	6%	**0%**
1000000	15%	8%	7%	**0%**
10000000	17%	7%	11%	**0%**

*Omitting ZTSB (40% RAP Outlier Sample)

The comparison of individual frequencies shows that the 40% mixture is significantly different at some frequencies, but does not indicate significant difference for the whole curve or among other mixtures. Therefore, a comparison of means for the whole master curve was performed. The results of this analysis are shown in Tables 3.5 and 3.6 and in Figure 3.7. Table 3.5 shows a list of the mean dynamic modulus, number of samples in the test, standard error, and confidence intervals for each RAP content. This information is displayed graphically in Figure 3.7; the dynamic modulus values for each RAP percentage are represented by the dots, the means of the respective RAP percentages are shown as the centerline of the diamonds and the ends of the diamonds represent the 95% confidence intervals. As seen in Table 3.5 and in Figure 3.7, the mean dynamic modulus value increases with increasing RAP content.

The results of the t-test analysis are shown in Table 3.6; the pairs are arranged in descending order based on the difference in means. The first two columns are the two RAP contents that are compared, the third column is the difference in mean dynamic modulus values, the fourth and fifth columns show the lower and upper confidence intervals (based on an alpha value of 0.05), and the sixth column represents the p-value of each pair of means. The horizontal bar graph at the far right of Table 3.6 shows each pair's dynamic modulus difference as the bars, and the 95% confidence intervals as lines. It can be seen that the only p-values less than alpha (0.05) are the comparisons of 40% vs. 0% and 40% vs. 100% (field cores). The 15% and 25% means are almost equal and the p-value for this comparison is 0.934, which indicates that the 15% and 25% dynamic modulus means have almost no difference.

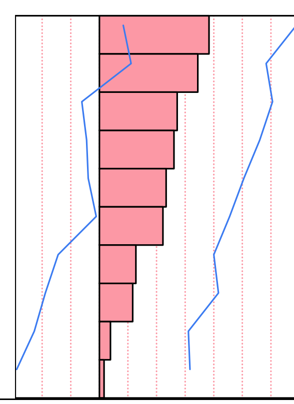
The circles in Figure 3.7 are a visual representation of the t-test. The bold red circle represents the control mean against which the other RAP percentage means are compared. A bold grey circle indicates that a mean is significantly different from the control mean, and a thin red circle indicates that a mean is not significantly different from the control. Using the 0% RAP mixture as the control, only the mean of the 40% RAP is significantly different.

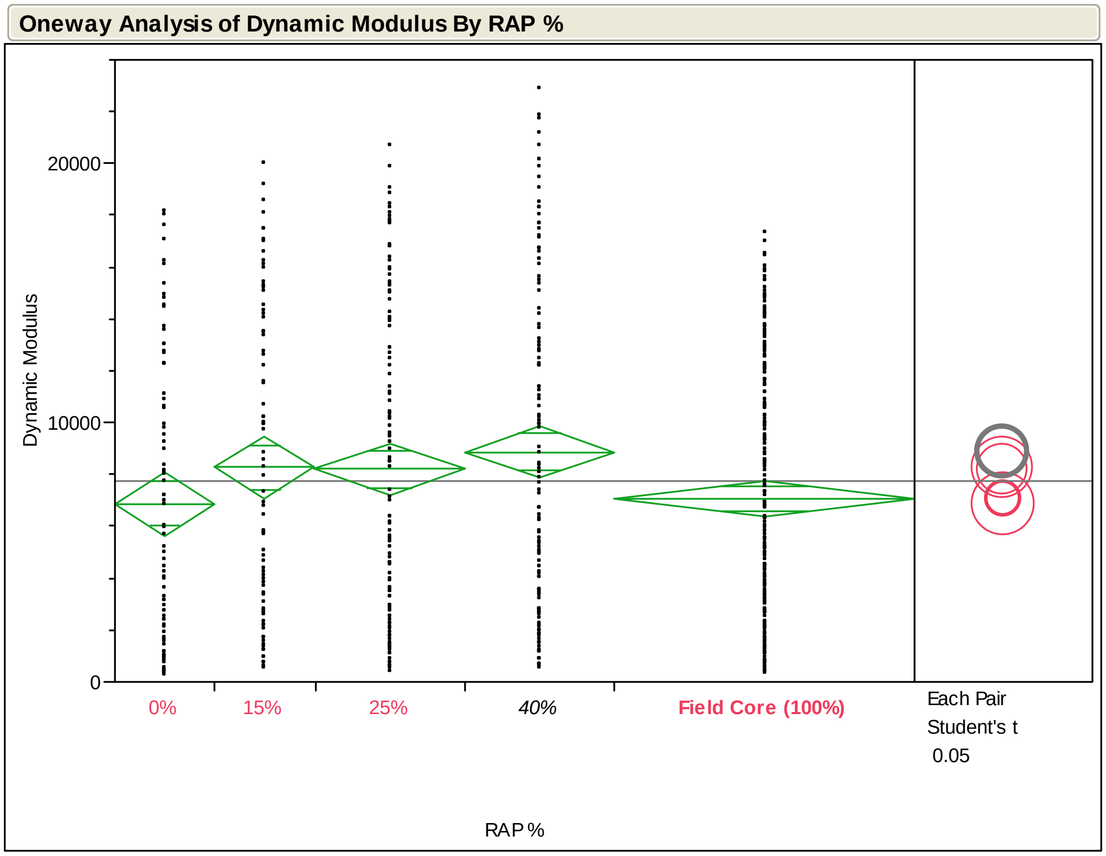
Table 3.5: Oneway Anova Test Results for Mean Dynamic Modulus Value Comparison at Different RAP Content

% RAP	Number of Observations	Mean	Standard Error	Lower 95%	Upper 95%
0%	80	6864	621	5645	8084
15%	80	8275	621	7056	9494
25%	120	8209	507	7213	9204
40%	120	8865	507	7869	9860
Field Core (100%)	240	7065	359	6361	7769

Table 3.6: Students t-test results for Mean Dynamic Modulus Value Comparison at Different RAP Content

Comparison between RAP Mixtures		Difference in Mean	Lower CL	Upper CL	p-Value
40%	0%	2000.5	426.4	3574.7	0.0128
40%	Field Core	1800.0	580.6	3019.3	0.0039
15%	0%	1410.7	-313.6	3135.2	0.1087
25%	0%	1344.3	-229.8	2918.5	0.0940
15%	Field Core	1210.2	-197.7	2618.2	0.0919
25%	Field Core	1143.7	-75.5	2363.1	0.0659
40%	25%	656.2	-751.7	2064.2	0.3604
40%	15%	589.8	-984.3	2163.9	0.4622
Field Core	0%	200.5	-1207.4	1608.5	0.7798
15%	25%	66.4	-1507.7	1640.6	0.9340





RAP lab made

Figure 3.7: Comparison of Mean Dynamic Modulus at Different RAP Contents

3.1.2 Field and Laboratory Compacted Plant Mixtures

The air void contents of both the field cores and laboratory compacted specimens are shown in Table 3.7. All specimens contained 15% RAP. The air void contents of the field cores were measured in the laboratory and the lab specimens were fabricated to match the same air void content to allow for direct comparisons of dynamic modulus and strength.

The dynamic modulus master curves for the field compacted cores and the laboratory compacted specimens are shown in Figures 3.8 and 3.9, respectively. The mean square errors for the master curve fits are shown on each figure. Figure 3.10 shows a comparison of the two average dynamic modulus master curves. The mean square error term for both sets of specimens is similar and the field cores have a lower dynamic modulus than the laboratory-compacted specimens.

Table 3.7: Air Voids Content of Plant-Mixed Field-Compacted and Plant-Mixed Laboratory-Compacted Test Specimens

Sample Preparation Method	Sample Name	Air Voids
Plant-Mixed, Laboratory-Compacted	PMTS 6	5.9
	PMTS 7	5.5
	PMTS 8	5.6
	PMTS 9	5.7
Plant-Mixed, Field-Compacted	NFC 7	5.3
	NFC 8	5.6
	NFC 9	6.0
	NFC 10	6.5
	NFC 11	5.0

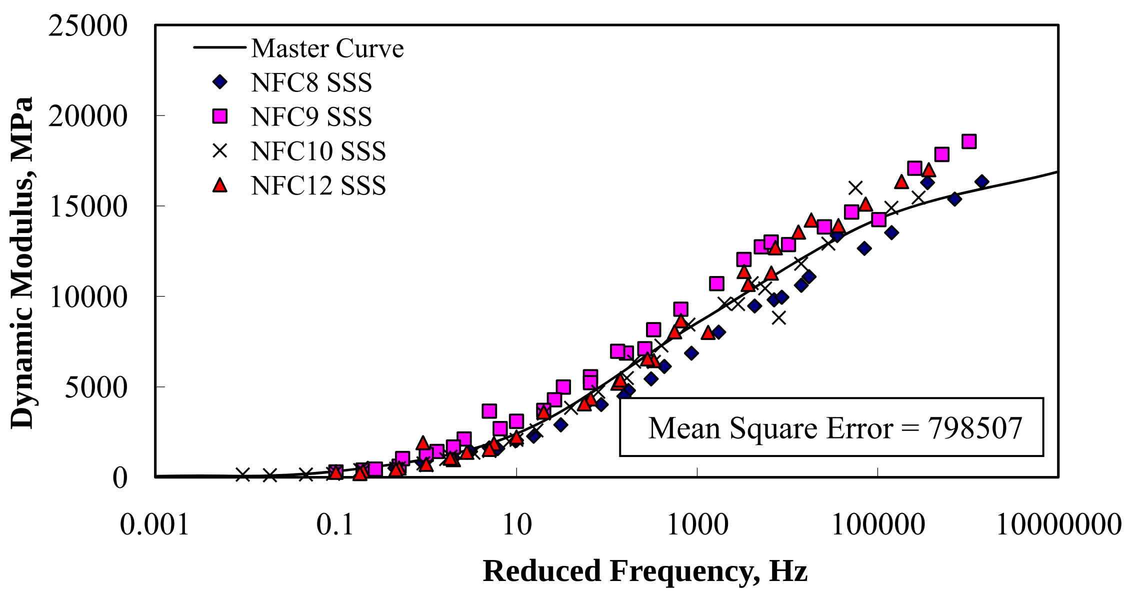


Figure 3.8: Dynamic Modulus Master Curve for Plant-Mixed, Field-Compacted Specimens

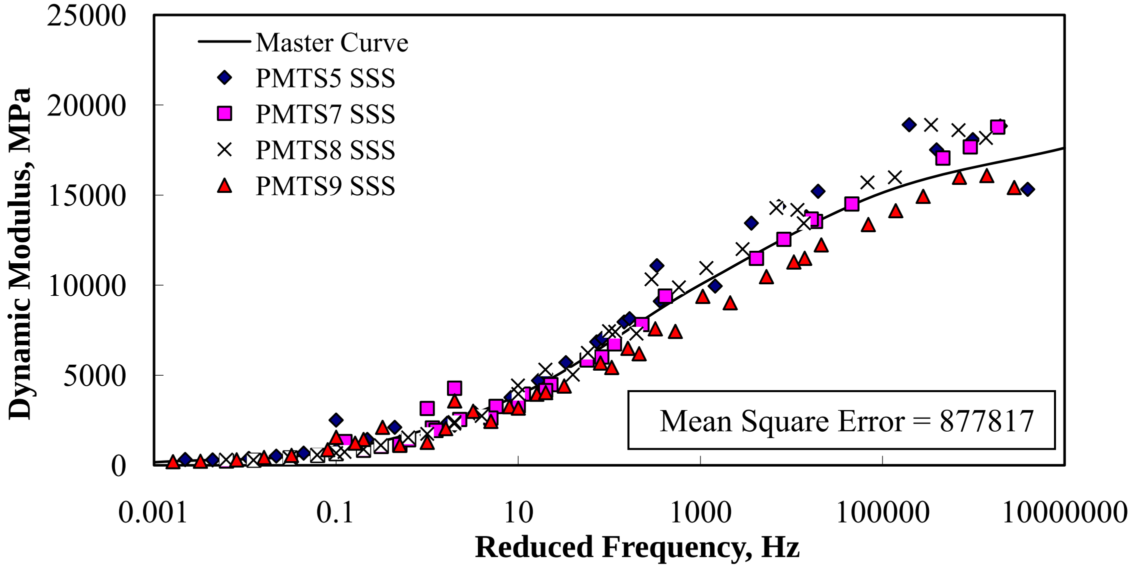


Figure 3.9: Dynamic Modulus Master Curve for Plant-Mixed Laboratory-Compacted Specimens

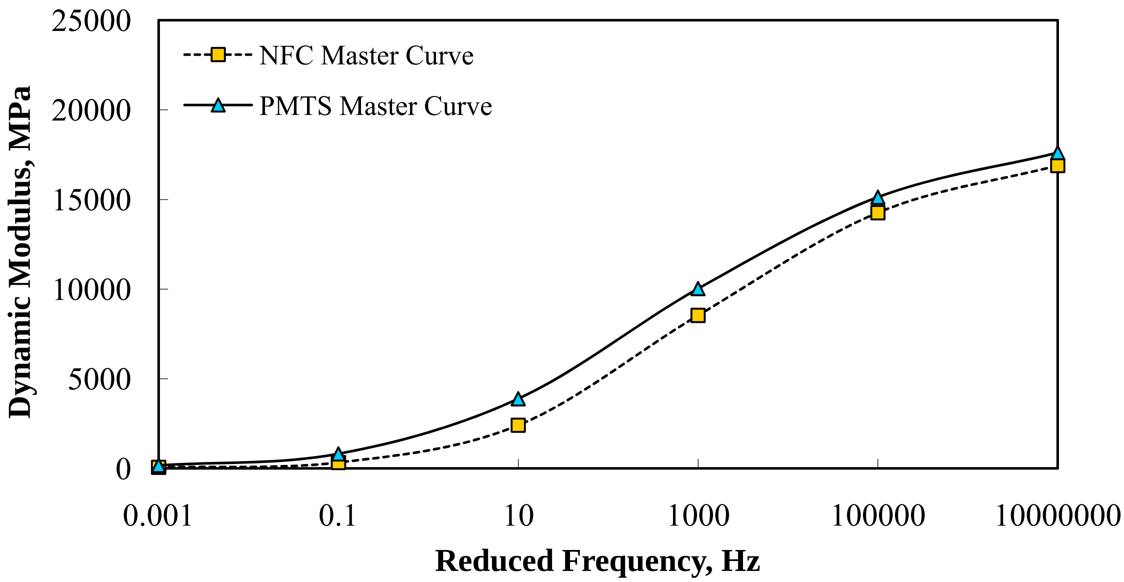


Figure 3.10: Comparison of Laboratory (PMTS) and Field Compacted (NFC) Dynamic Modulus Master Curves

<u>Statistical Analysis</u>

Table 3.8 shows the results of the t-tests performed on the individual frequencies of the dynamic modulus master curves for the Plant-Mixed Field-Compacted and Plant-Mixed Laboratory-Compacted samples. The lower frequencies show p-values below 5%, indicating a significant difference between the two master curves over this range. Table 3.9 and Figure 3.11 show the results of the comparison of mean dynamic modulus values for the field and laboratory

compacted specimens. The laboratory-compacted specimens have a significantly (p-value of 0.0469) greater mean than the field-compacted specimens.

Table 3.8: Dynamic Modulus Statistical Results for Plant-Mix Field-Compacted and Plant-Mix Laboratory-Compacted Specimens

Frequency (Hz)	PMTS - NFC
0.001	**1%**
0.01	**0%**
0.1	**0%**
1	**0%**
10	**1%**
100	**4%**
1000	14%
10000	27%
100000	43%
1000000	64%
10000000	80%

Table 3.9: One-way Anova Test Results for Mean Dynamic Modulus Value Comparison Between Plant-Mix Field-Compacted and Plant-Mix Laboratory-Compacted Specimens

Specimen Type	Number of Observations	Mean	Standard Error	Lower 95%	Upper 95%
NFC	159	5588	447	4708	6469
PMTS	160	6849	446	5971	7726

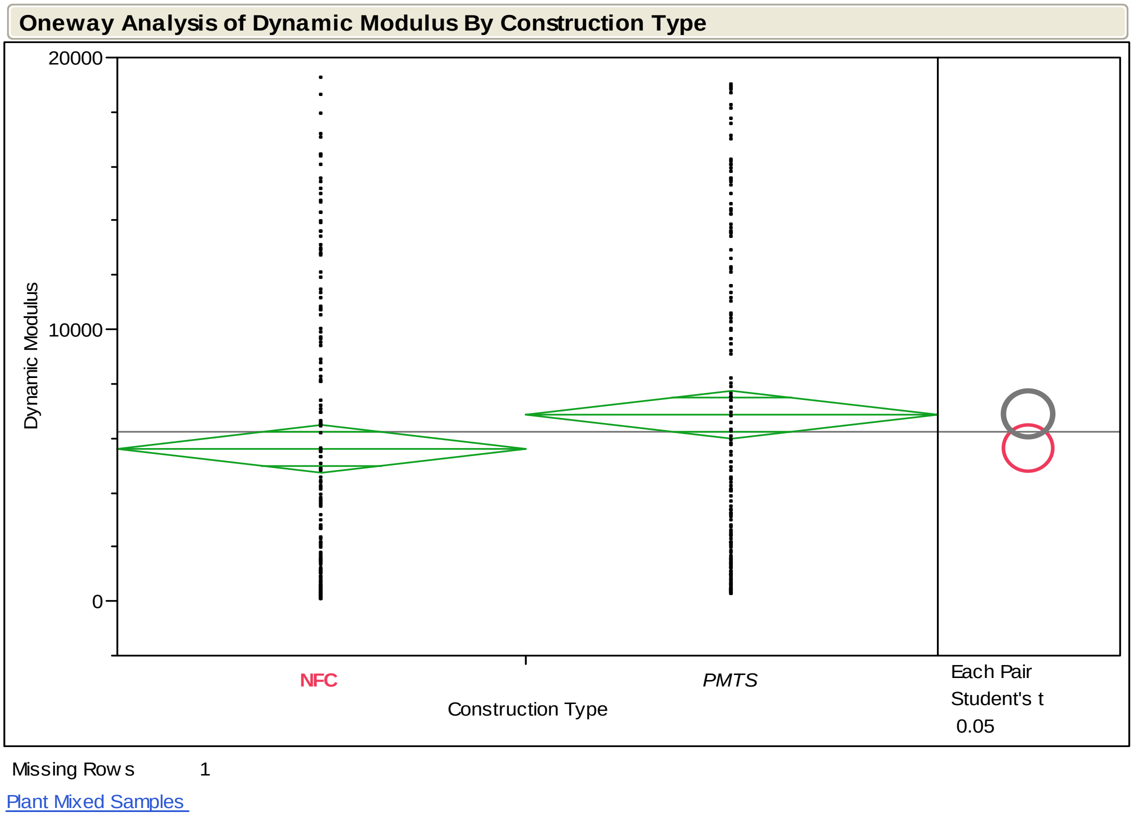


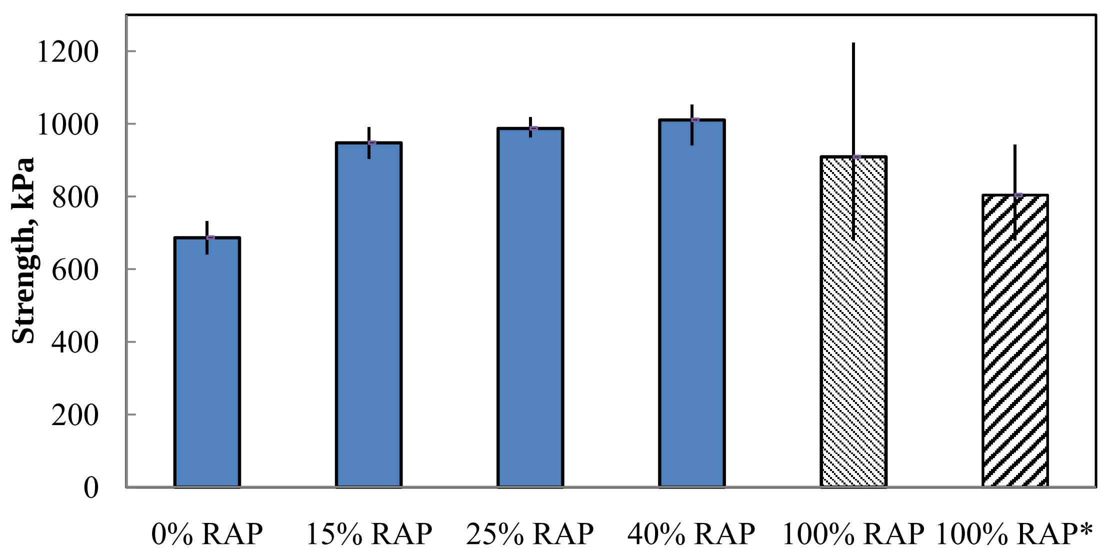
Figure 3.11: Comparison of Mean Dynamic Modulus Obtained by Plant-Mix Field-Compacted and Plant-Mix Laboratory-Compacted Specimens

3.2 STRENGTH TESTING

A summary of the indirect tensile strength testing for all specimens is shown in Table 3.10. Figure 3.12 shows the average measured strength for the millings RAP mixtures; the lines indicate the range of high and low values for each mixture. Figure 3.13 shows comparison of the Plant-Mixed Field-Compacted and Plant-Mixed Laboratory-Compacted specimens. The average strength of the RAP mixtures increased with the addition of RAP. This is similar to the trends seen with the dynamic modulus testing. The 100% RAP samples (old field cores) had lower strength, due to higher air void content (with the exception of sample FC5). The Plant-Mixed Laboratory-Compacted samples showed a higher strength than the Plant-Mixed Field-Compacted specimens, which is also the stiffer mixture from the dynamic modulus testing, and is believed to be associated with the difference in compaction methods.

Table 3.10: Strength Testing Results

Mix Type	Sample Name	Strength (kPa)	Average Strength (kPa)	Standard Deviation
0% RAP	WTSA	733	687	46
	WTSB	641		
15% RAP	XTSC	904	948	43
	XTSD	991		
25% RAP	YTSA	982	987	23
	YTSD	963		
	YTSMX	1018		
40% RAP	ZTSA	941	1011	50
	ZTSB	1053		
	ZTSF	1039		
100% RAP	FC2	680	909	54
	FC3	788		
	FC4	943		
	FC5	1225		
Plant Mixed – Laboratory Compacted	PMTS5	454	450	12
	PMTS7	429		
	PMTS8	486		
	PMTS9	431		
Plant Mixed – Field Compacted	NFC9	217	207	20
	NFC10	176		
	NFC12	229		



*FC5 – Omitting outlier sample FC5

Figure 3.12: Average Measured Strengths for the Millings RAP Mixtures

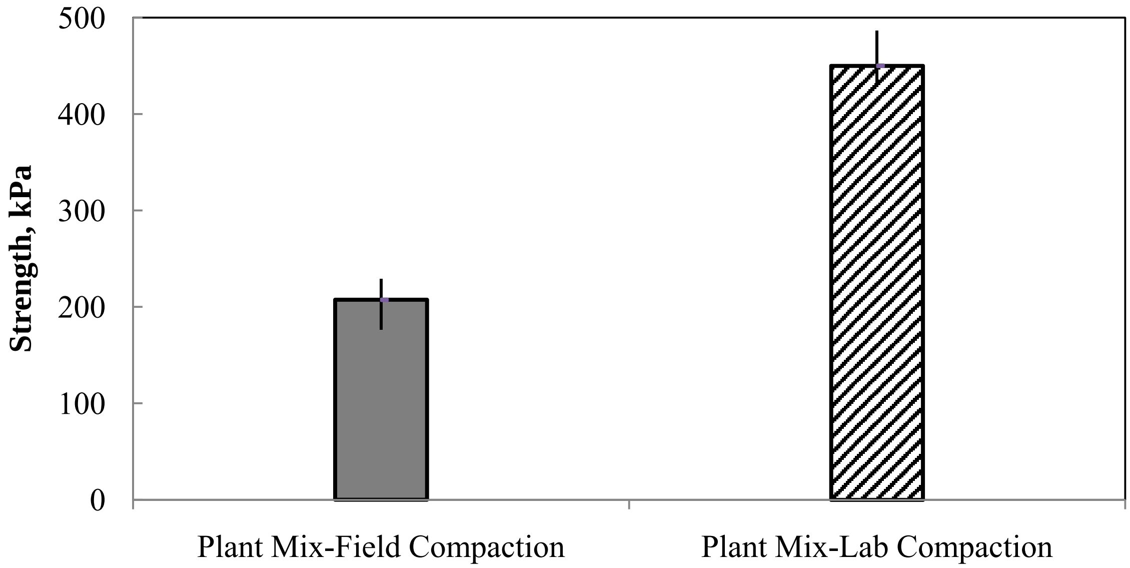


Figure 3.13: Average Measured Strengths for Plant-Mix Field Compacted and Plant-Mix Laboratory-Compacted Specimens

Statistical Analysis

Statistical analysis was done using the t-test with 95% confidence interval. Table 3.11 shows that the strength of the 0% RAP samples is significantly less than other RAP mixtures, with the exception of the field cores (100% RAP). The other RAP mixtures are not significantly different from each other.

Table 3.11: t-Test Results from Comparison of Laboratory and Field Compacted Specimens

	0% RAP	15% RAP	25% RAP	40% RAP
15% RAP	**5%**			
25% RAP	**0%**	38%		
40% RAP	**1%**	34%	58%	
Field Cores	28%	84%	60%	51%

The p-value for the comparison of Plant-Mixed Laboratory-Compacted and Plant-Mixed Field-Compacted samples was 0.0078; indicating a significant difference between the two compaction methods with respect to strength.

3.3 BLACK ROCK GRADATION STUDY

A mini study to examine the effect of gradation on the volumetric properties of a mixture was conducted. If all of the RAP binder does not release and blend with the virgin binder, then the effective gradation of the RAP aggregate is essentially coarser than expected, which will have an effect on the volumetric properties of the mixture. In that case, the RAP acts partially as a black rock and will change the overall gradation of the mixture.

In this study, the 40% RAP mixture was used. The aggregate structure for this mixture consists of 60% virgin aggregate and 40% RAP. The RAP portion of the aggregate structure was varied to reflect between 0% and 100% blending conditions by combining relative proportions of the extracted and black rock RAP gradations (Table 2.2). The 0 % blending assumes that none of the RAP breaks down to blend with virgin materials. The 100% blending assumes that the RAP completely breaks down and fully blends with virgin materials. The stockpile percentages for the five cases studied are shown in Table 3.12. Figure 3.14 shows the resulting gradations for each case. The 100% blending case results in the finest gradation because all of the asphalt is assumed to release from the aggregate; the 0% blending case is the coarsest gradation because all of the asphalt is assumed to remain on the aggregate, creating larger particles.

Table 3.12: Stockpile Percentages for the Black Rock Gradation Study

Percentage Blending	Stockpile % of total aggregate structure		
	Virgin Aggregate	RAP (Black rock)	RAP (Extracted)
0	60	40	0
25	60	30	10
50	60	20	20
75	60	10	30
100	60	0	40

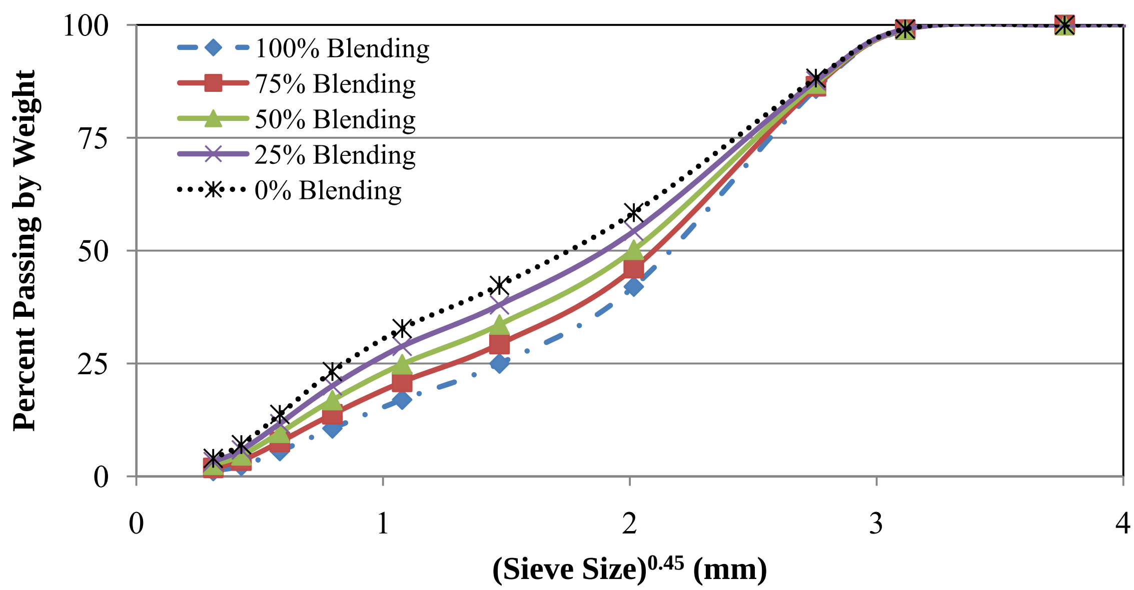


Figure 3.14: Final Gradations of Mix at Different Degrees of Blending

Raw aggregate materials from a single source were then used to fabricate specimens with each of these gradations at four different asphalt contents. Two replicate specimens were fabricated at each asphalt content and then the volumetric properties of these specimens were measured. The figures below present the average values.

Figures 3.15, 3.16, and 3.17 show the air void content, VMA, and VFA as a function of the blending condition for the four different asphalt contents, respectively. For all three volumetric properties, there is an approximate linear trend from 0% to 50% blending, after which the values approach a plateau up to the 100% blending condition. This trend is the same for all four asphalt contents that were tested. Figure 3.18 shows the air void content plotted as a function of asphalt content for the five blends and for the actual 40% RAP mixture tested in the main study. The 100%, 75%, and 50% blends are clustered together near the actual 40% RAP mixture. The 0% and 25% blends fall above this grouping.

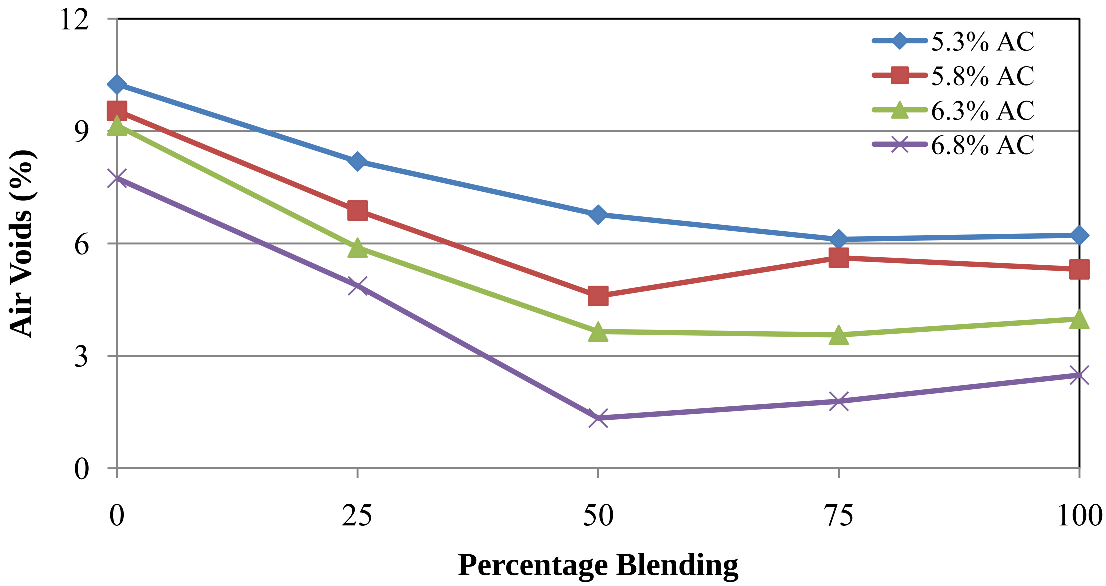


Figure 3.15: Variation of Air Void Content With Different Degrees of Blending

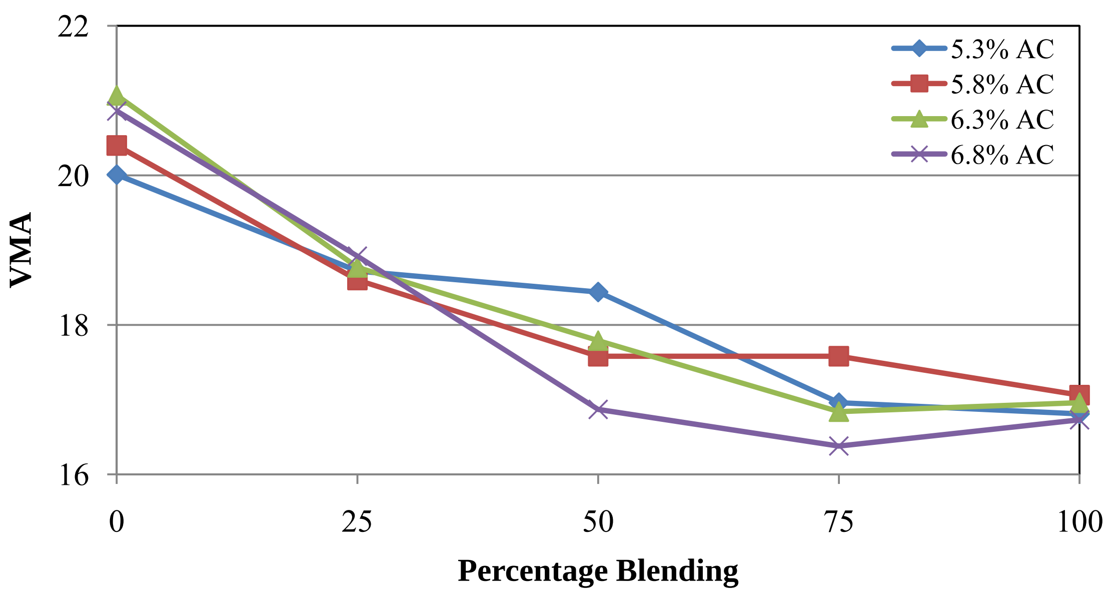


Figure 3.16: Variation of VMA With Different Degrees of Blending

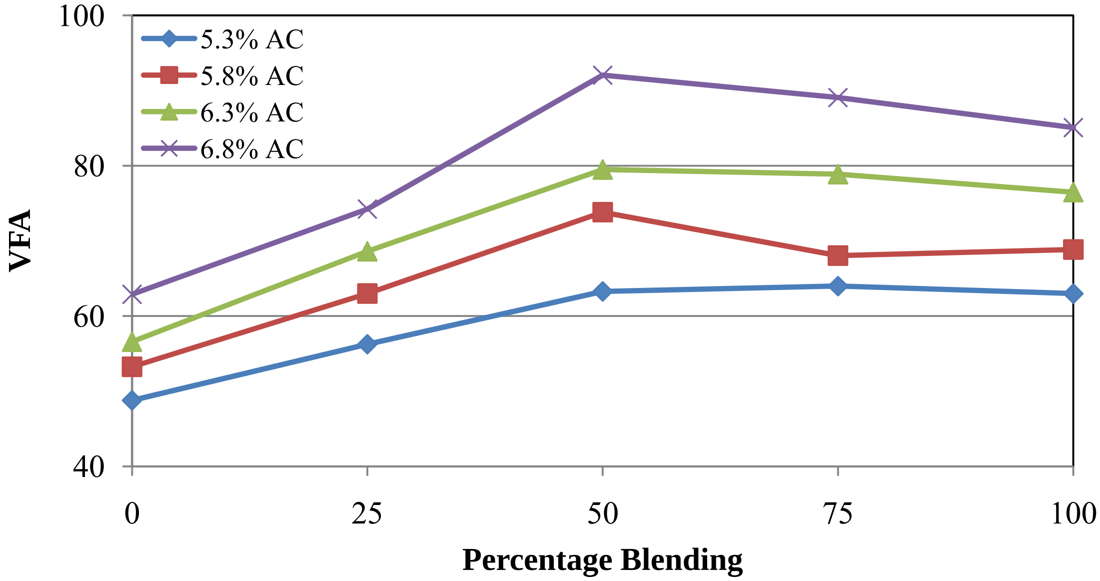


Figure 3.17: Variation of VFA With Different Degrees of Blending

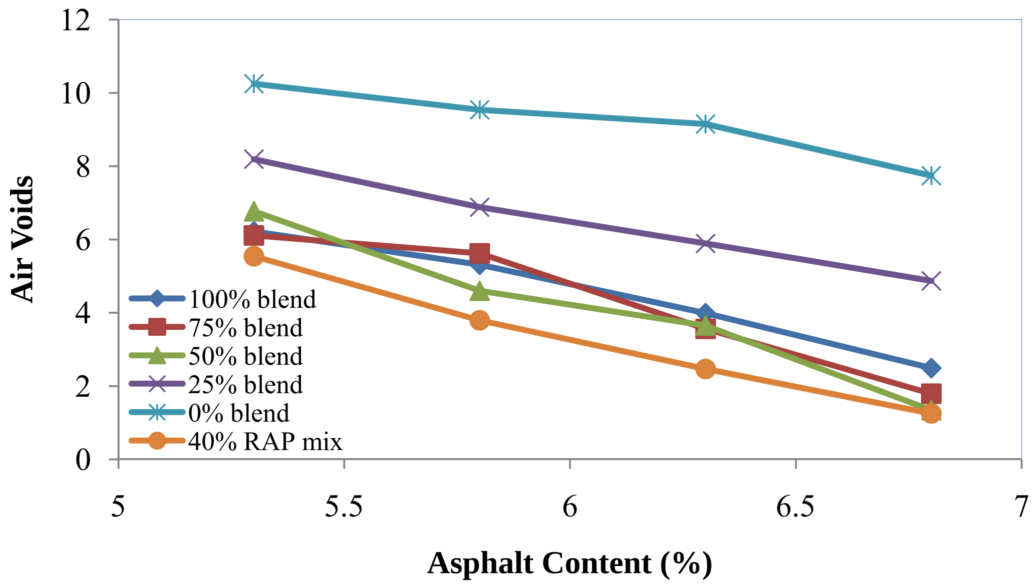


Figure 3.18: Variation of Air Voids With Asphalt Content at Different Degrees of Blending

Statistical analysis using a t-test was performed on the data and the p-values for each comparison are shown in Table 3.13. Conditions where the p-value is less than 0.05 are considered significantly different. The 0% and 25% blending conditions are statistically different than the other three conditions and the actual RAP mix. The 50%, 75%, and 100% blends are not significantly different from each other. The RAP mix is different from some of the higher blending conditions for different volumetric properties, but not for all of them.

Table 3.13: Statistical Analysis of Blending Conditions

Pair	Probability for a two tailed paired distribution		
	VA	VMA	VFA
0-25	**0.0017**	**0.0031**	**0.0021**
0-50	**0.0037**	**0.0105**	**0.0055**
0-75	**0.0024**	**0.0031**	**0.0059**
0-100	**0.0006**	**0.0006**	**0.0023**
0-RAP	**0.0009**	**0.0014**	**0.0023**
25-50	**0.0122**	0.0596	**0.0139**
25-75	**0.0100**	**0.0103**	**0.0199**
25-100	**0.0013**	**0.0008**	**0.0055**
25-RAP	**0.0006**	**0.0008**	**0.0026**
50-75	0.6540	0.1036	0.2251
50-100	0.3354	0.0917	0.0753
50-RAP	0.0511	**0.0117**	0.0624
75-100	0.3571	0.8134	0.2069
75-RAP	**0.0445**	0.1294	**0.0300**
100-RAP	**0.0083**	0.0633	**0.0059**

3.4 MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE ANALYSIS

The dynamic modulus master curves measured as part of this research project were input into the MEPDG to evaluate the predicted difference in performance for the various mixtures. A typical interstate pavement section was chosen (based on the LTPP section on I-393 in Concord) and just the top 2 inches of asphalt pavement was varied. The sections below summarize the input values and the results from the MEPDG runs.

3.4.1 MEPDG Input Parameters

General

A default input file for the MEPDG was created and used as a template for the suite of runs conducted. The analysis of the pavement section was conducted for a design life of 10 years as a new flexible pavement. Summer months were used for pavement construction and traffic open days. The design inputs were kept constant except for the top AC layer.

Traffic

Two traffic levels were used in this analysis to compare the effect of traffic volume on the trends observed. AADTT (average annual daily truck traffic) values of 5,000 and 10,000 were used with traffic growth rates of 5%.

Climate

The climate data was obtained from the MEPDG climate database (24) for the city of Concord, NH (Concord Municipal Airport).

Structure

The pavement structure consists of a 2" AC surface layer over a 4" AC binder layer, 12" crushed stone aggregate base, 15" crushed gravel aggregate subbase, and A3 subgrade. Detailed properties of the unbound layers can be found elsewhere (25).

AC Layer Properties

All six mixtures were used as the surface layer for the MEPDG Level 1 Analysis. Level 3 analysis was conducted on the four laboratory mixtures only. The Level 1 MEPDG input requires dynamic modulus values at a minimum of four frequencies and five temperatures. The master curves constructed from the laboratory frequency sweep tests were used with the time temperature shift factors to determine the appropriate dynamic modulus input values for each mixture. Extrapolation of the shift factors was required to obtain the high temperature data (the MEPDG requires that the high temperature dynamic modulus values be in the 125-130F range). The actual values used for each mixture are shown in Appendix E. For the analysis, the control mixture properties were used for the 4" binder course in all cases.

The MEPDG also requires that the effective binder content by volume (Vbe), unit weight (pcf), and as-constructed air voids be entered. For all mixtures, an as-constructed air void content of 7% was assumed. The effective binder contents and unit weights for each mixture were calculated and are summarized in Table 3.14 below.

The shear modulus and phase angle values for the asphalt binder are also required for Level 1 analysis. Values measured for a typical PG 64-28 asphalt binder were used for all mixtures and are shown in Table 3.15.

Level 3 analysis requires PG grade only and gradation parameters for input values. The gradation values from Table 2.3 were used and Table 3.14 shows the assumed PG grades for each of the RAP mixtures.

Table 3.14 Summary of MEPDG Input Values

Parameter	**Mixture**					
	Control	**15% RAP**	**25% RAP**	**40% RAP**	**PMLC**	**PMFC**
Vbe	11.7	11.6	12.1	12.3	12	12
Unit Wt (pcf)	144	145	145	144	143	146
Level 3 PG grade	64-28	64-28	70-22	76-16	n/a	n/a

Table 3.15: G* and δ Input Values for PG 64-28 Binder

Temp (^oF)	G* (Pa)	δ (deg)
136.4	6750	77.6
147.2	3270	80.1
158	1590	82.3

3.4.2 MEPDG Results

Dynamic Modulus

The dynamic modulus values at various temperatures and frequencies that are input into Level 1 MEPDG analysis are used by the software to construct master curves for each mixture. The Level 3 inputs are entered into an equation to predict the dynamic modulus of that mixture, which is then used in the further MEPDG analysis and predictions. The Level 1 and Level 3 dynamic modulus master curves for the laboratory RAP mixtures are shown in Figure 3.19. The Level 3 curves are stiffer and have a shallower slope than the Level 1 curves. They show an increasing stiffness with the increased RAP content, primarily due to the different assumed PG grades from Table 3.12. Figure 3.20 shows the dynamic modulus master curves for the PMFC and PMLC mixtures generated by the MEPDG software.

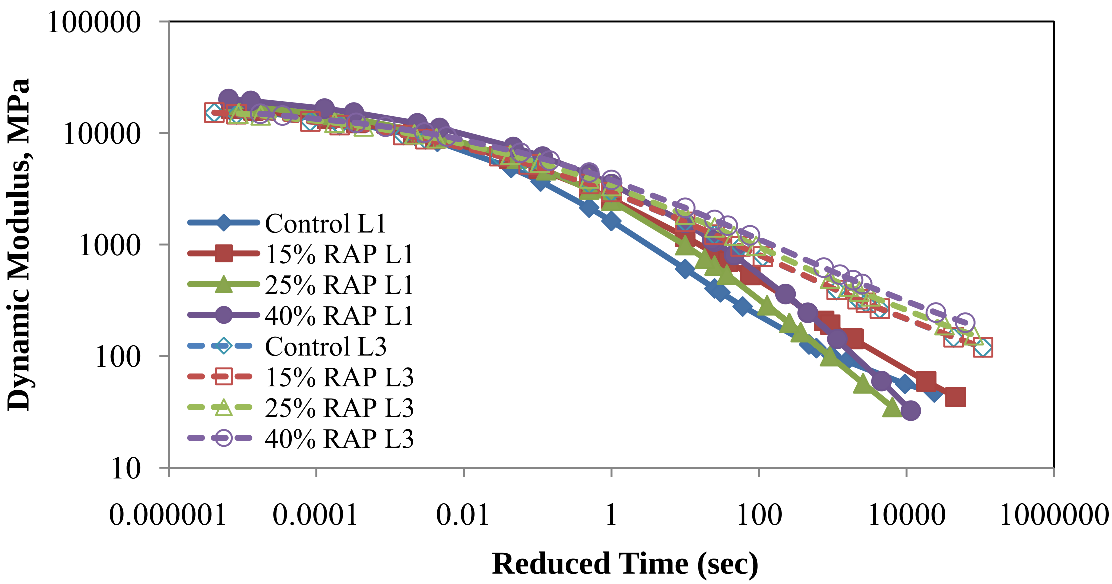


Figure 3.19: Laboratory RAP Mixture Dynamic Modulus Master Curves Generated by MEPDG for Level 1 and Level 3 Analysis

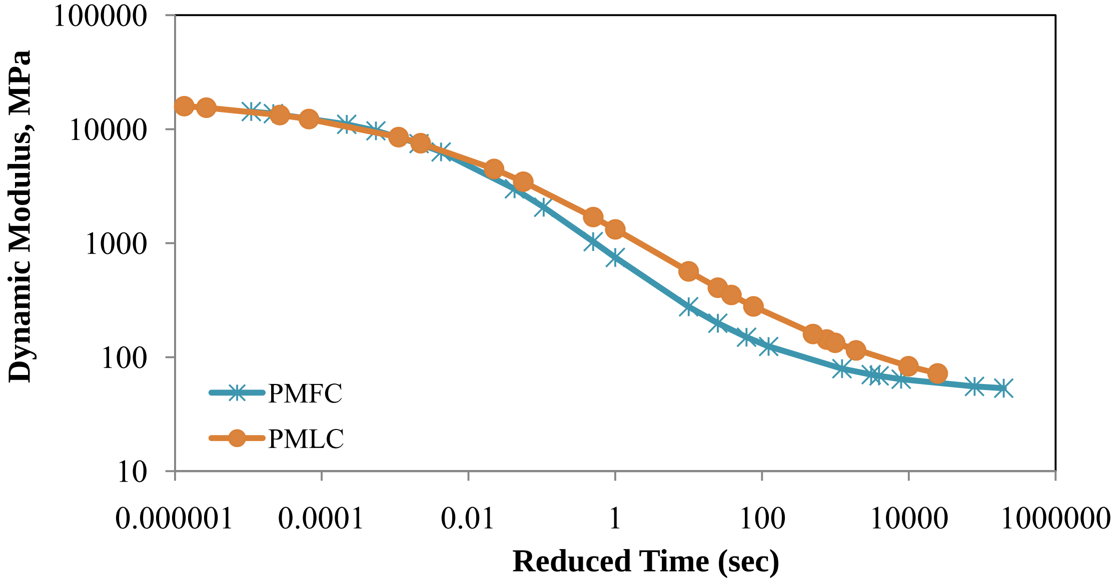


Figure 3.20: PMFC and PMLC Dynamic Modulus Master Curves Generated by MEPDG for Level 1 Analysis

<u>Predicted Performance</u>

The distresses summarized in this section are longitudinal cracking, alligator cracking, and rutting in the asphalt concrete layer. The thermal cracking module in the MEPDG did not return any results for this pavement; this problem has been reported by others and it is assumed that there is an error in the MEPDG software for the thermal cracking analysis. Figures 3.21-3.23 summarize the longitudinal cracking, alligator cracking and rutting results, respectively. Each figure shows the results of the Level 1 analysis at both traffic levels (10k and 5k traffic) for all mixtures and the Level 3 analysis for the lab mixtures only.

In the Level 1 analysis, the four laboratory mixtures show a decreasing amount of distress as the RAP percentage increases for both traffic levels. The increasing RAP content increases the stiffness of the mixture, reducing the strain level, or amount of flexure in the section, thereby reducing the amount of distress. The Level 3 analysis is slightly different; the 15% RAP mixture shows slightly more longitudinal cracking than the control mixture and the same amount of alligator cracking and rutting as the control mixture. The amount of distress then decreases with the 25% and 40% RAP mixtures. The difference between Level 1 and Level 3 inputs changes the predicted distresses. For longitudinal cracking, Level 3 inputs result in more cracking. For alligator cracking, the two analysis levels are very close, with the Level 1 inputs resulting in slightly higher cracking for the 15% and 40% mixtures. The amount of rutting predicted for Level 1 inputs was higher than that from Level 3 for all mixtures. These differences in Level 1 versus Level 3 are due to a combination of the mixture properties (dynamic modulus) and binder properties, which affect the amount of aging that happens over time.

For all distresses and both traffic levels, the laboratory compacted specimens (PMLC) show better performance than the field compacted specimens (PMFC).

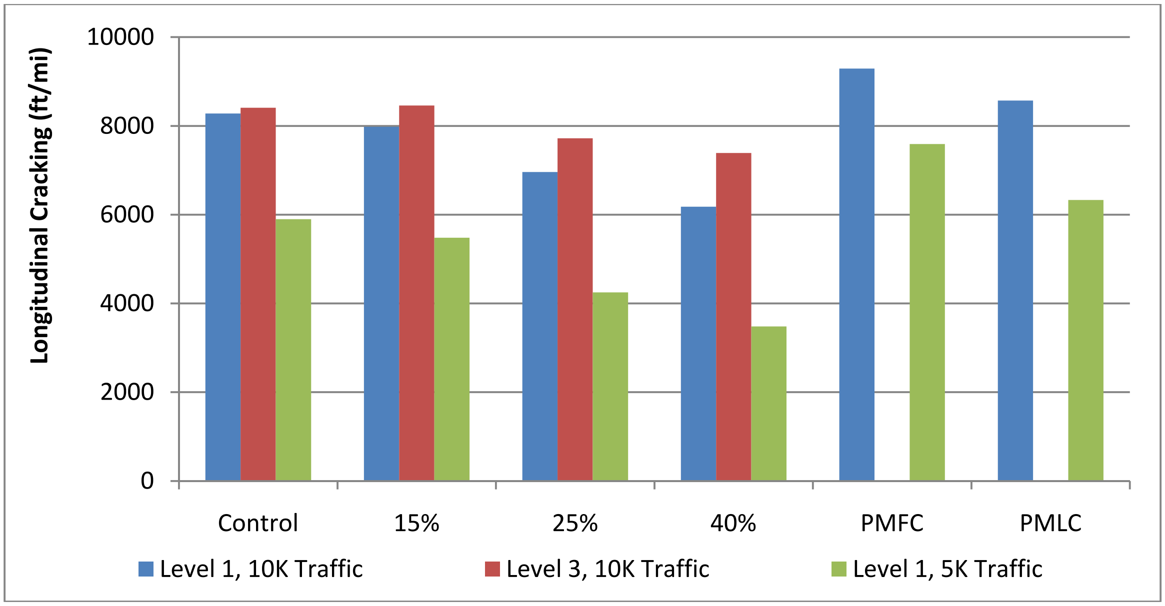


Figure 3.21: Longitudinal Cracking Predictions from MEPDG

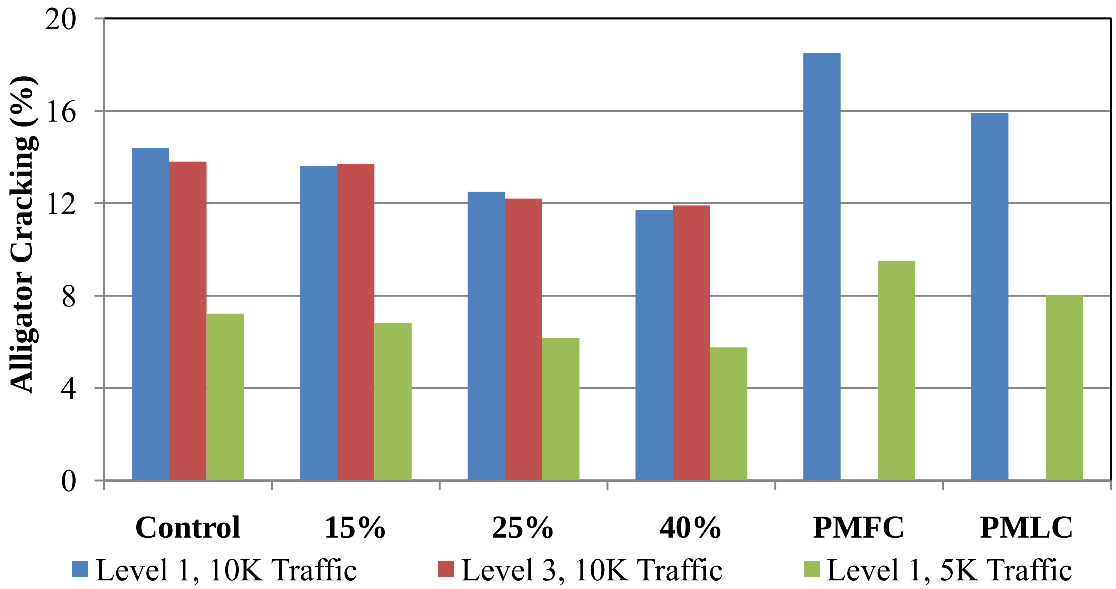


Figure 3.22: Alligator Cracking Predictions from MEPDG

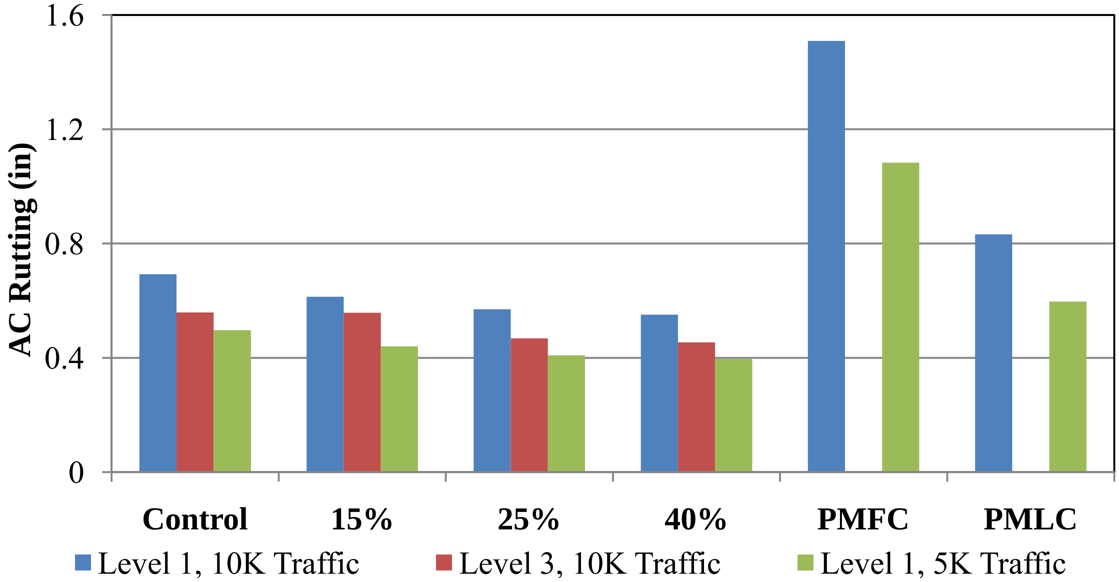


Figure 3.23: AC Rutting Predictions from MEPDG

4.0 SUMMARY AND CONCLUSIONS

The objective of this research was to determine how the addition of RAP affects the volumetric properties, dynamic modulus, and strength of a typical asphalt concrete mixture used in New Hampshire. An existing 12.5 mm surface course mixture containing 15% RAP was used as the basis for mix designs using 0%, 15%, 25%, and 40% RAP. The gradation for each mix design was kept as close as possible to the original 15% RAP design. The RAP was fabricated from millings obtained from a known location. In addition to millings, field cores were obtained for testing. Plant mix and field cores from a new 12.5 mm surface course were obtained to compare laboratory and field compaction.

Specimens of each mixture were fabricated in the laboratory and tested in the IDT mode for dynamic modulus and strength. Statistical analysis was performed to determine if significant differences in performance existed between the various RAP contents. Additionally, the mixture information was used to conduct Level 1 and Level 3 analysis in the MEPDG. A mini-study to determine the effect of aggregate gradation on volumetric properties was also conducted.

The testing of the laboratory produced RAP mixtures resulted in the following observations:

- The VMA and VFA of the control and 15% RAP mixtures were very similar.
- The VMA increased with the 25% and 40% RAP mixtures.
- The VFA increased with the 25% RAP mixture, and then decreased slightly for the 40% RAP mixture.
- The average dynamic modulus curve increases (becomes stiffer) with increasing RAP content. However, only the mean and the low frequency dynamic modulus values of the 40% RAP mixture were statistically different from the control mixture.
- The average IDT strength increases with increasing RAP content. The three RAP contents are significantly different from the control mixture, but are not significantly different from each other.

Specimens fabricated from plant mixture were tested and compared to field cores obtained from the same mixture to evaluate differences in compaction method:

- The average dynamic modulus curve of the laboratory compacted specimens was greater than that for the field cores, however the difference was only statistically significant for the lower frequencies.
- The IDT strength of the laboratory compacted specimens is significantly greater than that for the field compacted specimens.

Aggregate gradations representing different proportions of blending between the virgin and RAP materials for the 40% RAP mixture were evaluated to determine the effect of gradation on the volumetric properties.

- A linear trend from 0% to 50% blending was observed for air voids, VMA and VFA.
- Above 50% blending, the volumetric properties approach a plateau value.
- The actual 40% RAP mixture was very close to the 50%-100% blend mixtures.

The MEPDG analysis for the mixtures showed the following:

- The dynamic modulus master curves generated from the Level 3 inputs are stiffer and have a shallower slope than those generated from the Level 1 inputs.
- The amount of predicted cracking (longitudinal and alligator) and rutting generally decreases with increasing RAP contents.
- Level 1 and Level 3 analysis show same trends among the mixtures, but in some cases the Level 1 predictions are more conservative, and in other cases the Level 3 predictions are more conservative.
- The predicted performance of the laboratory compacted mixture is better than the performance of the field compacted mixture.

Overall, this research project showed that the percentage of RAP affects the overall properties of the mixture with respect to volumetrics, dynamic modulus, and strength. However, a statistically significant difference from the virgin mixture was only seen at the 40% RAP level. Laboratory compacted specimens were found to have a significantly higher dynamic modulus and strength than field compacted specimens. Using the MEPDG analysis, the predicted performance of the RAP mixtures in a surface course was equivalent to, or better than the virgin mixture with respect to longitudinal cracking, alligator cracking, and rutting. It is recommended that further research be conducted on plant produced mixtures and the thermal cracking properties of the mixtures be evaluated.

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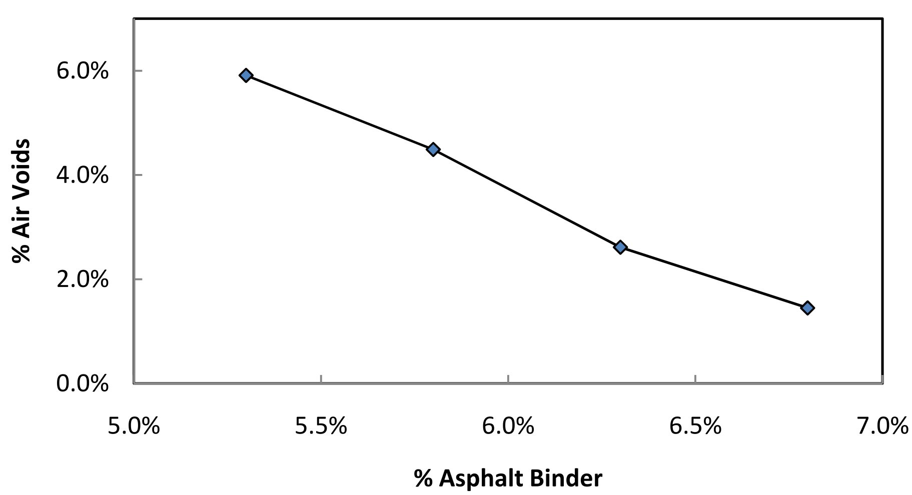
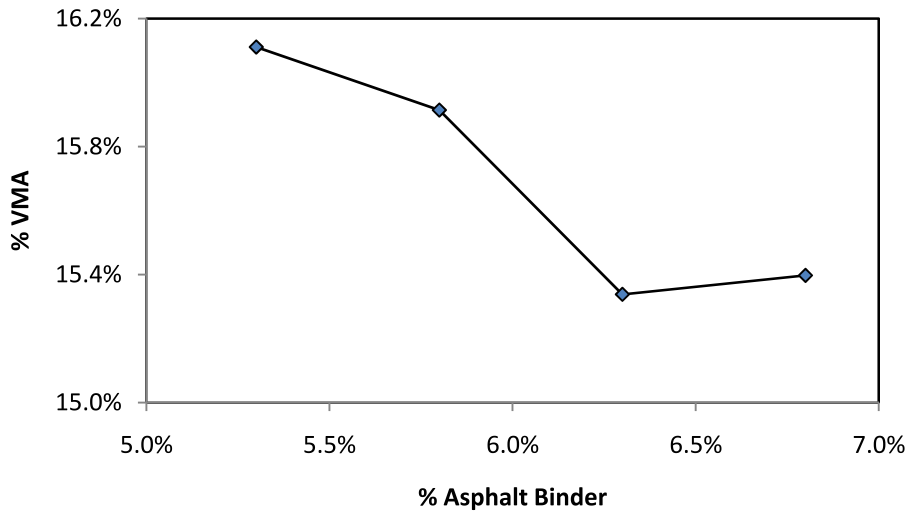
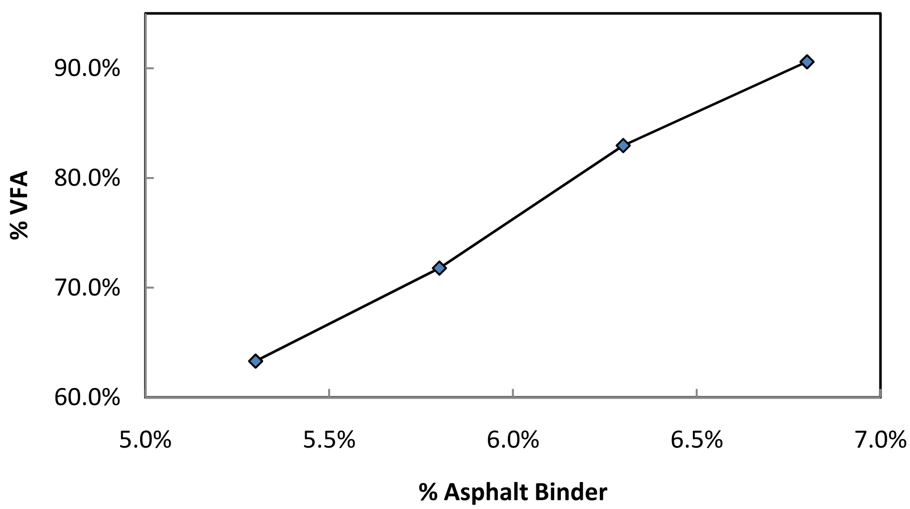
6.0 APPENDICES

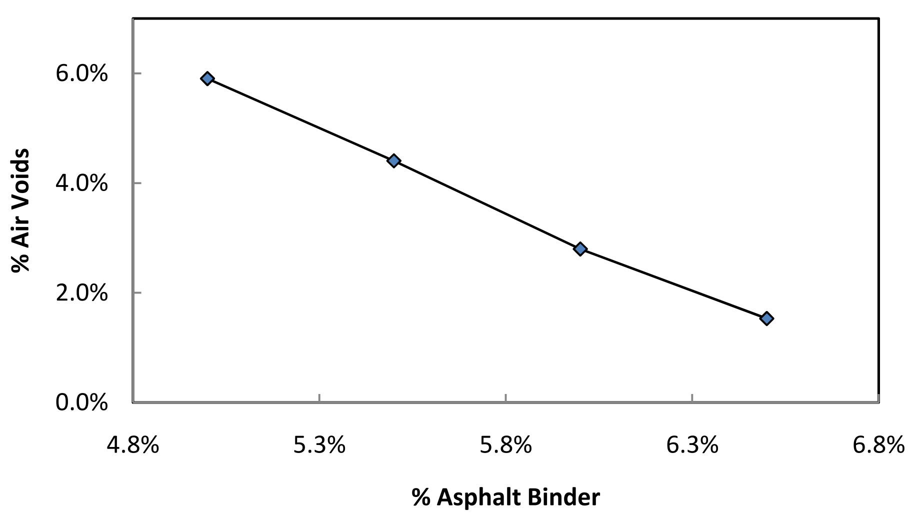
Appendix A – Design Mixture Properties

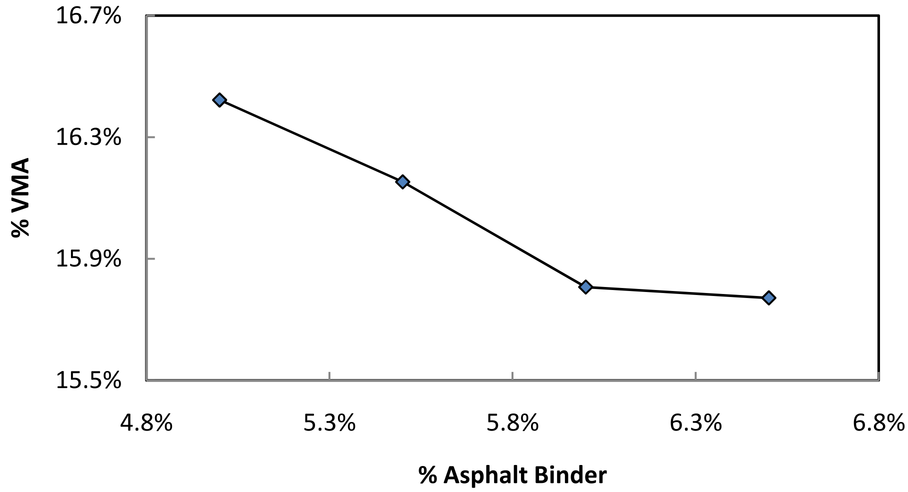


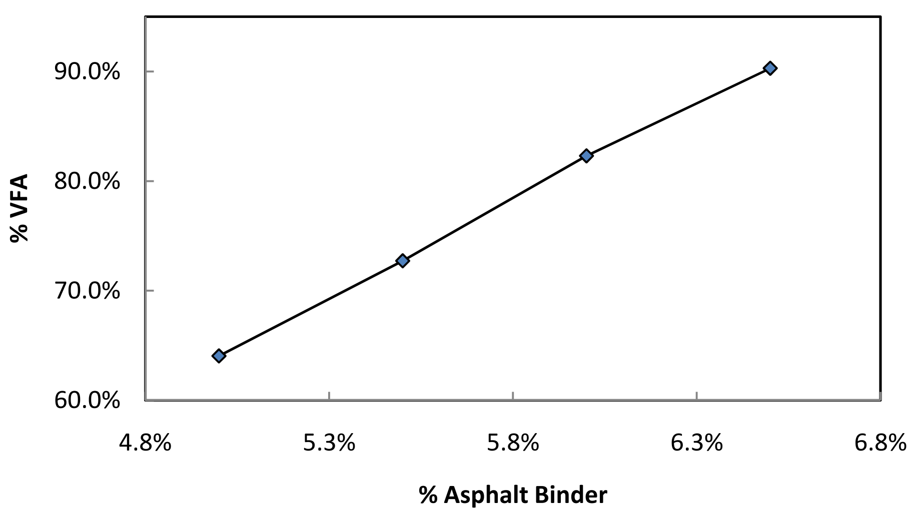




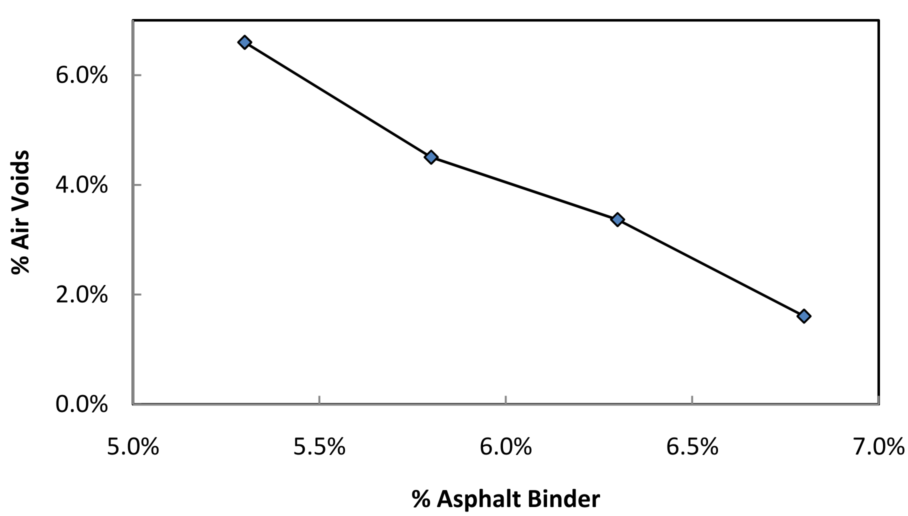
A1: Design mixture properties for 0% RAP

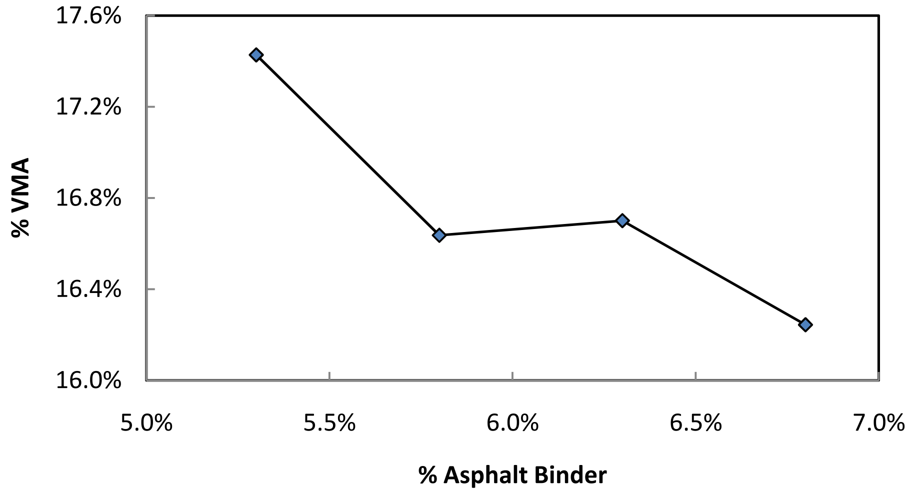


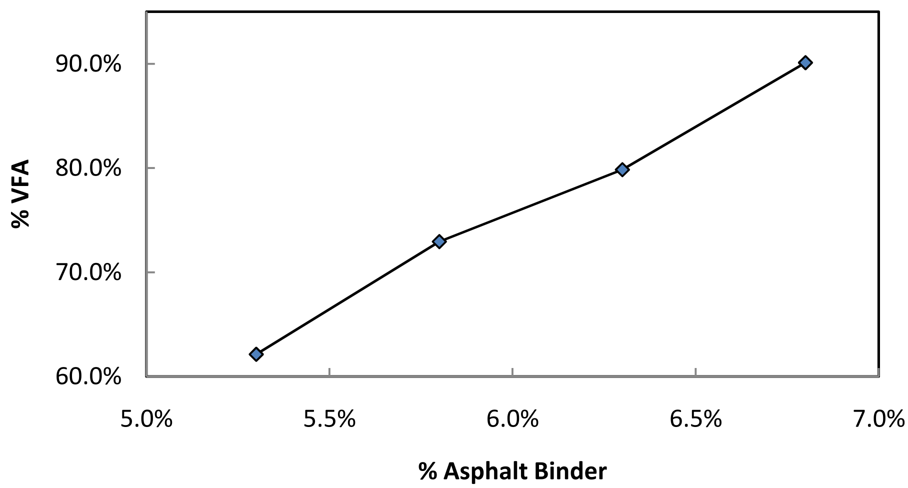




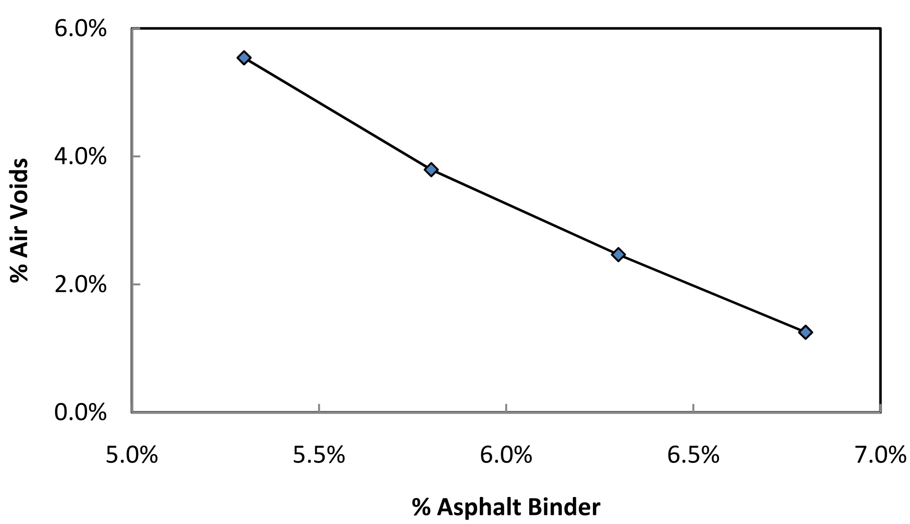
A2: Design mixture properties for 15% RAP

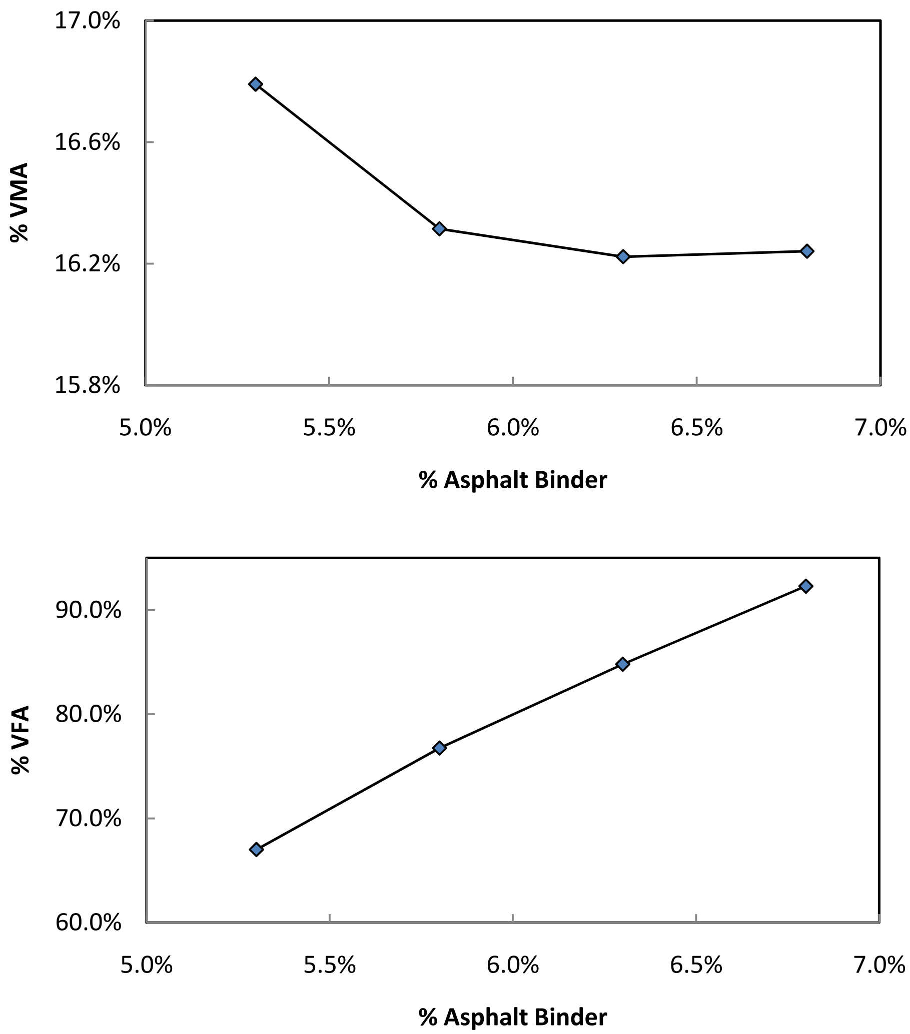






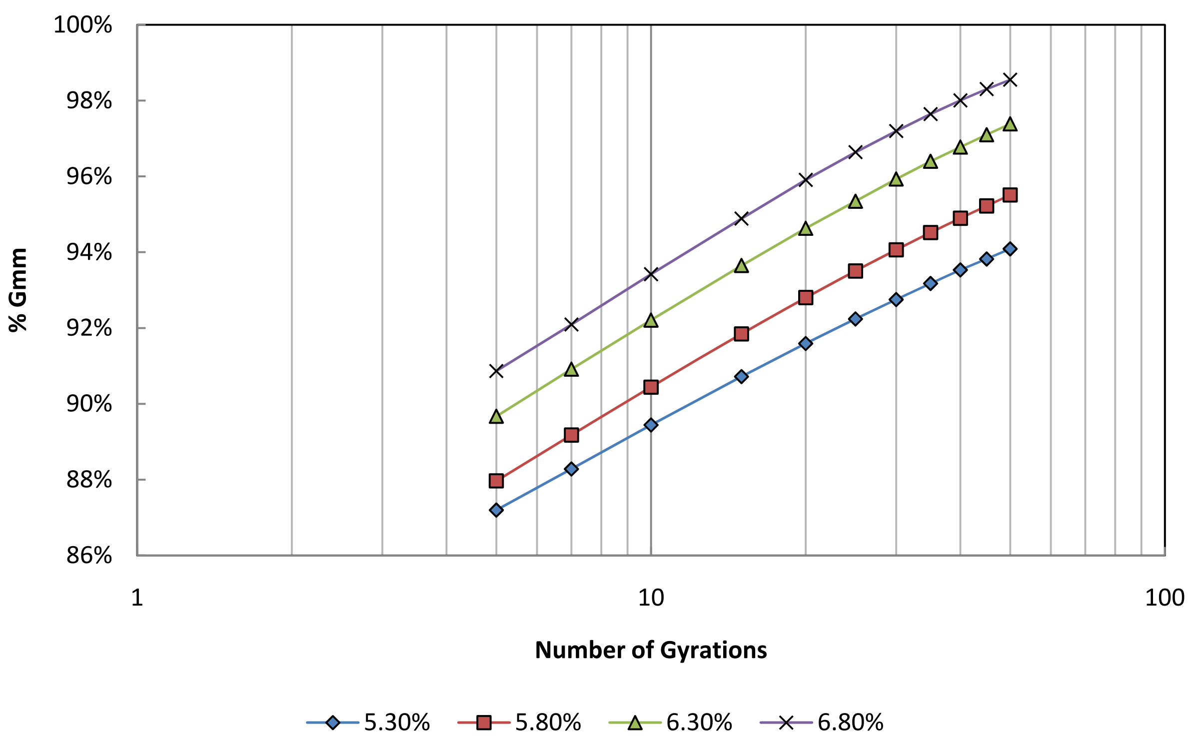
A3: Design mixture properties for 25% RAP



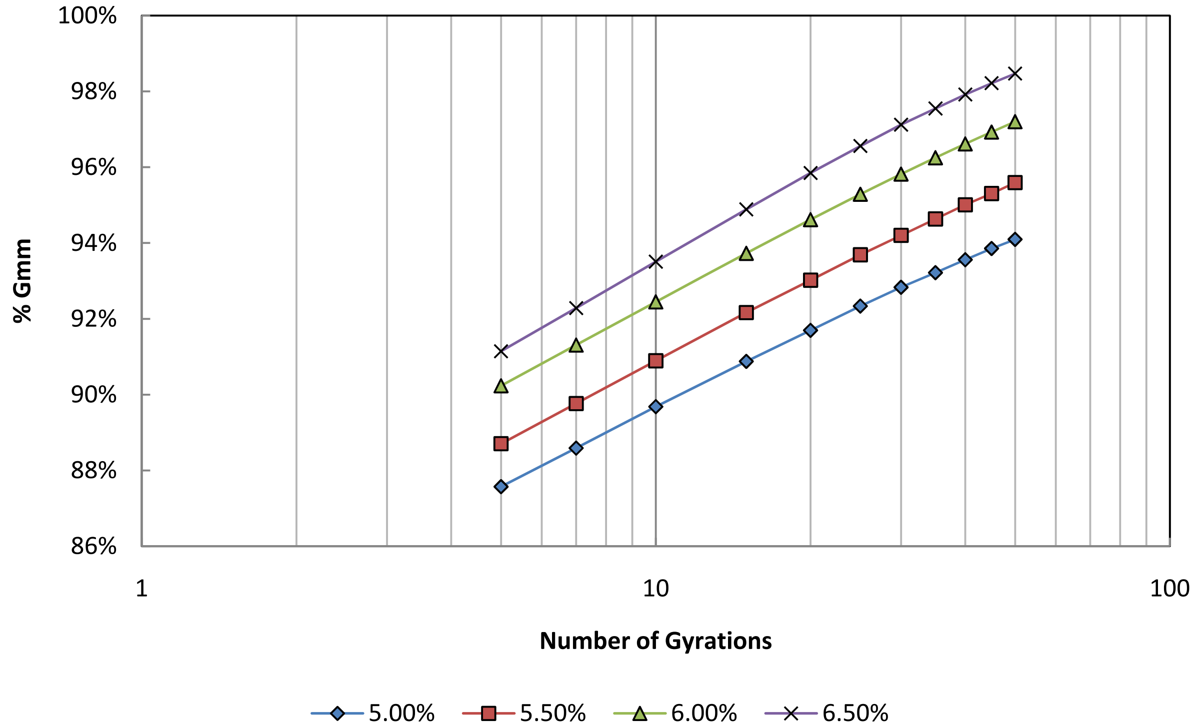


A4: Design mixture properties for 40% RAP

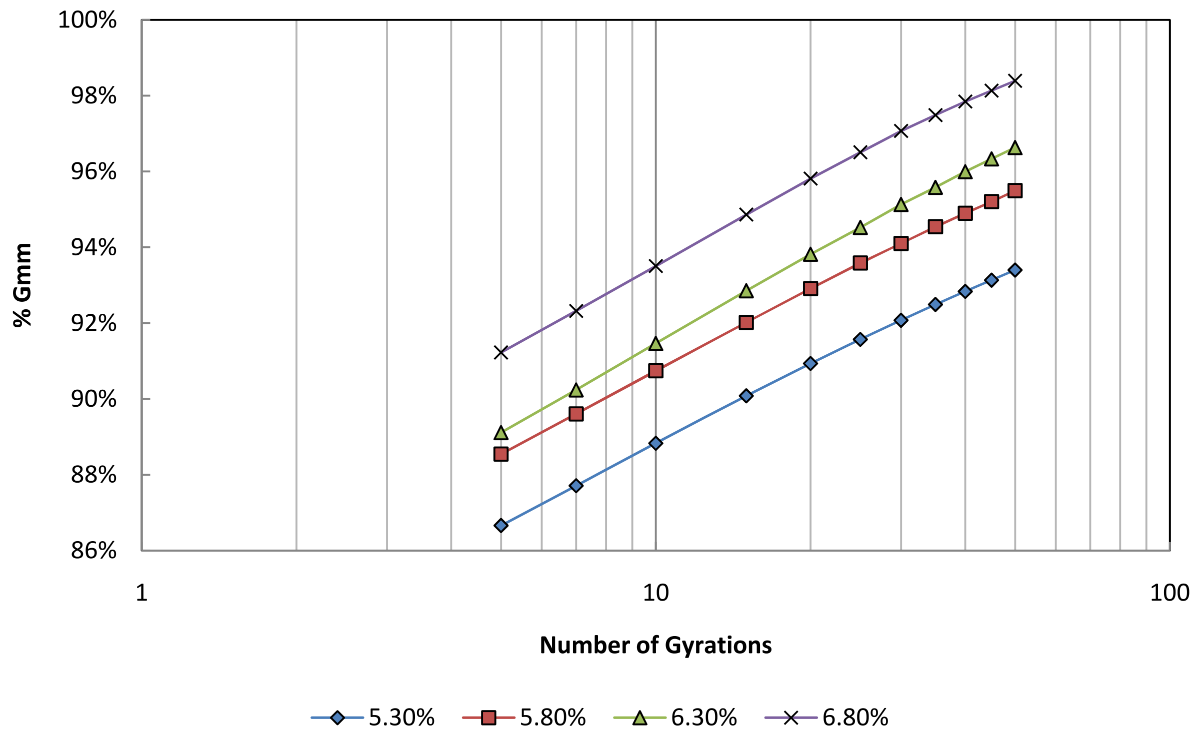
Appendix B – Mix Design Densification Curves



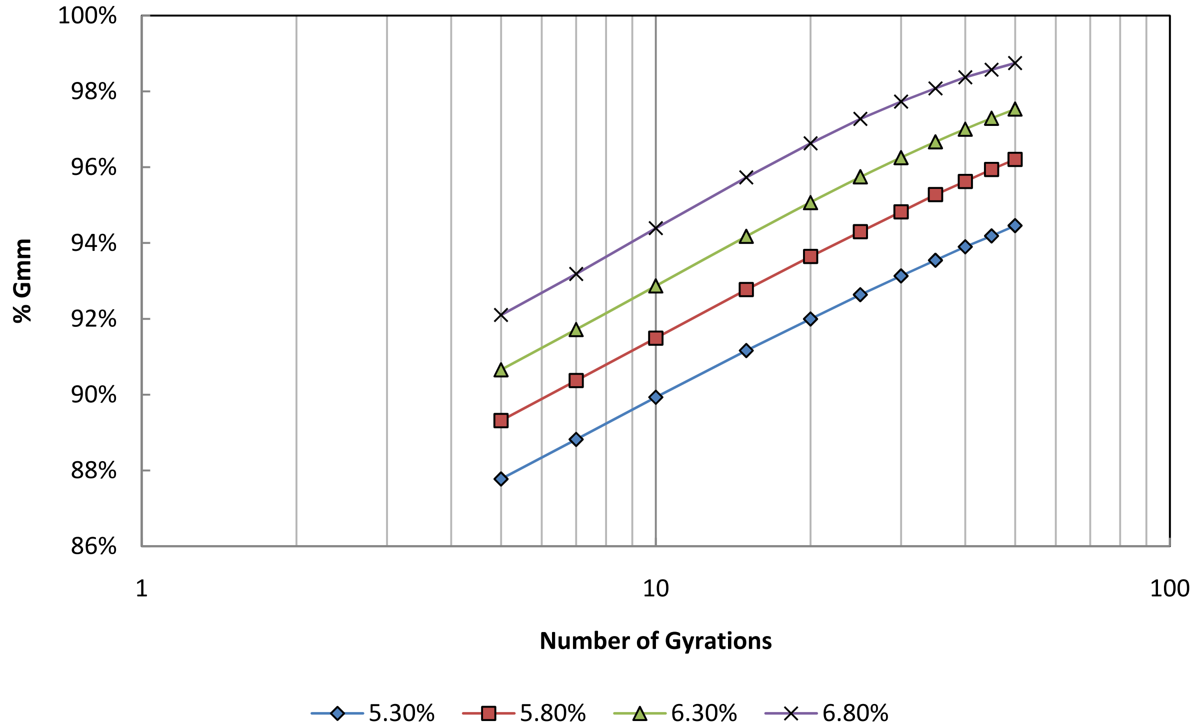
B1: 0% RAP mix design densification curves



B2: 15% RAP mix design densification curves



B3: 25% RAP mix design densification curves



B4: 40% RAP mix design densification curves

APPENDIX C – Indirect Tension Testing Data

C1: WTSA SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1200	1 + 2
-10	10	1175	1 + 2
-10	5	1150	3 + 4
-10	2	900	1 + 2
-10	1	750	1 + 2
-10	0.5	650	1 + 2
-10	0.2	575	1 + 2
-10	0.1	525	1 + 2
0	20	950	1 + 2
0	10	800	1 + 2
0	5	675	1 + 2
0	2	600	1 + 2
0	1	500	1 + 2
0	0.5	475	1 + 2
0	0.2	425	1 + 2
0	0.1	400	1 + 2
10	20	600	1 + 2
10	10	550	1 + 2
10	5	400	1 + 2
10	2	325	1 + 2
10	1	250	1 + 2
10	0.5	225	1 + 2
10	0.2	200	1 + 2
10	0.1	150	1 + 2
20	20	375	1 + 2
20	10	325	1 + 2
20	5	225	1 + 2
20	2	150	1 + 2
20	1	125	1 + 2
20	0.5	75	1 + 2
20	0.2	65	1 + 2
20	0.1	40	1 + 2
30	20	225	1 + 2
30	10	150	1 + 2
30	5	100	1 + 2
30	2	60	1 + 2
30	1	50	1 + 2
30	0.5	40	1 + 2
30	0.2	30	1 + 2
30	0.1	25	1 + 2

C2: WTSB RSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1150	1 + 2
-10	10	1075	1 + 2
-10	5	1000	1 + 2
-10	2	850	1 + 2
-10	1	750	1 + 2
-10	0.5	675	1 + 2
-10	0.2	625	1 + 2
-10	0.1	550	1 + 2
0	20	1000	1 + 2
0	10	900	1 + 2
0	5	800	1 + 2
0	2	675	1 + 2
0	1	575	1 + 2
0	0.5	500	1 + 2
0	0.2	425	1 + 2
0	0.1	375	1 + 2
10	20	700	1 + 2
10	10	600	1 + 2
10	5	500	1 + 2
10	2	400	1 + 2
10	1	300	1 + 2
10	0.5	225	1 + 2
10	0.2	175	1 + 2
10	0.1	140	1 + 2
20	20	375	1 + 2
20	10	300	1 + 2
20	5	225	1 + 2
20	2	135	1 + 2
20	1	85	1 + 2
20	0.5	65	1 + 2
20	0.2	-	1 + 2
20	0.1	-	1 + 2
30	20	350	1 + 2
30	10	250	1 + 2
30	5	150	1 + 2
30	2	75	1 + 2
30	1	40	1 + 2
30	0.5	30	1 + 2
30	0.2	20	1 + 2
30	0.1	10	1 + 2

C3: XTSC SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1150	3 + 4
-10	10	1050	3 + 4
-10	5	950	3 + 4
-10	2	875	3 + 4
-10	1	825	3 + 4
-10	0.5	800	3 + 4
-10	0.2	750	3 + 4
-10	0.1	900 ?	3 + 4
0	20	1000	3 + 4
0	10	900	3 + 4
0	5	775	3 + 4
0	2	675	3 + 4
0	1	600	3 + 4
0	0.5	550	3 + 4
0	0.2	500	3 + 4
0	0.1	475	3 + 4
10	20	700	1 + 2
10	10	600	1 + 2
10	5	500	1 + 2
10	2	400	1 + 2
10	1	300	1 + 2
10	0.5	200	1 + 2
10	0.2	175	1 + 2
10	0.1	150 (1000 accidental)	1 + 2
20	20	400	1 + 2
20	10	300	1 + 2
20	5	200	1 + 2
20	2	125	1 + 2
20	1	75	1 + 2
20	0.5	75	1 + 2
20	0.2	65	1 + 2
20	0.1	50	1 + 2
30	20	300	1 + 2
30	10	200	1 + 2
30	5	100	1 + 2
30	2	70	1 + 2
30	1	45	1 + 2
30	0.5	35	1 + 2
30	0.2	25	1 + 2
30	0.1	20	1 + 2

C4: XTSD SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1125	1 + 2
-10	10	1025	1 + 2
-10	5	925	1 + 2
-10	2	850	1 + 2
-10	1	775	1 + 2
-10	0.5	750	1 + 2
-10	0.2	700	1 + 2
-10	0.1	675	1 + 2
0	20	1000	1 + 2
0	10	900	1 + 2
0	5	725	1 + 2
0	2	675	1 + 2
0	1	600	1 + 2
0	0.5	550	1 + 2
0	0.2	525	1 + 2
0	0.1	-	1 + 2
10	20	700	1 + 2
10	10	600	1 + 2
10	5	500	1 + 2
10	2	400	1 + 2
10	1	300	1 + 2
10	0.5	200	1 + 2
10	0.2	175	1 + 2
10	0.1	150	1 + 2
20	20	400	1 + 2
20	10	300	1 + 2
20	5	200	1 + 2
20	2	150	1 + 2
20	1	100	1 + 2
20	0.5	75	1 + 2
20	0.2	65	1 + 2
20	0.1	50	1 + 2
30	20	300	1 + 2
30	10	200	1 + 2
30	5	100	1 + 2
30	2	50	1 + 2
30	1	35	1 + 2
30	0.5	30	1 + 2
30	0.2	20	1 + 2
30	0.1	15	1 + 2

C5: YTSA SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1100	1 + 2
-10	10	100	1 + 2
-10	5	925	1 + 2
-10	2	850	1 + 2
-10	1	775	1 + 2
-10	0.5	700	1 + 2
-10	0.2	650	1 + 2
-10	0.1	625	1 + 2
0	20	950	1 + 2
0	10	850	1 + 2
0	5	75	1 + 2
0	2	650	1 + 2
0	1	575	1 + 2
0	0.5	525	1 + 2
0	0.2	475	1 + 2
0	0.1	435	1 + 2
10	20	700	1 + 2
10	10	600	1 + 2
10	5	500	1 + 2
10	2	400	1 + 2
10	1	325	1 + 2
10	0.5	250	1 + 2
10	0.2	200	1 + 2
10	0.1	175	1 + 2
20	20	425	3 + 4
20	10	325	3 + 4
20	5	225	3 + 4
20	2	150	3 + 4
20	1	115	3 + 4
20	0.5	95	3 + 4
20	0.2	75	3 + 4
20	0.1	60 (100 accidental)	3 + 4
30	20	300	3 + 4
30	10	200	3 + 4
30	5	120	3 + 4
30	2	90	3 + 4
30	1	65	3 + 4
30	0.5	50	3 + 4
30	0.2	40	3 + 4
30	0.1	30	3 + 4

C6: YTSMX SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1050	-
-10	10	950	-
-10	5	850	-
-10	2	775	-
-10	1	725	-
-10	0.5	675	-
-10	0.2	640	-
-10	0.1	625	-
0	20	950	-
0	10	850	-
0	5	750	-
0	2	650	-
0	1	575	-
0	0.5	525	-
0	0.2	475	-
0	0.1	435	-
10	20	725	-
10	10	625	-
10	5	525	-
10	2	425	-
10	1	325	-
10	0.5	250	-
10	0.2	200	-
10	0.1	175	-
20	20	400	-
20	10	300	-
20	5	210	-
20	2	135	-
20	1	85	-
20	0.5	55	-
20	0.2	40	-
20	0.1	30	-
30	20	300	-
30	10	225	-
30	5	150	-
30	2	80	-
30	1	45	-
30	0.5	25	-
30	0.2	20	-
30	0.1	15	-

C7: ZTSA SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1250	1 + 2
-10	10	-	1 + 2
-10	5	900	1 + 2
-10	2	975	1 + 2
-10	1	900	1 + 2
-10	0.5	800	1 + 2
-10	0.2	700	1 + 2
-10	0.1	700	1 + 2
0	20	700	1 + 2
0	10	600	1 + 2
0	5	550	1 + 2
0	2	500	1 + 2
0	1	475	1 + 2
0	0.5	440	1 + 2
0	0.2	400	1 + 2
0	0.1	375	1 + 2
10	20	750	1 + 2
10	10	725	1 + 2
10	5	675	1 + 2
10	2	575	1 + 2
10	1	475	1 + 2
10	0.5	400	1 + 2
10	0.2	350	1 + 2
10	0.1	300	1 + 2
20	20	570	1 + 2
20	10	500	1 + 2
20	5	400	1 + 2
20	2	300	1 + 2
20	1	210	1 + 2
20	0.5	150	1 + 2
20	0.2	125	1 + 2
20	0.1	100	1 + 2
30	20	300	1 + 2
30	10	200	1 + 2
30	5	125	1 + 2
30	2	90	1 + 2
30	1	80	1 + 2
30	0.5	60	1 + 2
30	0.2	30	1 + 2
30	0.1	25	1 + 2

C8: ZTSF SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1025	-
-10	10	925	-
-10	5	825	-
-10	2	800	-
-10	1	750	-
-10	0.5	700	-
-10	0.2	650	-
-10	0.1	625	-
0	20	1025	-
0	10	925	-
0	5	825	-
0	2	725	-
0	1	640	-
0	0.5	600	-
0	0.2	575	-
0	0.1	550	-
10	20	725	-
10	10	625	-
10	5	525	-
10	2	425	-
10	1	325	-
10	0.5	250	-
10	0.2	200	-
10	0.1	175	-
20	20	425	-
20	10	325	-
20	5	250	-
20	2	160	-
20	1	110	-
20	0.5	85	-
20	0.2	65	-
20	0.1	50	-
30	20	300	-
30	10	225	-
30	5	150	-
30	2	90	-
30	1	65	-
30	0.5	45	-
30	0.2	30	-
30	0.1	20	-

C9: FC2 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	100	3 + 4
-10	10	900	3 + 4
-10	5	825	3 + 4
-10	2	750	3 + 4
-10	1	675	3 + 4
-10	0.5	600	3 + 4
-10	0.2	550	1 + 2
-10	0.1	-	1 + 2
0	20	900 (1200 accidental)	1 + 2
0	10	800	1 + 2
0	5	700	1 + 2
0	2	600	1 + 2
0	1	500	1 + 2
0	0.5	350	1 + 2
0	0.2	275	1 + 2
0	0.1	225	1 + 2
10	20	650	1 + 2
10	10	550	1 + 2
10	5	450	1 + 2
10	2	350	1 + 2
10	1	250	1 + 2
10	0.5	150	1 + 2
10	0.2	75	1 + 2
10	0.1	50	1 + 2
20	20	400	1 + 2
20	10	300	1 + 2
20	5	200	1 + 2
20	2	125	1 + 2
20	1	85	1 + 2
20	0.5	60	1 + 2
20	0.2	40	1 + 2
20	0.1	-	1 + 2
30	20	300 broken	1 + 2
30	10		
30	5		
30	2		
30	1		
30	0.5		
30	0.2		
30	0.1		

C10: FC3 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1000	1 + 2
-10	10	900	1 + 2
-10	5	800 (1300 accidental)	1 + 2
-10	2	725	1 + 2
-10	1	650	1 + 2
-10	0.5	575	1 + 2
-10	0.2	525	1 + 2
-10	0.1	485	1 + 2
0	20	900	1 + 2
0	10	800	1 + 2
0	5	700	1 + 2
0	2	625	1 + 2
0	1	550	1 + 2
0	0.5	500	1 + 2
0	0.2	450	1 + 2
0	0.1	475	1 + 2
10	20	650	1 + 2
10	10	550	1 + 2
10	5	450	1 + 2
10	2	340	1 + 2
10	1	250	1 + 2
10	0.5	200	1 + 2
10	0.2	150	1 + 2
10	0.1	125	1 + 2
20	20	400	1 + 2
20	10	300	1 + 2
20	5	200	1 + 2
20	2	125	1 + 2
20	1	100	1 + 2
20	0.5	75	1 + 2
20	0.2	65	1 + 2
20	0.1	50	1 + 2
30	20	300	1 + 2
30	10	200	1 + 2
30	5	125	1 + 2
30	2	60 (160lb for 30 cycles)	1 + 2
30	1	35	1 + 2
30	0.5	25	1 + 2
30	0.2	20	1 + 2
30	0.1	15	1 + 2

C11: FC4 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1100 (4300 accident)	1 + 2
-10	10	1000	1 + 2
-10	5	900	1 + 2
-10	2	800	1 + 2
-10	1	725	1 + 2
-10	0.5	675	1 + 2
-10	0.2	650	1 + 2
-10	0.1	625	1 + 2
0	20	1000	1 + 2
0	10	900	1 + 2
0	5	800	1 + 2
0	2	725	1 + 2
0	1	625	1 + 2
0	0.5	525	1 + 2
0	0.2	425	1 + 2
0	0.1	375	1 + 2
10	20	675	1 + 2
10	10	575	1 + 2
10	5	475	1 + 2
10	2	400	1 + 2
10	1	325	1 + 2
10	0.5	250	1 + 2
10	0.2	200	1 + 2
10	0.1	185	1 + 2
20	20	400	1 + 2
20	10	300	1 + 2
20	5	200	1 + 2
20	2	125	1 + 2
20	1	110	1 + 2
20	0.5	100	1 + 2
20	0.2	85	1 + 2
20	0.1	70	1 + 2
30	20	375	1 + 2
30	10	260	1 + 2
30	5	125	1 + 2
30	2	60	1 + 2
30	1	40	1 + 2
30	0.5	30	1 + 2
30	0.2	20	1 + 2
30	0.1	15	1 + 2

C12: FC5 RSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1050	1 + 2
-10	10	900	1 + 2
-10	5	850	1 + 2
-10	2	750	1 + 2
-10	1	700	1 + 2
-10	0.5	675 (2400 accidental)	1 + 2
-10	0.2	625	1 + 2
-10	0.1	625	1 + 2
0	20	1000	1 + 2
0	10	850	1 + 2
0	5	800	1 + 2
0	2	650	1 + 2
0	1	600	1 + 2
0	0.5	550	1 + 2
0	0.2	525	1 + 2
0	0.1	500	1 + 2
10	20	570	3 + 4
10	10	550	3 + 4
10	5	520	3 + 4
10	2	500	3 + 4
10	1	400	3 + 4
10	0.5	310	3 + 4
10	0.2	260	3 + 4
10	0.1	210	3 + 4
20	20	550	3 + 4
20	10	460	3 + 4
20	5	360	3 + 4
20	2	280	3 + 4
20	1	200	3 + 4
20	0.5	180	3 + 4
20	0.2	150	3 + 4
20	0.1	150	3 + 4
30	20	300	3 + 4
30	10	225	3 + 4
30	5	175	3 + 4
30	2	125	3 + 4
30	1	100	3 + 4
30	0.5	85	3 + 4
30	0.2	65	3 + 4
30	0.1	40	3 + 4

C13: FC6 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1000	1 + 2
-10	10	925	1 + 2
-10	5	875	1 + 2
-10	2	800	1 + 2
-10	1	700	1 + 2
-10	0.5	650 (2230 accidental)	1 + 2
-10	0.2	600 (2400 accidental)	1 + 2
-10	0.1	575	1 + 2
0	20	1000	1 + 2
0	10	925	1 + 2
0	5	825	1 + 2
0	2	700	1 + 2
0	1	640	1 + 2
0	0.5	600	1 + 2
0	0.2	550	1 + 2
0	0.1	535	1 + 2
10	20	725	1 + 2
10	10	625	1 + 2
10	5	550	1 + 2
10	2	450	1 + 2
10	1	400	1 + 2
10	0.5	400	1 + 2
10	0.2	375	1 + 2
10	0.1	350	1 + 2
20	20	450	1 + 2
20	10	375	1 + 2
20	5	300	1 + 2
20	2	250	1 + 2
20	1	250	1 + 2
20	0.5	225	1 + 2
20	0.2	220	1 + 2
20	0.1	200	1 + 2
30	20	350	1 + 2
30	10	250	1 + 2
30	5	185	1 + 2
30	2	140	1 + 2
30	1	110	1 + 2
30	0.5	95	1 + 2
30	0.2	80	1 + 2
30	0.1	75	1 + 2

C14: FC7 RSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1000 (2300 accidental)	1 + 2
-10	10	900	1 + 2
-10	5	800	1 + 2
-10	2	750	1 + 2
-10	1	700	1 + 2
-10	0.5	650 (2400 accidental)	1 + 2
-10	0.2	640	1 + 2
-10	0.1	625	1 + 2
0	20	1000	1 + 2
0	10	850	1 + 2
0	5	750	1 + 2
0	2	625	1 + 2
0	1	575	1 + 2
0	0.5	525	1 + 2
0	0.2	500	1 + 2
0	0.1	475	1 + 2
10	20	720	1 + 2
10	10	675	1 + 2
10	5	600	1 + 2
10	2	500	1 + 2
10	1	400	1 + 2
10	0.5	350	1 + 2
10	0.2	300	1 + 2
10	0.1	250	1 + 2
20	20	500	1 + 2
20	10	400	1 + 2
20	5	300	1 + 2
20	2	225	1 + 2
20	1	175	1 + 2
20	0.5	150	1 + 2
20	0.2	125	1 + 2
20	0.1	100	1 + 2
30	20	300	1 + 2
30	10	225	1 + 2
30	5	150	1 + 2
30	2	125	1 + 2
30	1	100	1 + 2
30	0.5	75	1 + 2
30	0.2	65	1 + 2
30	0.1	40	1 + 2

C15: NFC7SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	1000	1 + 2
-10	10	900	1 + 2
-10	5	800	1 + 2
-10	2	700	1 + 2
-10	1	600	1 + 2
-10	0.5	525	1 + 2
-10	0.2	475	1 + 2
-10	0.1	450	1 + 2
0	20	900	1 + 2
0	10	775	1 + 2
0	5	675	1 + 2
0	2	575	1 + 2
0	1	475	1 + 2
0	0.5	375	1 + 2
0	0.2	325	1 + 2
0	0.1	300	1 + 2
9	20	800	1 + 2
9	10	650	1 + 2
9	5	500	1 + 2
10	2	300	1 + 2
10	1	200	1 + 2
10	0.5	100	1 + 2
10	0.2	50	1 + 2
10	0.1	25	1 + 2
20	20	400 broken	1 + 2
20	10		
20	5		
20	2		
20	1		
20	0.5		
20	0.2		
20	0.1		
30	20		
30	10		
30	5		
30	2		
30	1		
30	0.5		
30	0.2		
30	0.1		

C16: NFC8 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	800	1 + 2
-10	10	700	1 + 2
-10	5	625	1 + 2
-10	2	550	1 + 2
-10	1	475	1 + 2
-10	0.5	425	1 + 2
-10	0.2	410	1 + 2
-10	0.1	375	1 + 2
0	20	650	1 + 2
0	10	550	1 + 2
0	5	450	1 + 2
0	2	350	1 + 2
0	1	250	1 + 2
0	0.5	175	1 + 2
0	0.2	150	1 + 2
0	0.1	135	1 + 2
10	20	400	1 + 2
10	10	300	1 + 2
10	5	200	1 + 2
10	2	125	1 + 2
10	1	80	1 + 2
10	0.5	70	1 + 2
10	0.2	55	1 + 2
10	0.1	45	1 + 2
20	20	300	1 + 2
20	10	225	1 + 2
20	5	135	1 + 2
20	2	60	1 + 2
20	1	30	1 + 2
20	0.5	25	1 + 2
20	0.2	20	1 + 2
20	0.1	15	1 + 2
30	20	broken	1 + 2
30	10		
30	5		
30	2		
30	1		
30	0.5		
30	0.2		
30	0.1		

C17: NFC9 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	800	1 + 2
-10	10	700	1 + 2
-10	5	625	1 + 2
-10	2	550	1 + 2
-10	1	475	1 + 2
-10	0.5	425	1 + 2
-10	0.2	400	1 + 2
-10	0.1	375	1 + 2
0	20	650	1 + 2
0	10	550	1 + 2
0	5	450	1 + 2
0	2	375	1 + 2
0	1	275	1 + 2
0	0.5	225	1 + 2
0	0.2	200	1 + 2
0	0.1	185	1 + 2
10	20	425	1 + 2
10	10	325	1 + 2
10	5	225	1 + 2
10	2	160 (400 accidental)	1 + 2
10	1	135	1 + 2
10	0.5	100	1 + 2
10	0.2	85	1 + 2
10	0.1	75	1 + 2
20	20	325	1 + 2
20	10	235	1 + 2
20	5	135	1 + 2
20	2	60	1 + 2
20	1	35	1 + 2
20	0.5	25	1 + 2
20	0.2	20	1 + 2
20	0.1	15	1 + 2
30	20	70	1 + 2
30	10	55 broken	1 + 2
30	5		
30	2		
30	1		
30	0.5		
30	0.2		
30	0.1		

C18: NFC10 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	850	1 + 2
-10	10	750	1 + 2
-10	5	675	1 + 2
-10	2	600	1 + 2
-10	1	525	1 + 2
-10	0.5	475	1 + 2
-10	0.2	475	1 + 2
-10	0.1	450	1 + 2
0	20	675	1 + 2
0	10	575	1 + 2
0	5	475	1 + 2
0	2	400	1 + 2
0	1	253	1 + 2
0	0.5	300	1 + 2
0	0.2	275	1 + 2
0	0.1	250	1 + 2
10	20	450	1 + 2
10	10	350	1 + 2
10	5	250	1 + 2
10	2	175	1 + 2
10	1	125	1 + 2
10	0.5	95	1 + 2
10	0.2	65	1 + 2
10	0.1	50	1 + 2
20	20	300	1 + 2
20	10	210	1 + 2
20	5	120	1 + 2
20	2	60	1 + 2
20	1	40	1 + 2
20	0.5	30	1 + 2
20	0.2	25	1 + 2
20	0.1	15	1 + 2
30	20	60	1 + 2
30	10	45	1 + 2
30	5	35	1 + 2
30	2	25	1 + 2
30	1	15	1 + 2
30	0.5	10	1 + 2
30	0.2	7	1 + 2
30	0.1	5	1 + 2

C19: NFC12 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	900	1 + 2
-10	10	800	1 + 2
-10	5	700	1 + 2
-10	2	625	1 + 2
-10	1	550	1 + 2
-10	0.5	500	1 + 2
-10	0.2	475	1 + 2
-10	0.1	450	1 + 2
0	20	700	1 + 2
0	10	600	1 + 2
0	5	500	1 + 2
0	2	425	1 + 2
0	1	350	1 + 2
0	0.5	325	1 + 2
0	0.2	300	1 + 2
0	0.1	275	1 + 2
10	20	500	1 + 2
10	10	400	1 + 2
10	5	300	1 + 2
10	2	225	1 + 2
10	1	175	1 + 2
10	0.5	135	1 + 2
10	0.2	110	1 + 2
10	0.1	100	1 + 2
20	20	325	1 + 2
20	10	235	1 + 2
20	5	135	1 + 2
20	2	60	1 + 2
20	1	40	1 + 2
20	0.5	25	1 + 2
20	0.2	20	1 + 2
20	0.1	15	1 + 2
30	20	70	1 + 2
30	10	55	1 + 2
30	5	45	1 + 2
30	2	35 broken	1 + 2
30	1		
30	0.5		
30	0.2		
30	0.1		

C20: PMTS5 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	900	1 + 2
-10	10	800	1 + 2
-10	5	750	1 + 2
-10	2	675	3 + 4
-10	1	625	3 + 4
-10	0.5	575	3 + 4
-10	0.2	525	3 + 4
-10	0.1	500	3 + 4
0	20	750	3 + 4
0	10	650	3 + 4
0	5	575	3 + 4
0	2	500	3 + 4
0	1	450	3 + 4
0	0.5	400	3 + 4
0	0.2	375	3 + 4
0	0.1	325	3 + 4
10	20	500	3 + 4
10	10	400	3 + 4
10	5	325	3 + 4
10	2	250	3 + 4
10	1	175	3 + 4
10	0.5	125	3 + 4
10	0.2	85	3 + 4
10	0.1	65	3 + 4
20	20	350	3 + 4
20	10	250	3 + 4
20	5	160	3 + 4
20	2	90	3 + 4
20	1	60	3 + 4
20	0.5	50	3 + 4
20	0.2	45	3 + 4
20	0.1	40	3 + 4
30	20	150	3 + 4
30	10	75	3 + 4
30	5	50	3 + 4
30	2	35	3 + 4
30	1	25	3 + 4
30	0.5	15	3 + 4
30	0.2	10	3 + 4
30	0.1	7	3 + 4

C21: PMTS7 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	900	3 + 4
-10	10	800	3 + 4
-10	5	750	3 + 4
-10	2	675	3 + 4
-10	1	625	3 + 4
-10	0.5	575	3 + 4
-10	0.2	525	3 + 4
-10	0.1	500	3 + 4
0	20	750	3 + 4
0	10	650	3 + 4
0	5	575	3 + 4
0	2	500	3 + 4
0	1	450	3 + 4
0	0.5	400	3 + 4
0	0.2	365	3 + 4
0	0.1	325	3 + 4
10	20	500	3 + 4
10	10	400	3 + 4
10	5	325	3 + 4
10	2	250	3 + 4
10	1	175	3 + 4
10	0.5	125	3 + 4
10	0.2	85	3 + 4
10	0.1	65	3 + 4
20	20	350	3 + 4
20	10	250	3 + 4
20	5	160	3 + 4
20	2	90	3 + 4
20	1	60	3 + 4
20	0.5	50	3 + 4
20	0.2	45	3 + 4
20	0.1	40	3 + 4
30	20	150	3 + 4
30	10	90	3 + 4
30	5	50	3 + 4
30	2	35	3 + 4
30	1	25	3 + 4
30	0.5	15	3 + 4
30	0.2	15	3 + 4
30	0.1	7	3 + 4

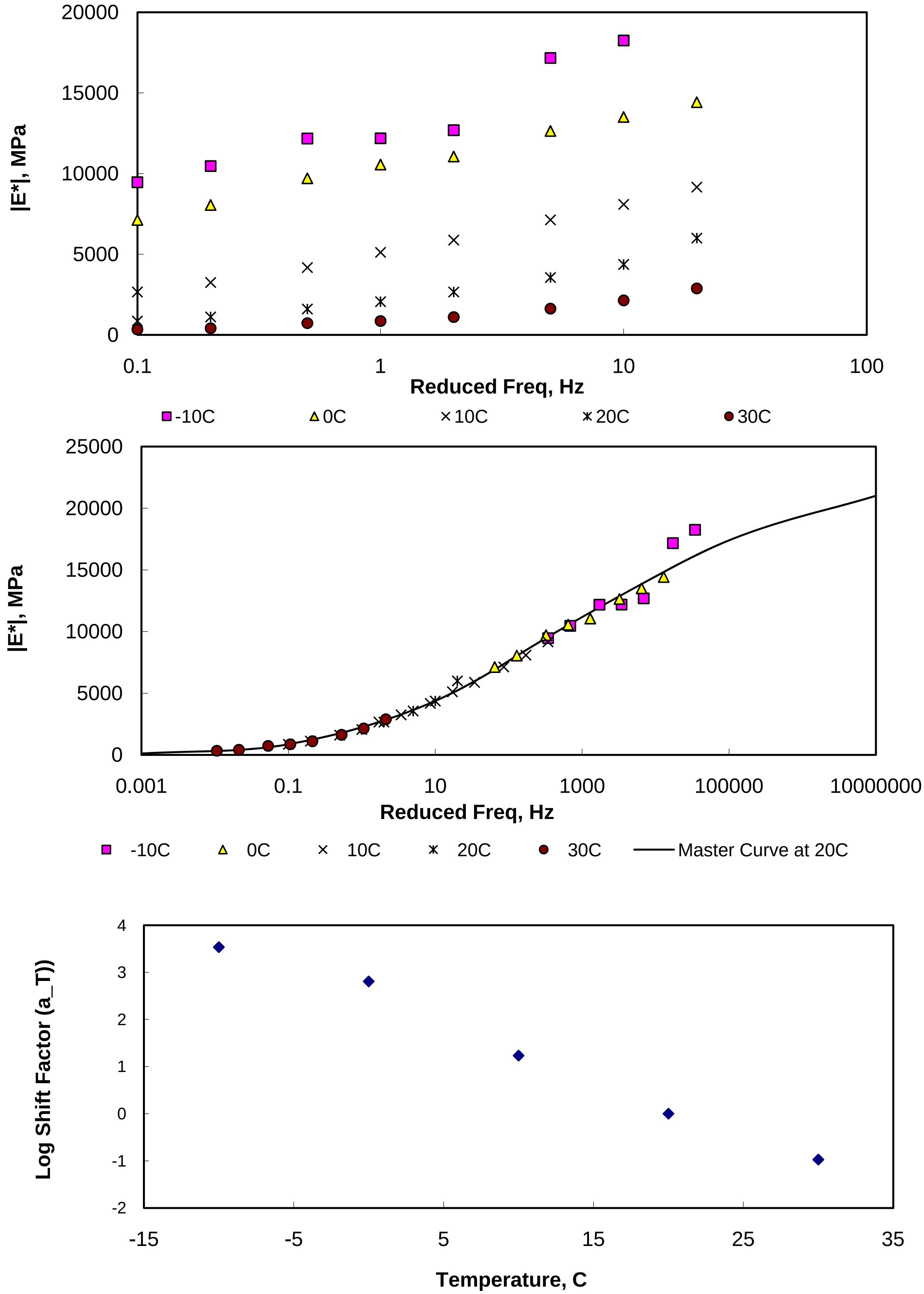
C22: PMTS8 SSS indirect tension testing data

TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	900	3 + 4
-10	10	800	3 + 4
-10	5	750	3 + 4
-10	2	675	3 + 4
-10	1	625	3 + 4
-10	0.5	575	3 + 4
-10	0.2	525	3 + 4
-10	0.1	500	3 + 4
0	20	750	3 + 4
0	10	650	3 + 4
0	5	575	3 + 4
0	2	500	3 + 4
0	1	450	3 + 4
0	0.5	400	3 + 4
0	0.2	365	3 + 4
0	0.1	325	3 + 4
10	20	500	3 + 4
10	10	400	3 + 4
10	5	325	3 + 4
10	2	250	3 + 4
10	1	175	3 + 4
10	0.5	125	3 + 4
10	0.2	85	3 + 4
10	0.1	65	3 + 4
20	20	200	3 + 4
20	10	150	3 + 4
20	5	100	3 + 4
20	2	75	3 + 4
20	1	60	3 + 4
20	0.5	45	3 + 4
20	0.2	35	3 + 4
20	0.1	30	3 + 4
30	20	150	3 + 4
30	10	90	3 + 4
30	5	50	3 + 4
30	2	35	3 + 4
30	1	25	3 + 4
30	0.5	25	3 + 4
30	0.2	15	3 + 4
30	0.1	10	3 + 4

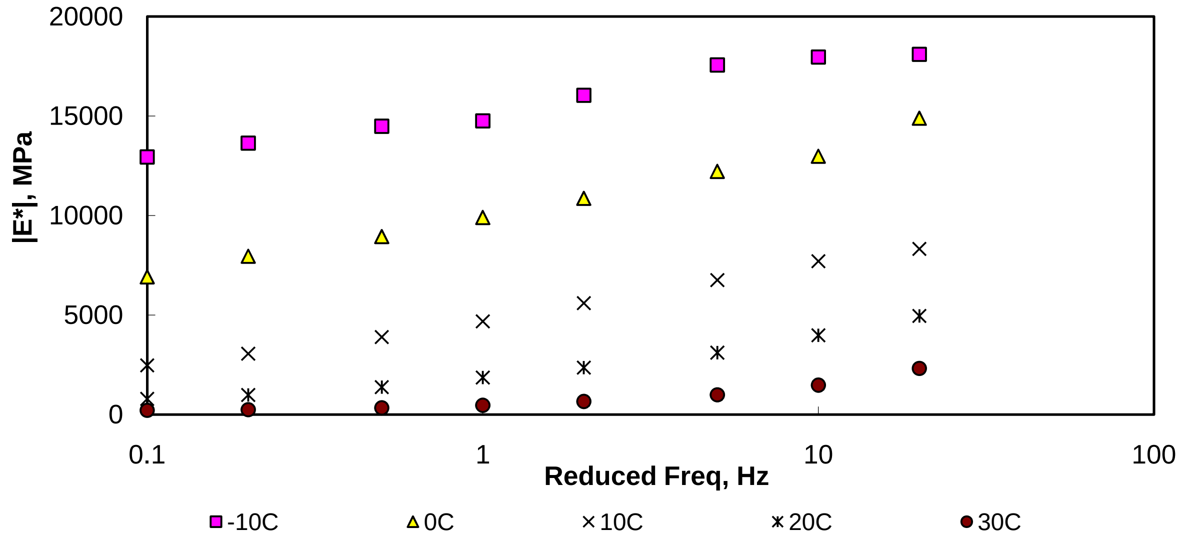
C23: PMTS9 SSS indirect tension testing data

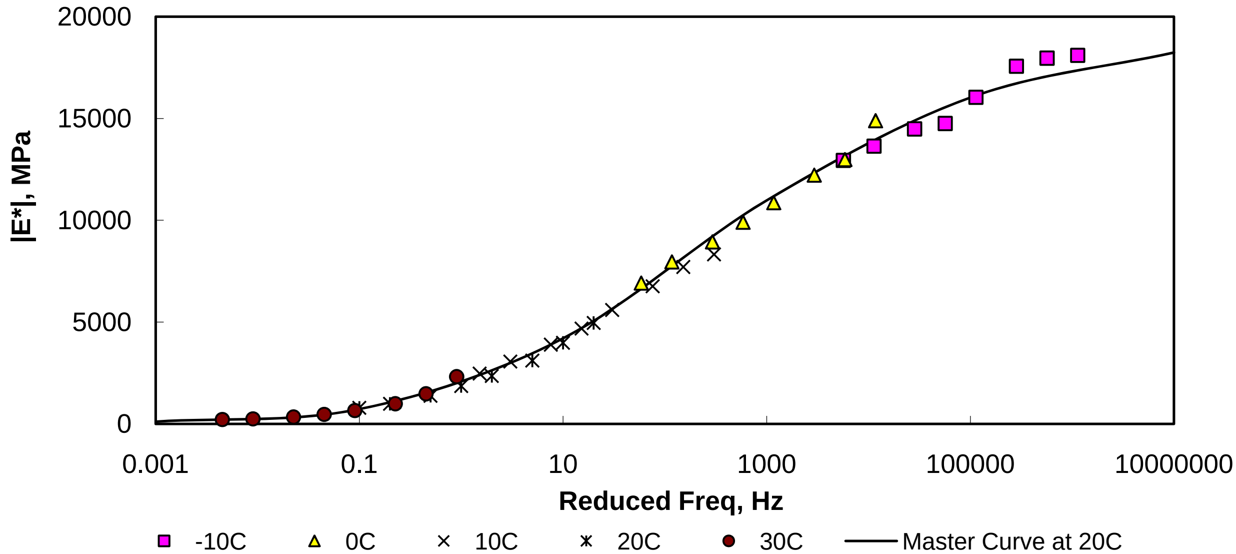
TESTING TEMPERATURE (°C)	FREQUENCY	LOAD (LBS)	LVDT BACK FACE
-10	20	900	3 + 4
-10	10	800	3 + 4
-10	5	750	3 + 4
-10	2	675	3 + 4
-10	1	625	3 + 4
-10	0.5	575	3 + 4
-10	0.2	525	3 + 4
-10	0.1	500	3 + 4
0	20	750	3 + 4
0	10	650	3 + 4
0	5	575	3 + 4
0	2	500	3 + 4
0	1	450	3 + 4
0	0.5	400	3 + 4
0	0.2	365	3 + 4
0	0.1	325	3 + 4
10	20	500	3 + 4
10	10	400	3 + 4
10	5	325	3 + 4
10	2	250	3 + 4
10	1	175	3 + 4
10	0.5	125	3 + 4
10	0.2	85	3 + 4
10	0.1	65	3 + 4
20	20	350	3 + 4
20	10	250	3 + 4
20	5	160	3 + 4
20	2	90	3 + 4
20	1	60	3 + 4
20	0.5	50	3 + 4
20	0.2	45	3 + 4
20	0.1	40	3 + 4
30	20	150	3 + 4
30	10	90	3 + 4
30	5	50	3 + 4
30	2	35	3 + 4
30	1	25	3 + 4
30	0.5	20	3 + 4
30	0.2	15	3 + 4
30	0.1	10	3 + 4

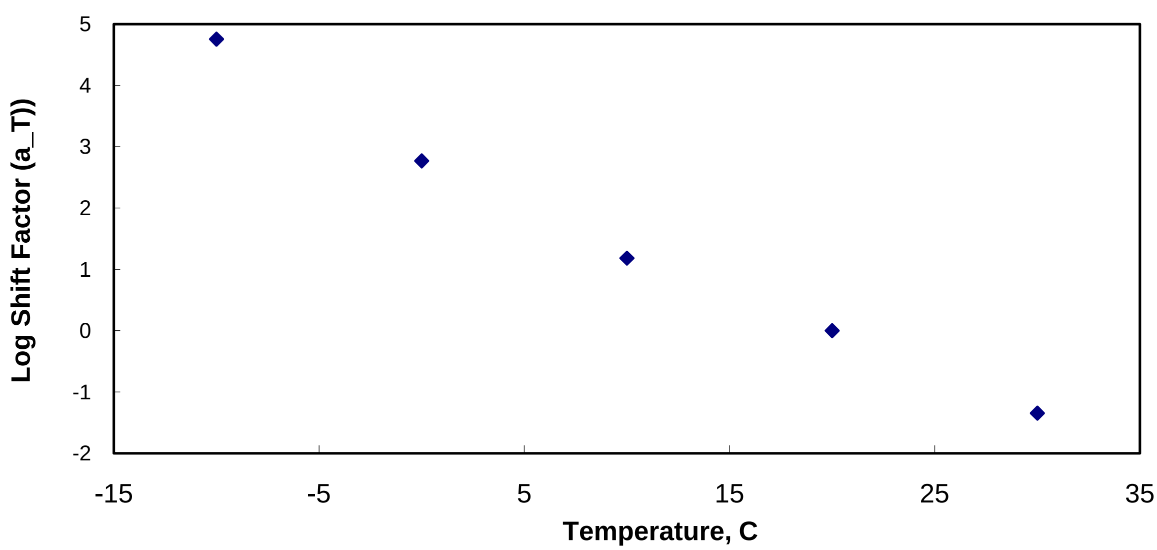
APPENDIX D – Dynamic Modulus Values, Master Curves, and Time-Temperature Shift Factors



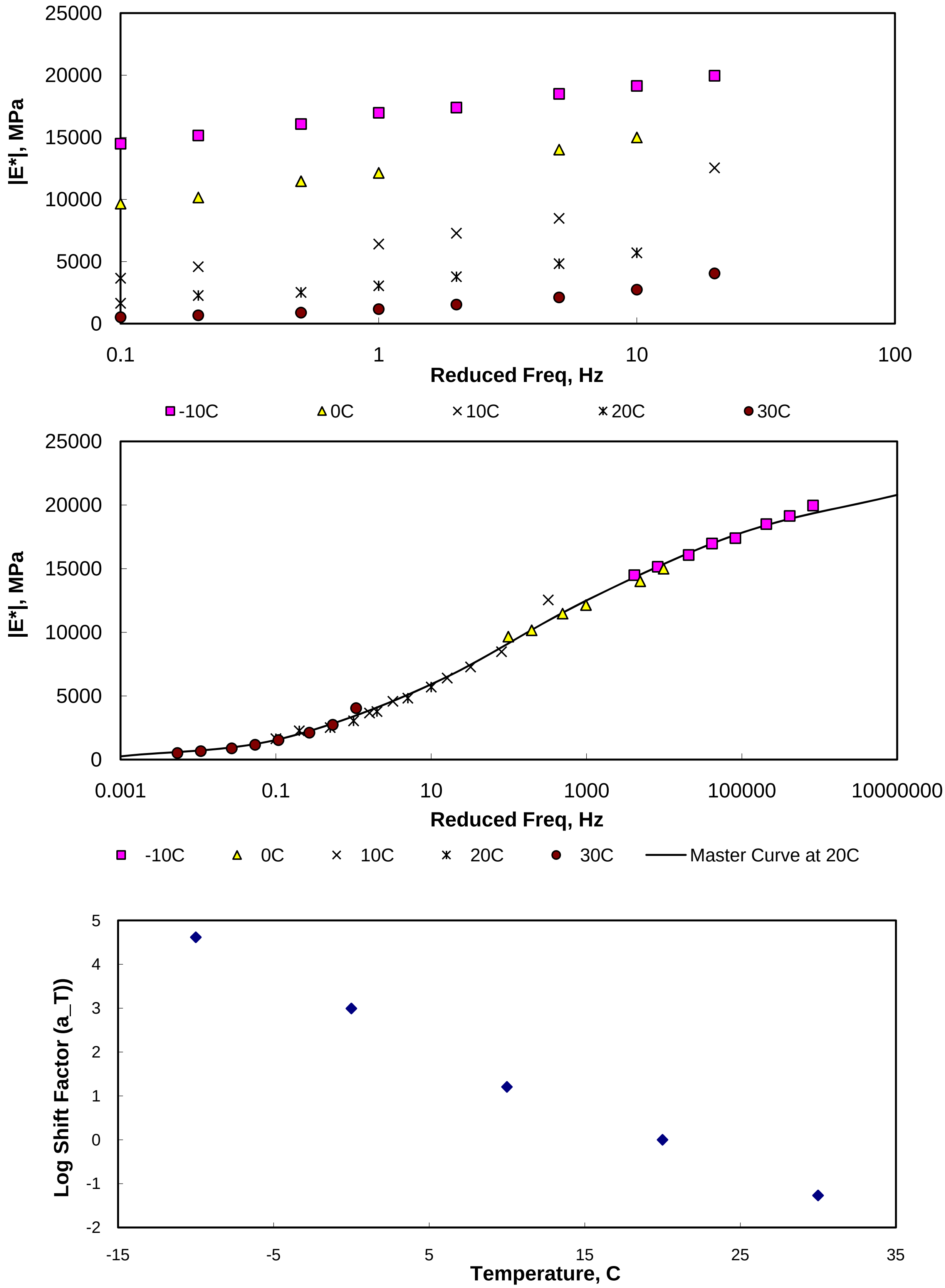
D1: WTSA SSS - 0% RAP IDT dynamic modulus curves & shift factors



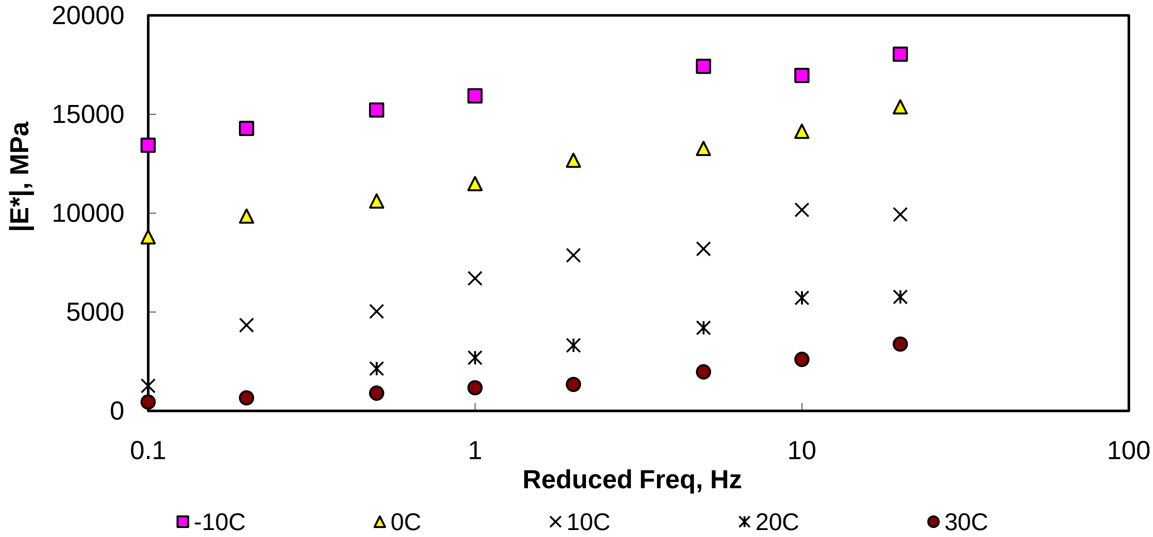


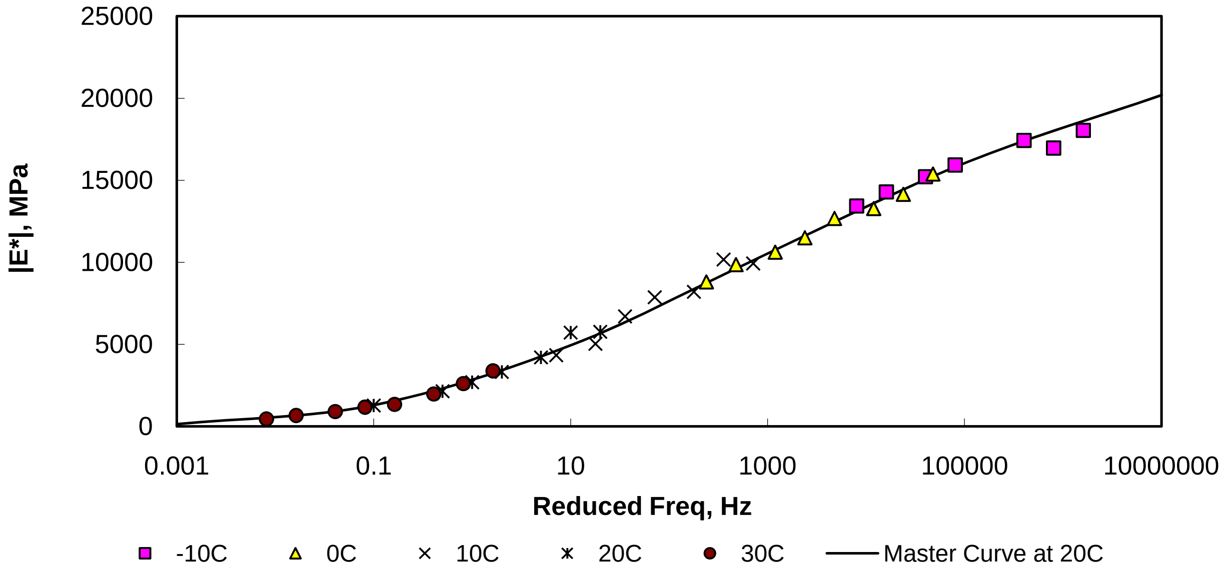


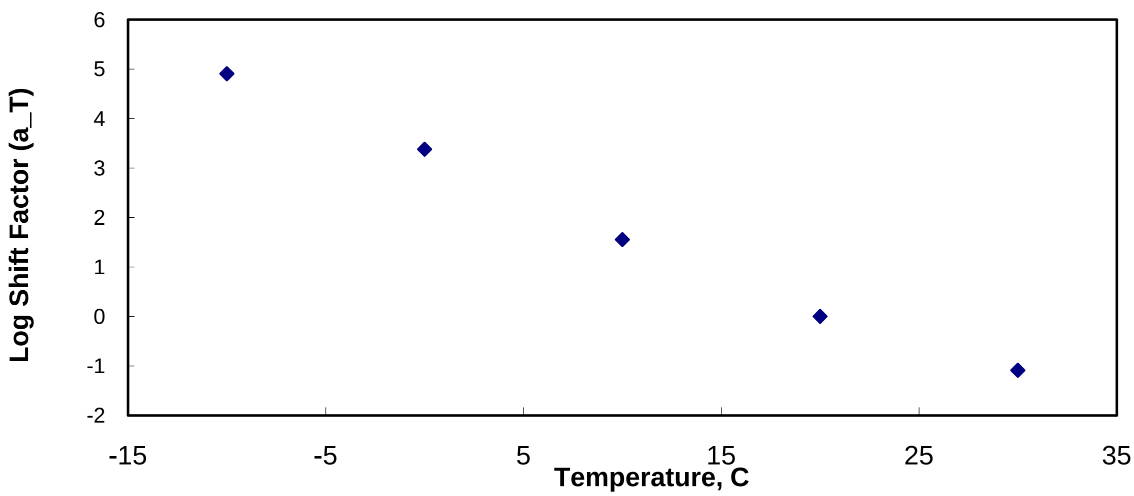
D2: WTSB RSS - 0% RAP IDT dynamic modulus curves & shift factors



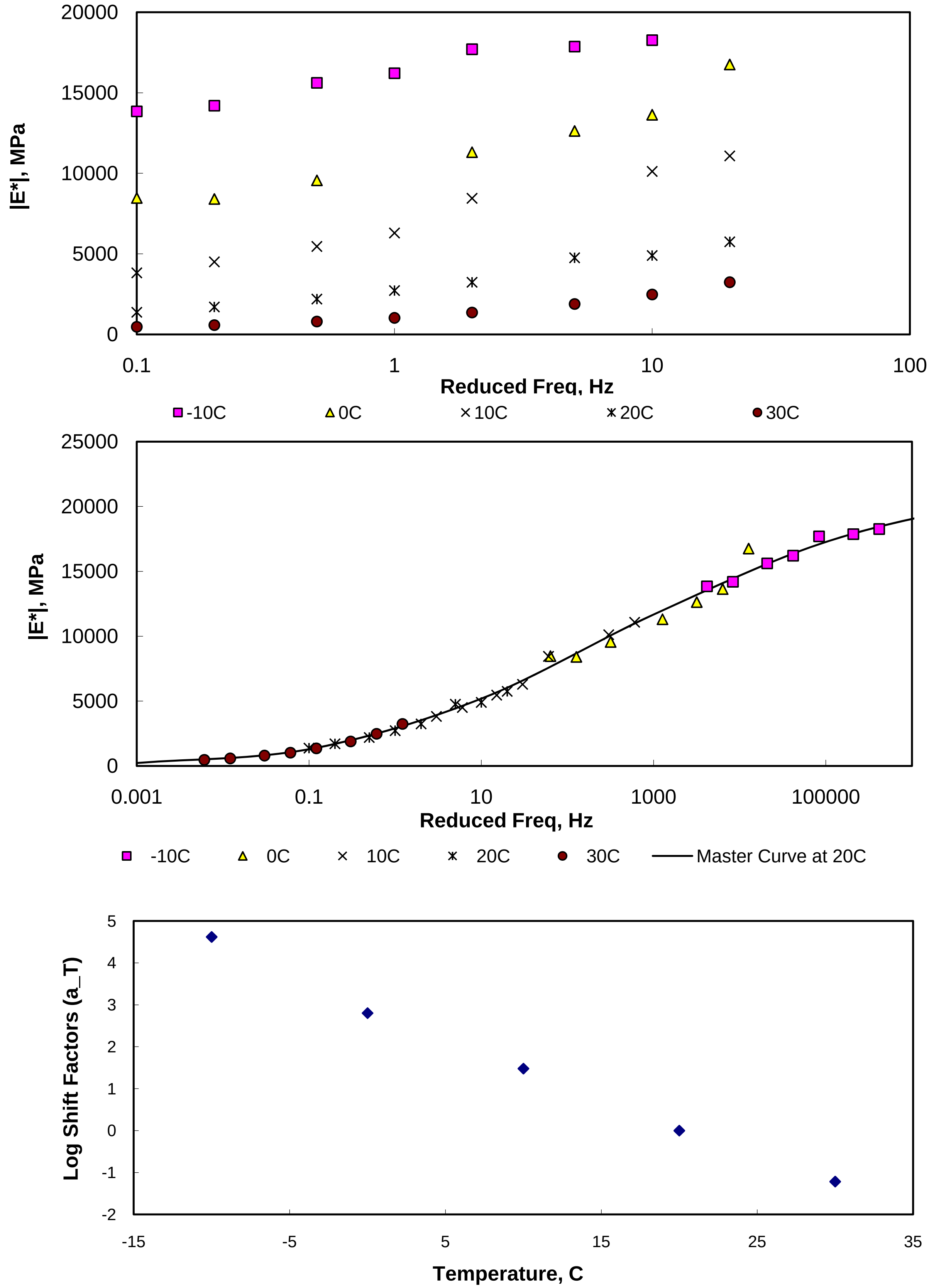
D3: XTSC SSS - 15% RAP IDT dynamic modulus curves & shift factors



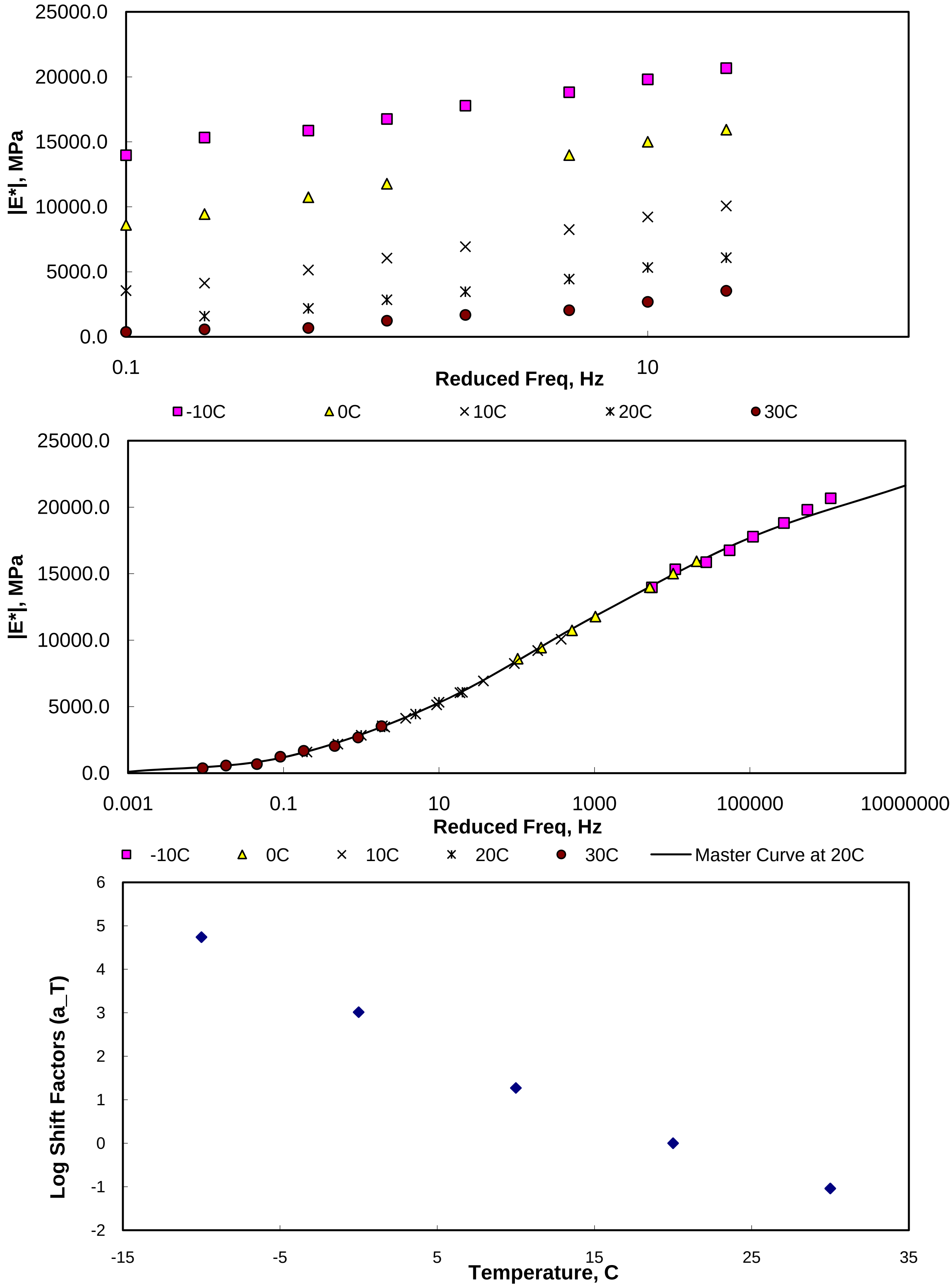




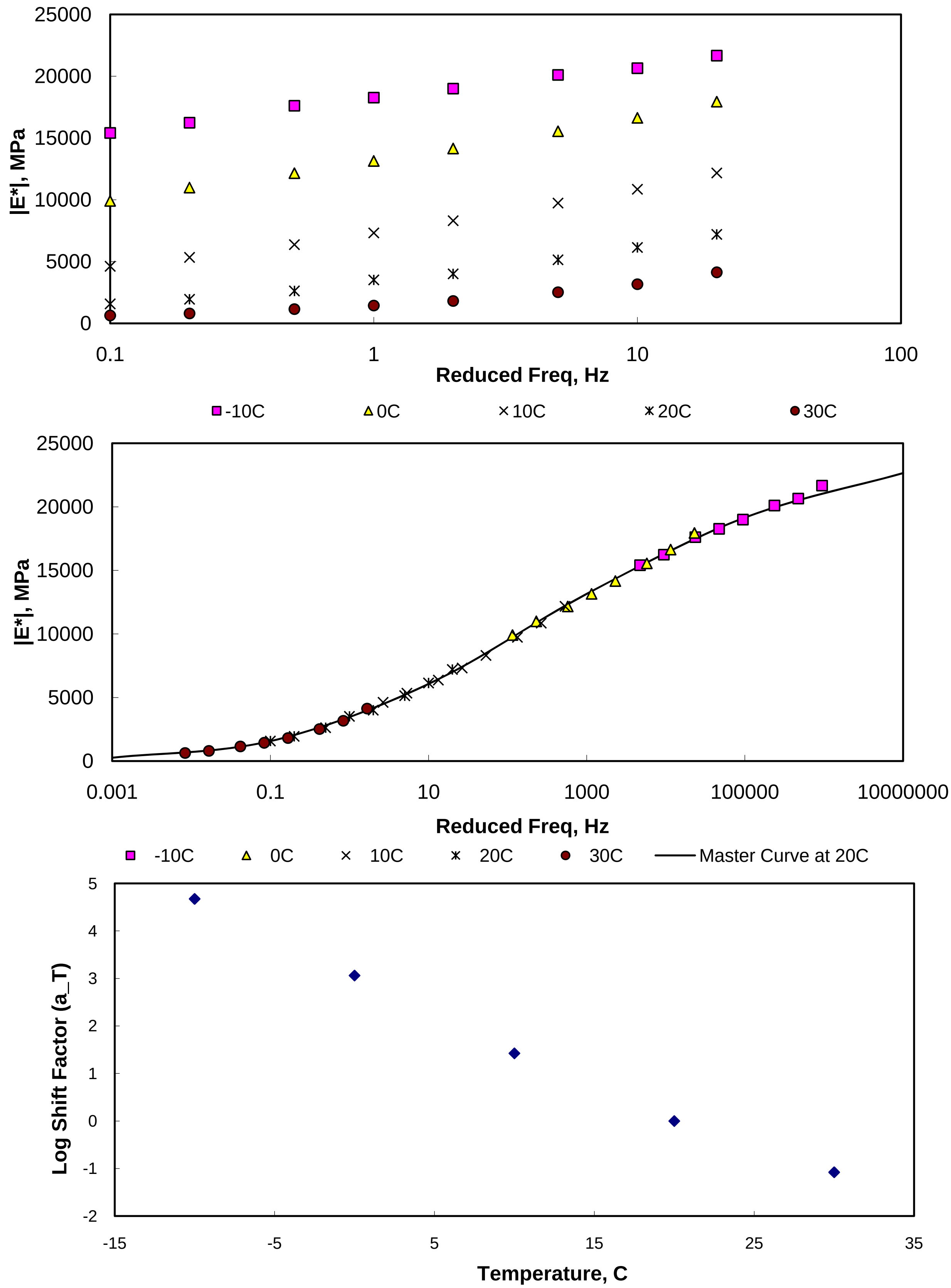
D4: XTSD SSS - 15% RAP IDT dynamic modulus curves & shift factors



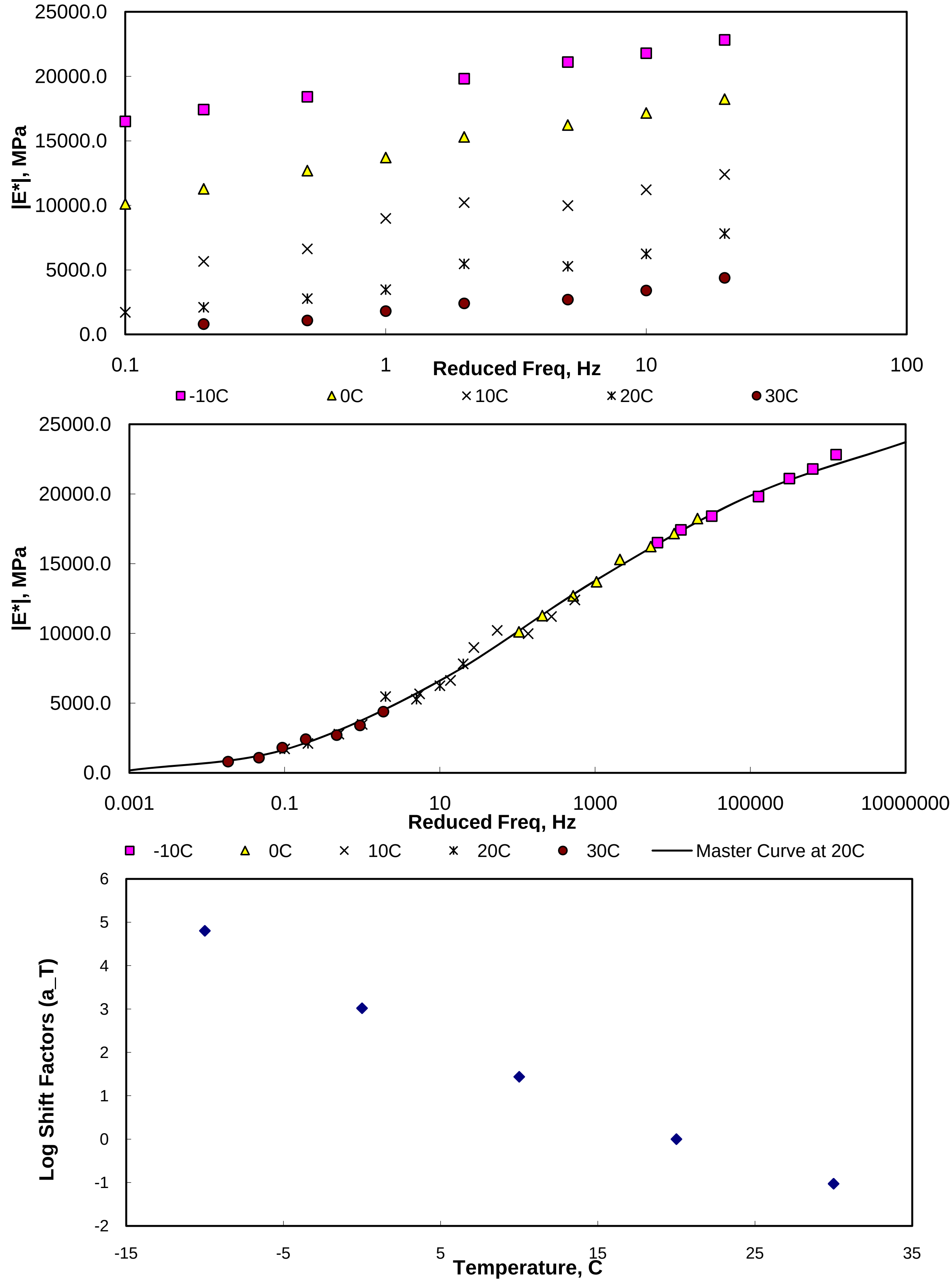
D5: YTSA SSS - 25% RAP IDT dynamic modulus curves & shift factors



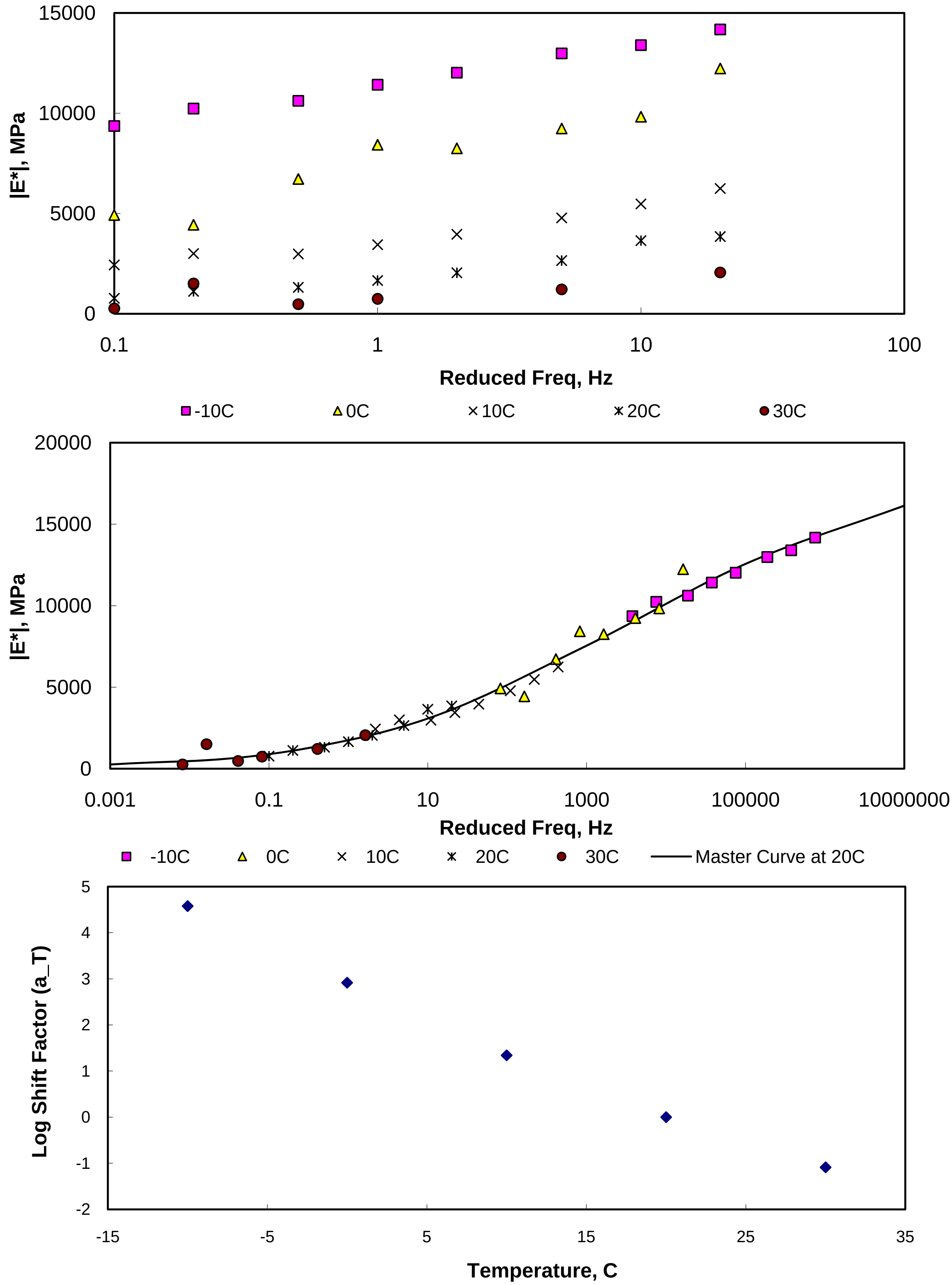
D6: YTSMX SSS - 25% RAP IDT dynamic modulus curves & shift factors



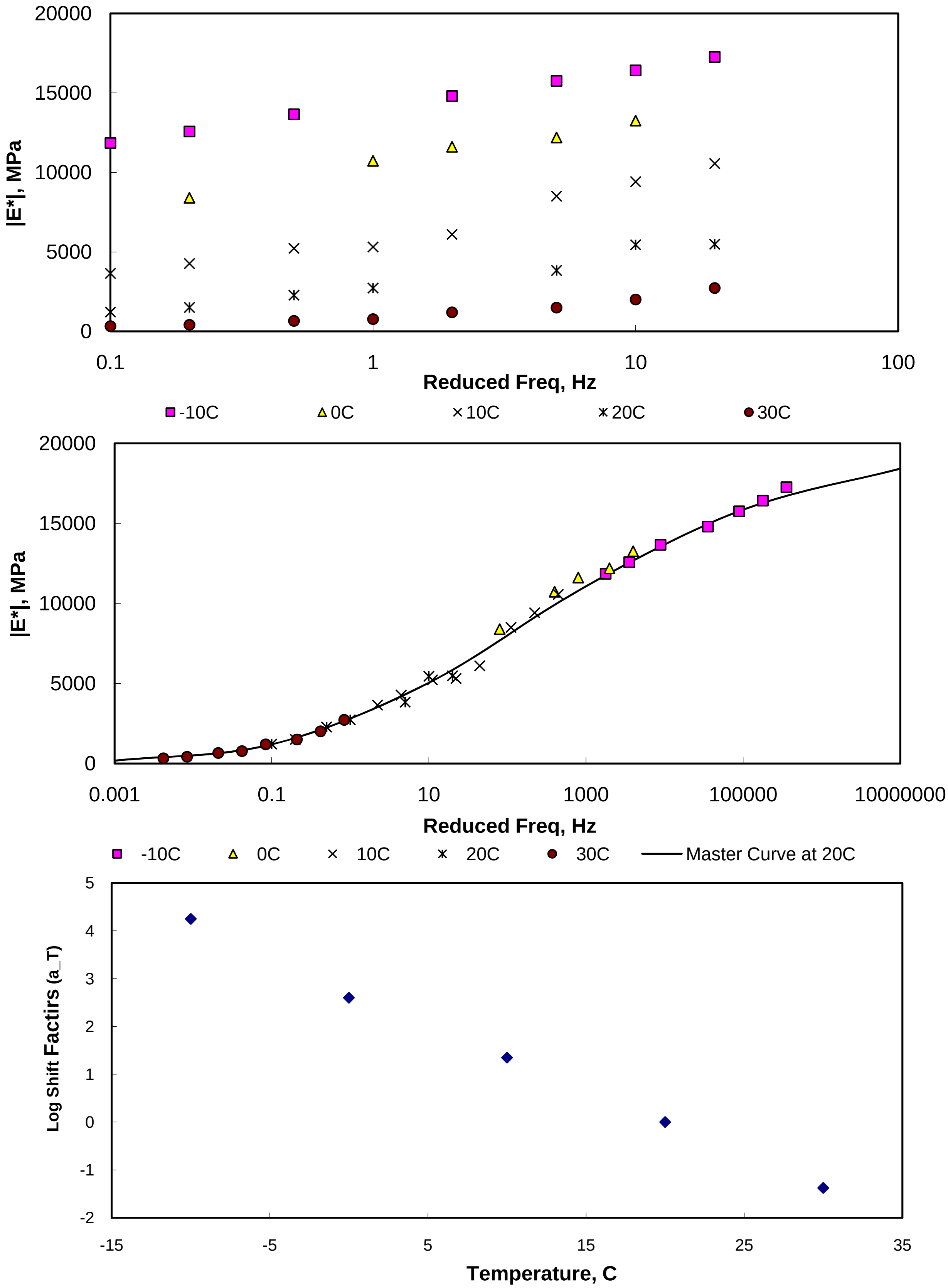
D7: ZTSA SSS - 40% RAP IDT dynamic modulus curves & shift factors



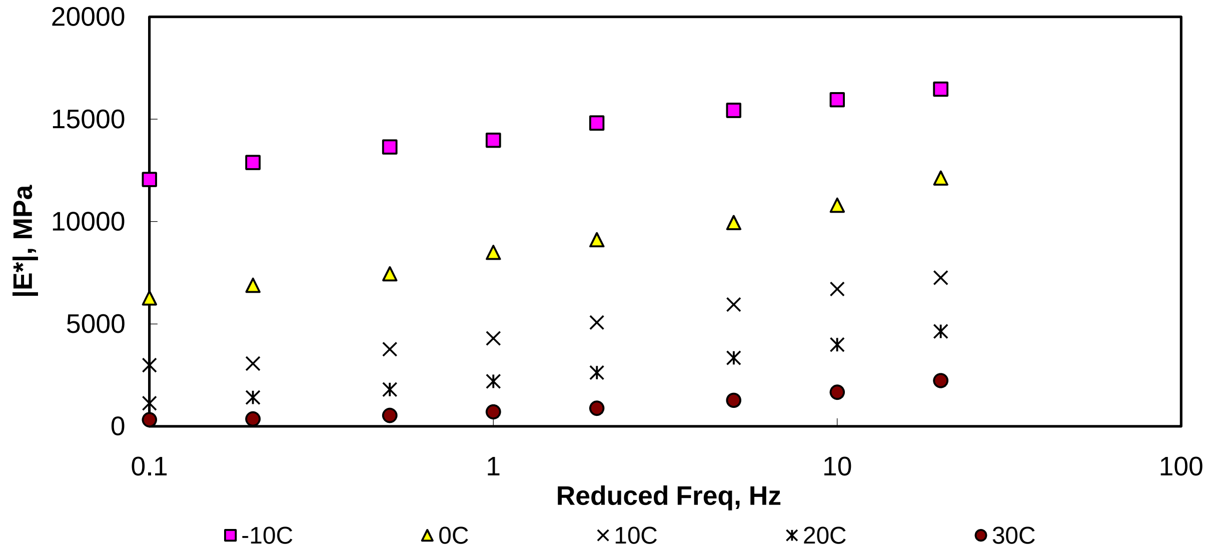
D8: ZTSF SSS - 40% RAP IDT dynamic modulus curves & shift factors

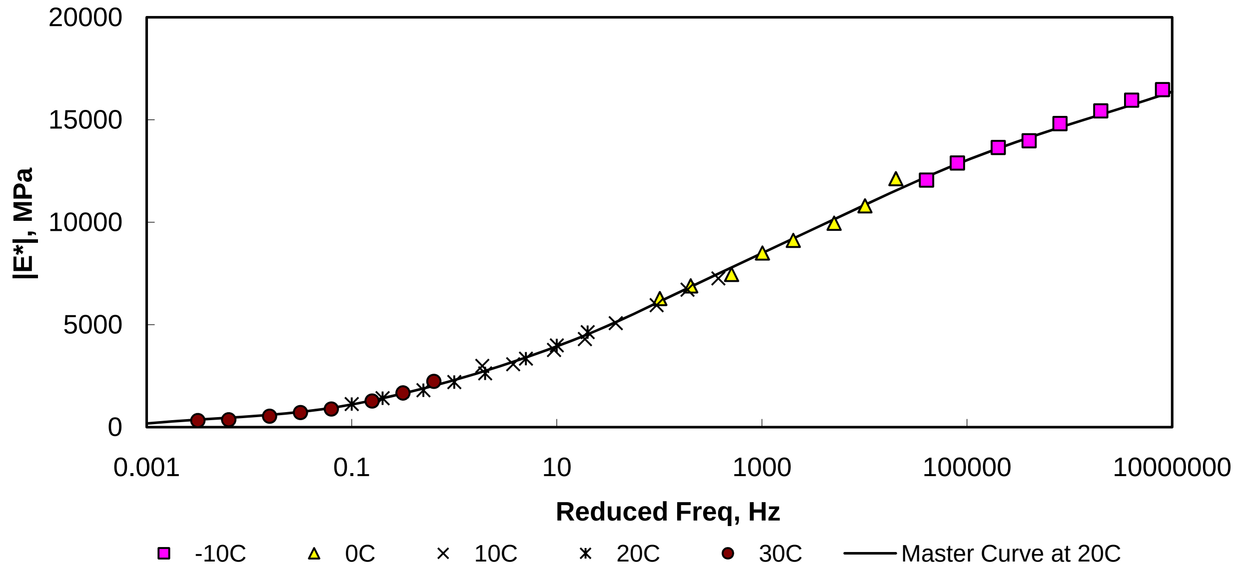


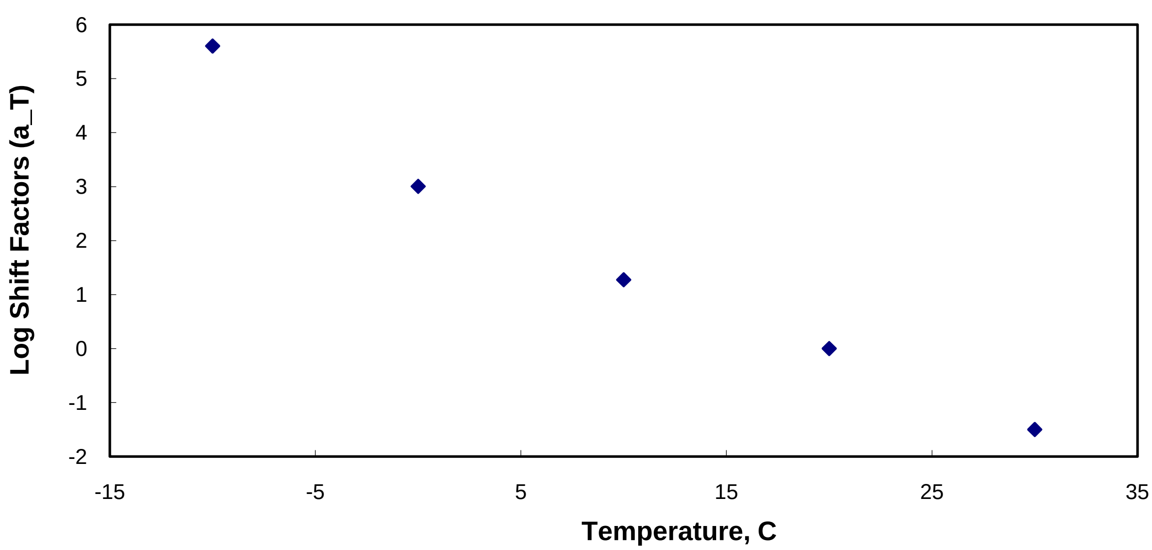
D9: FC2 SSS - 100% RAP IDT dynamic modulus curves & shift factors



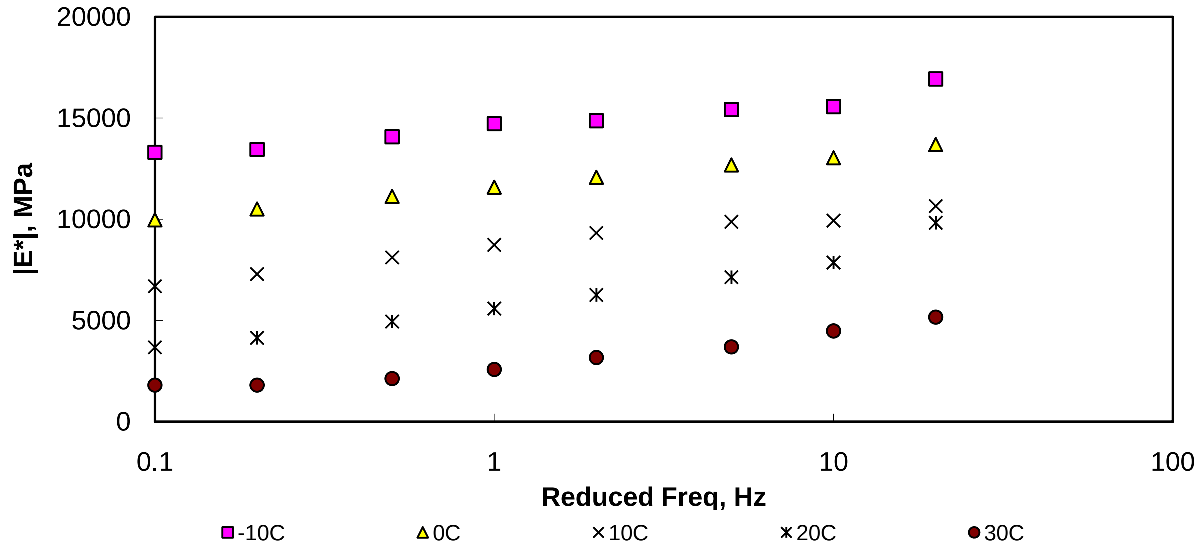
D10: FC3 SSS - 100% RAP IDT dynamic modulus curves & shift factors

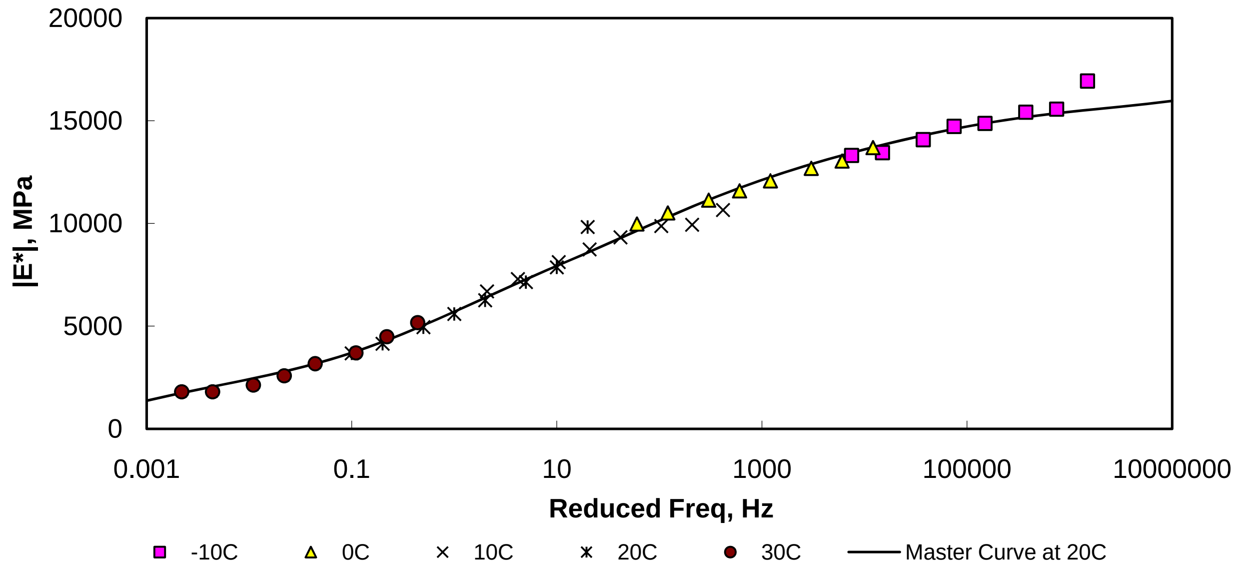


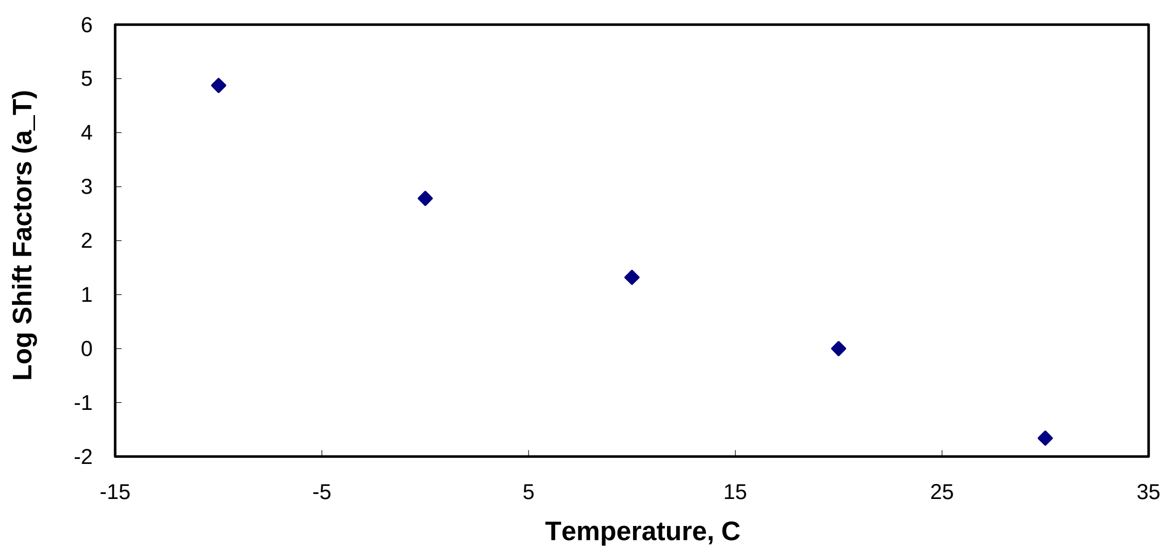




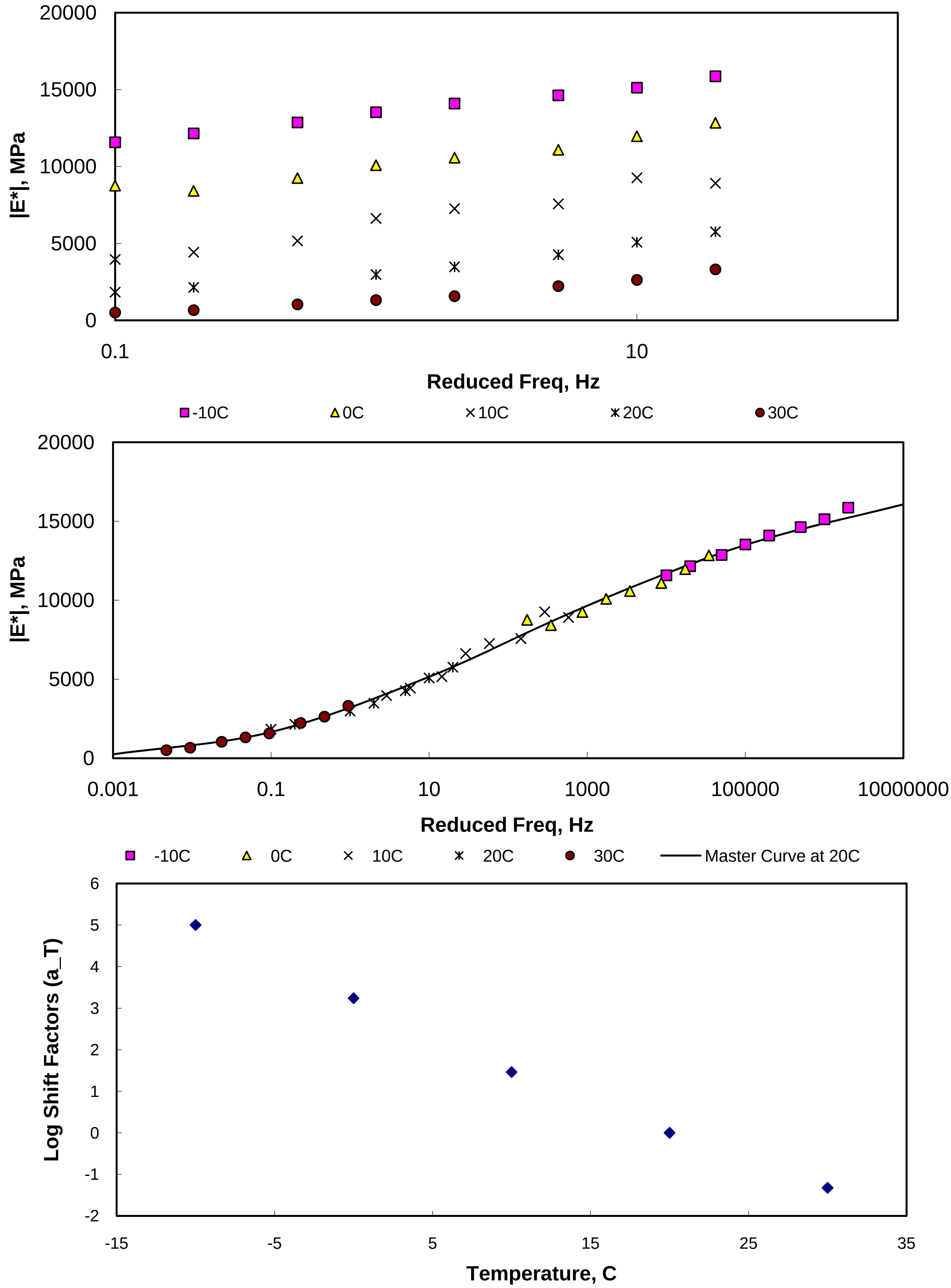
D11: FC4 SSS - 100% RAP IDT dynamic modulus curves & shift factors



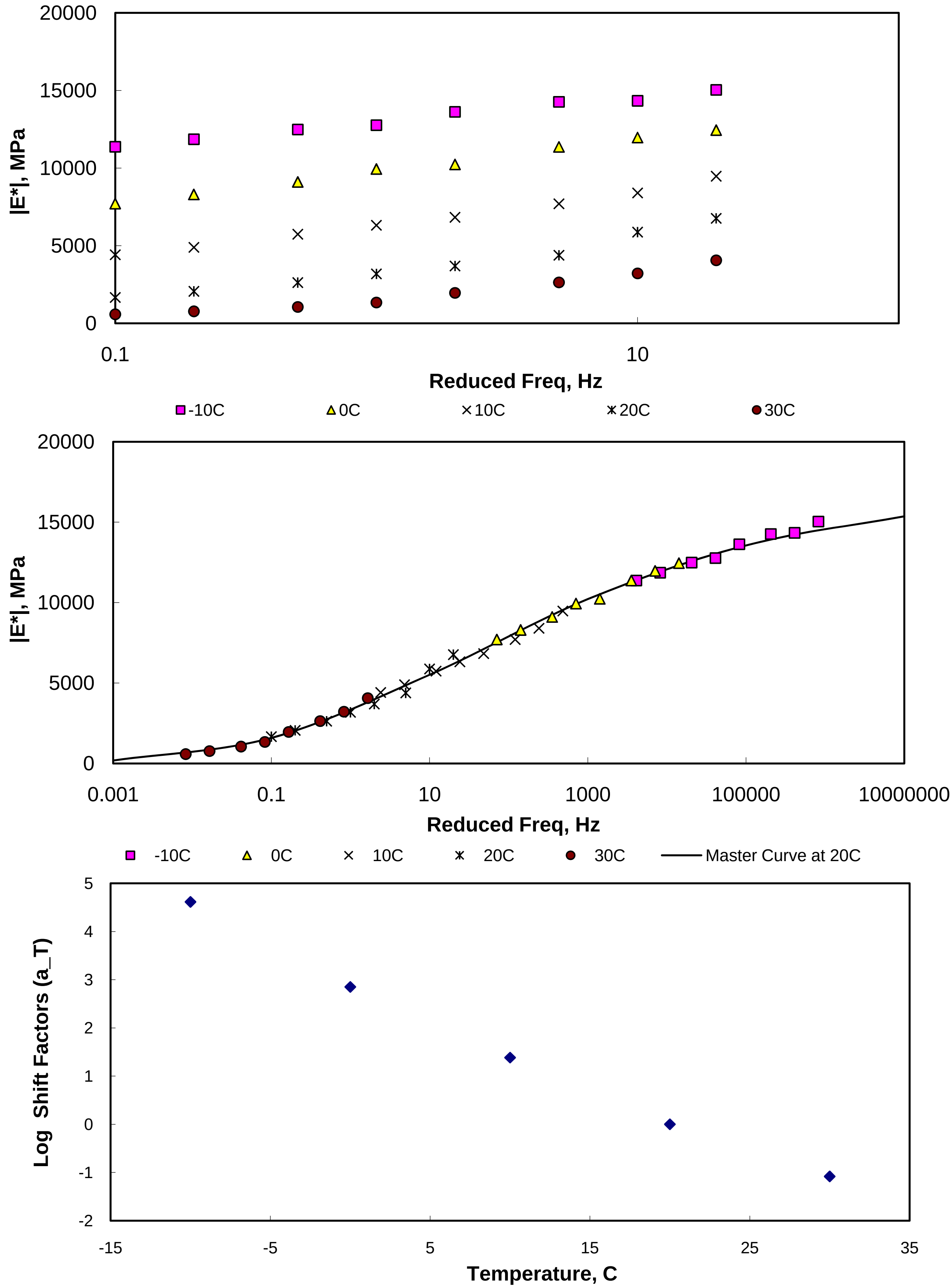




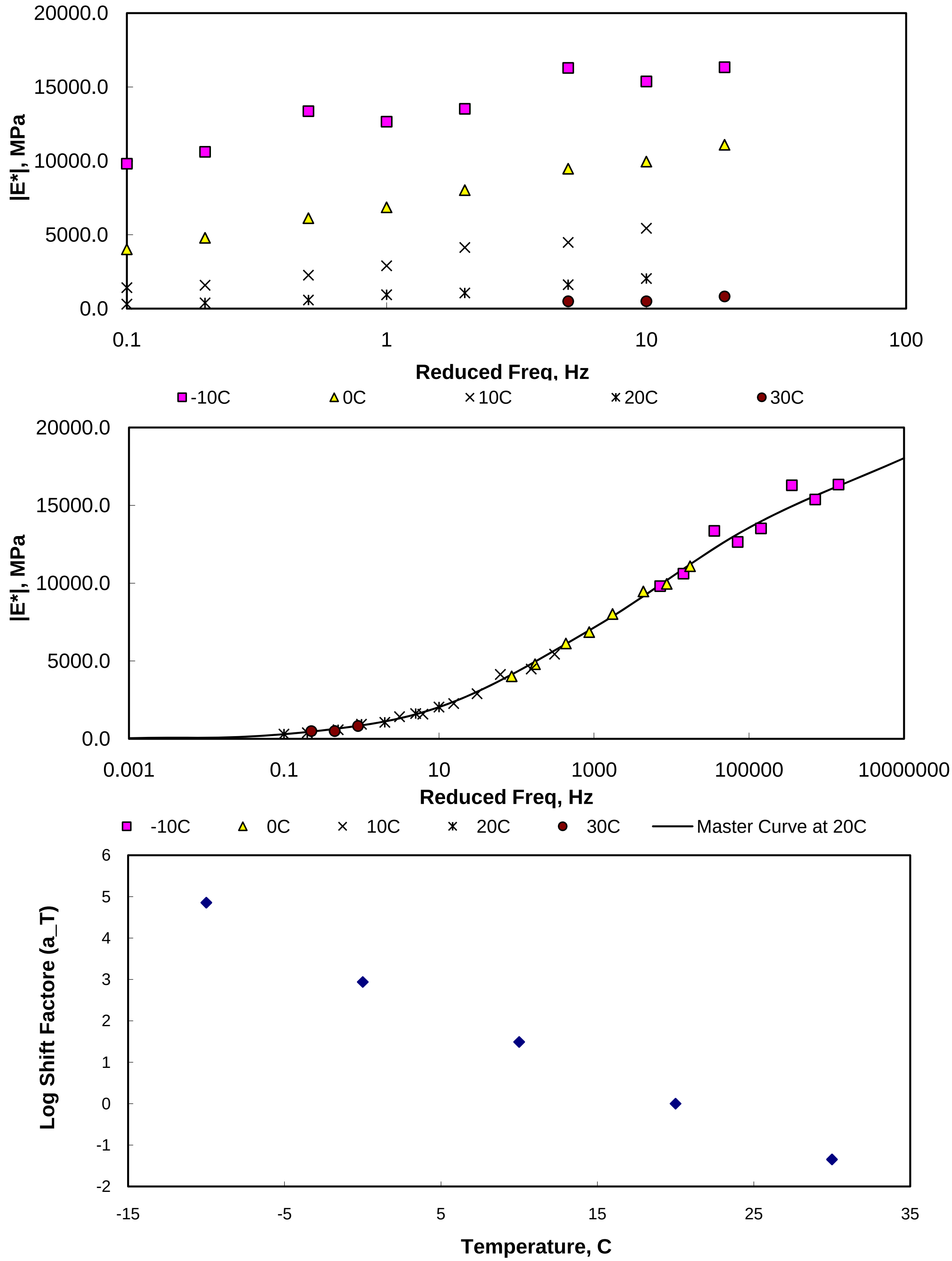
D12: FC5 RSS - 100% RAP IDT dynamic modulus curves & shift factors



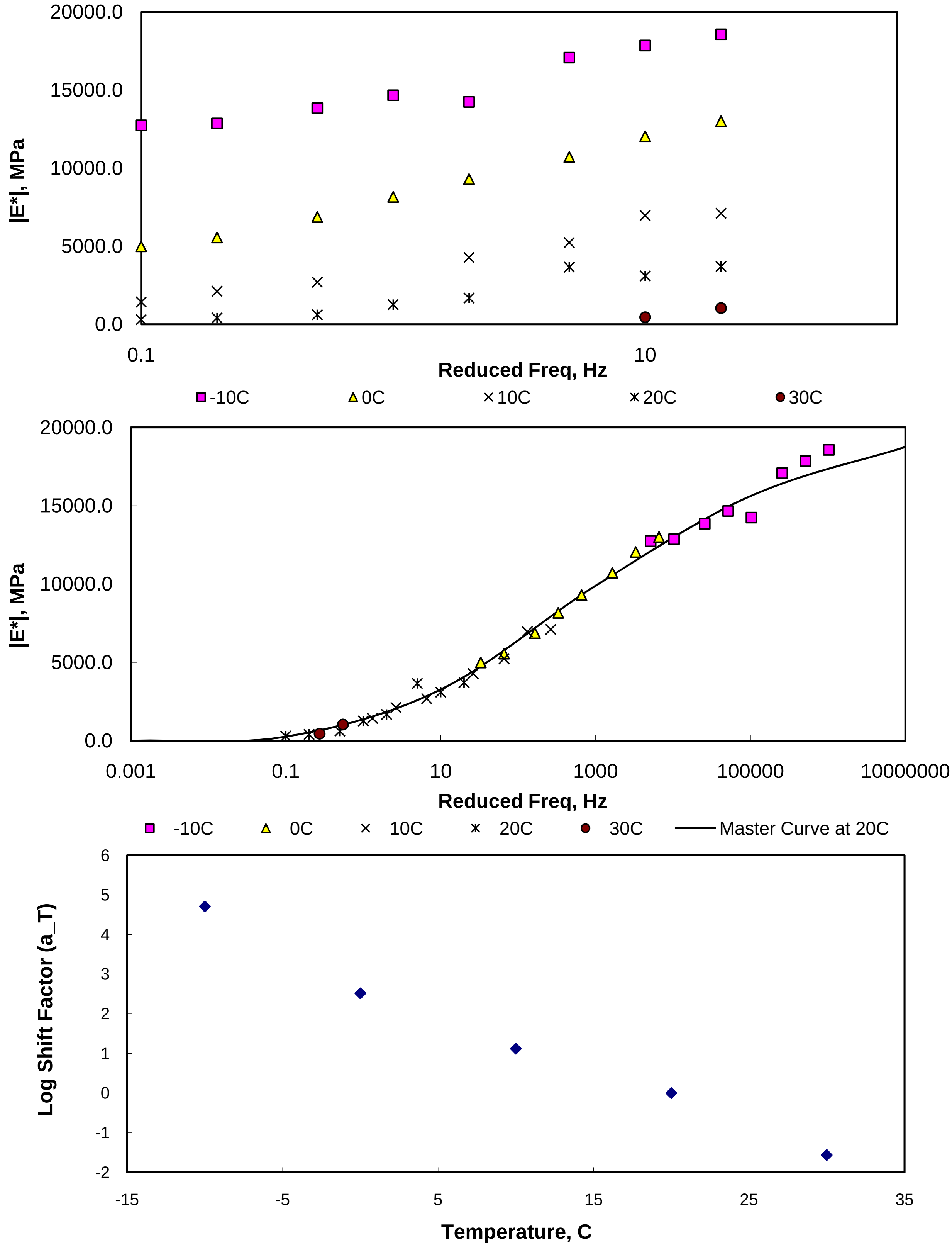
D13: FC6 SSS - 100% RAP IDT dynamic modulus curves & shift factors



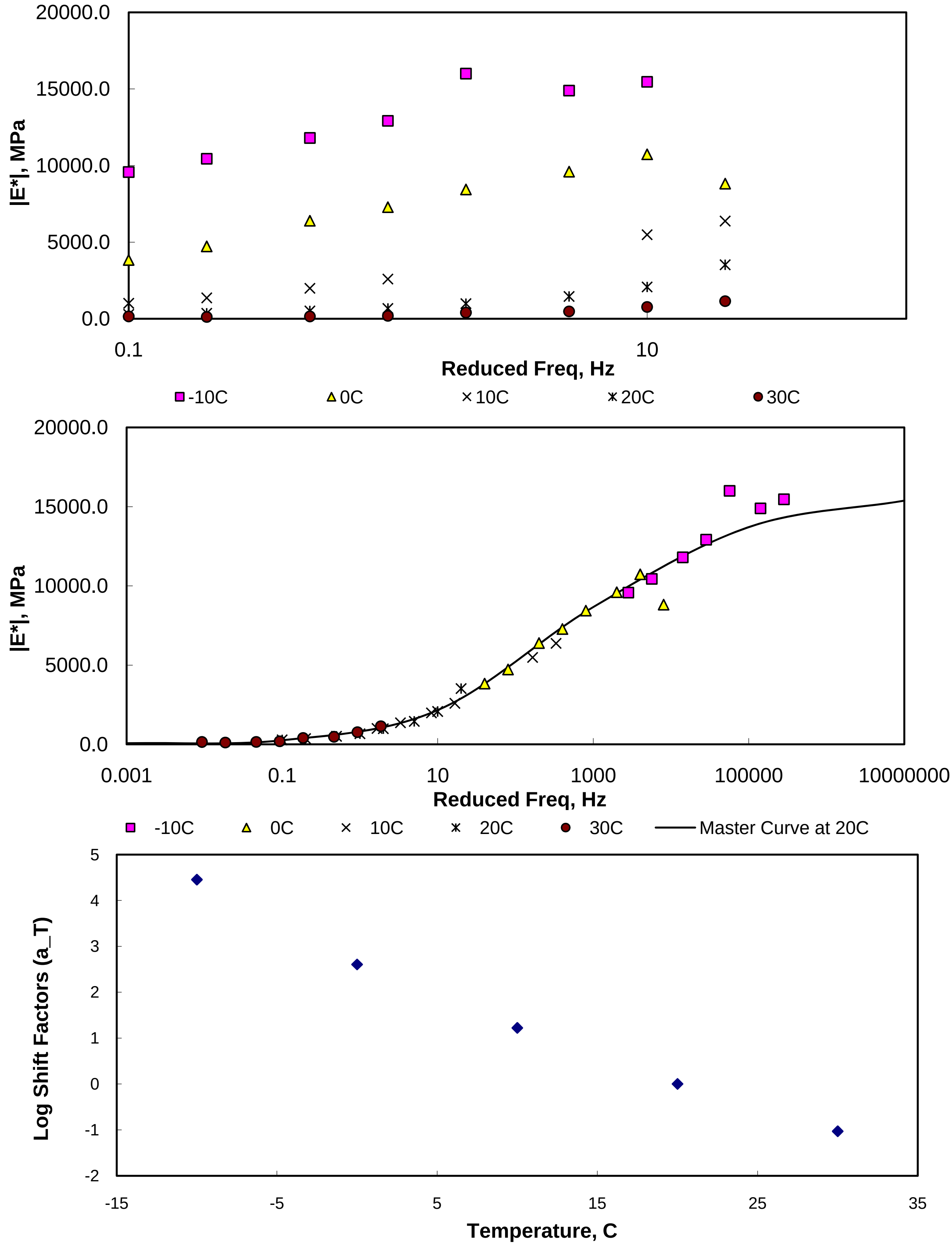
D14: FC7 RSS - 100% RAP IDT dynamic modulus curves & shift factors



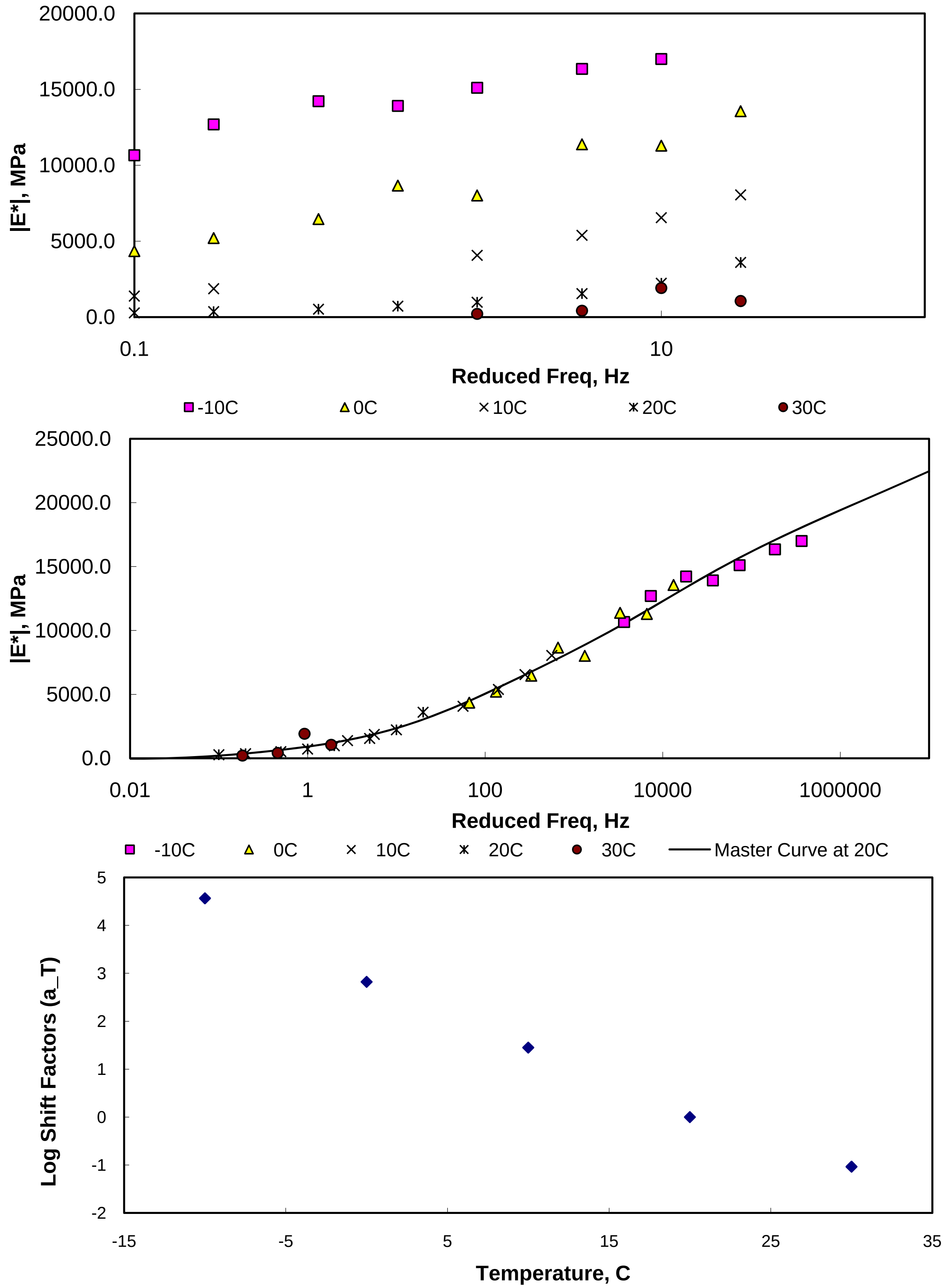
D15: NFC8 SSS - IDT dynamic modulus curves & shift factors, sample failed after 5Hz testing at 30°C



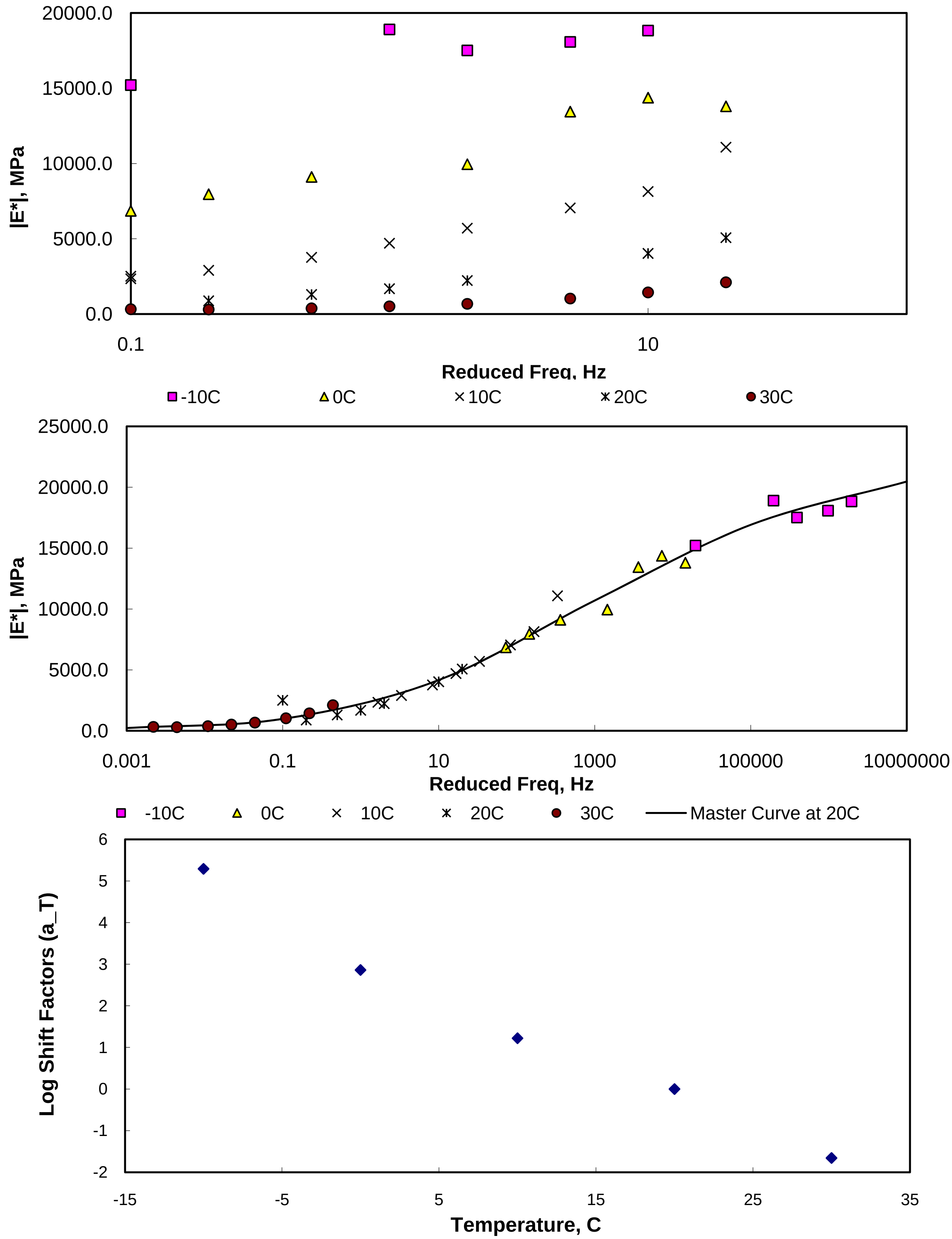
D16: NFC9 SSS - IDT dynamic modulus curves & shift factors, sample failed after 10Hz testing at 30℃



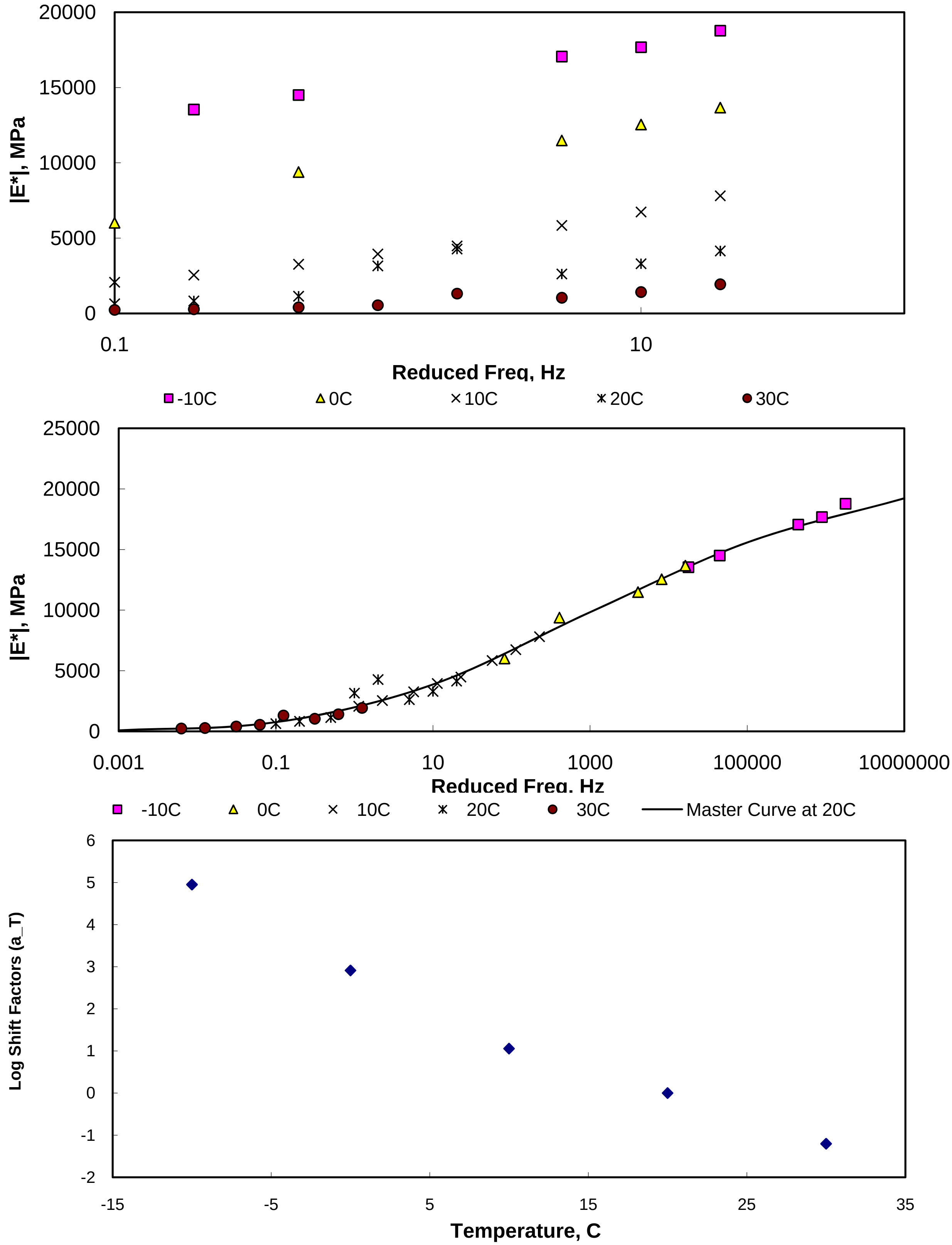
D17: NFC10 SSS - IDT dynamic modulus curves & shift factors



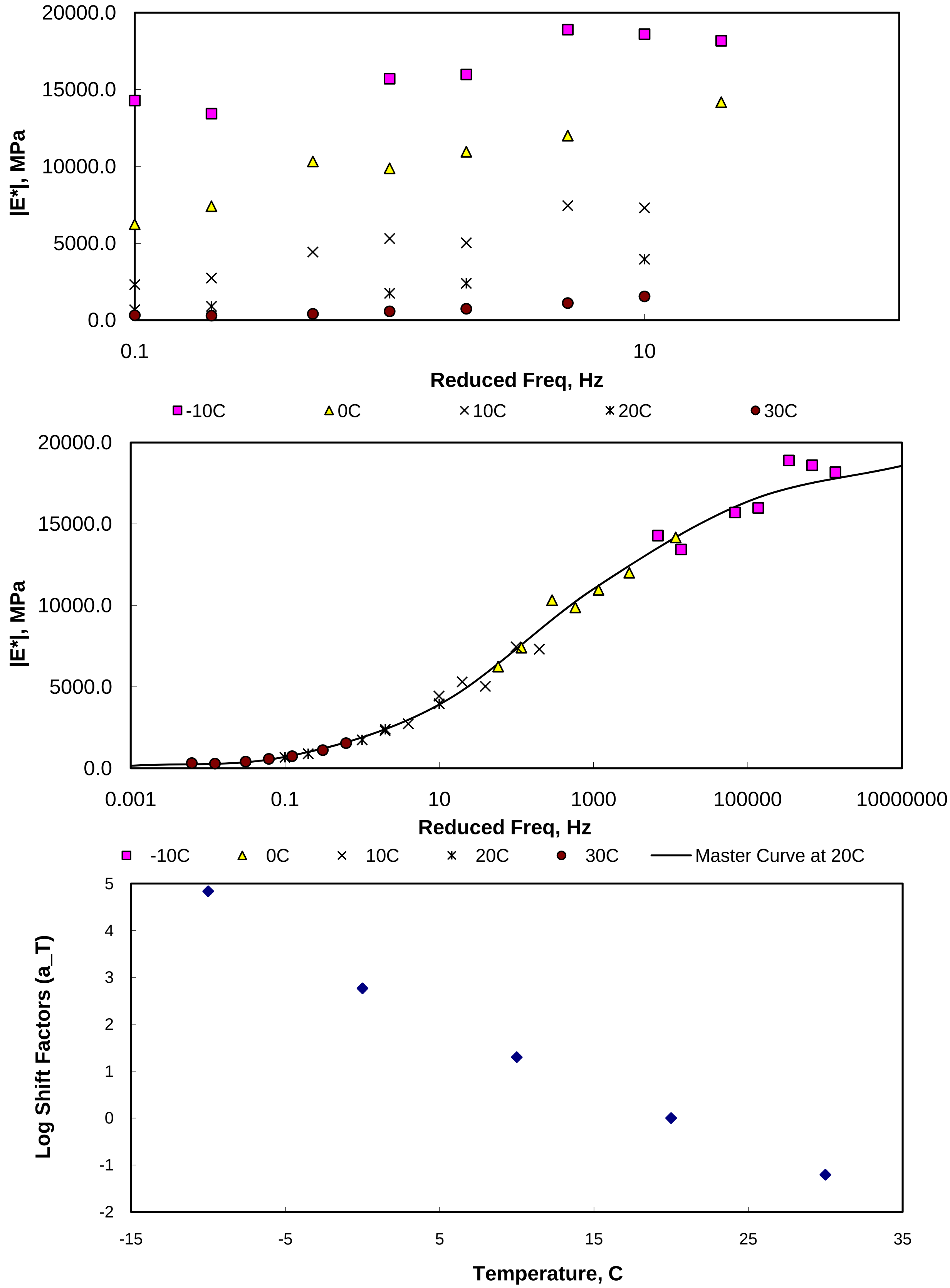
D18: NFC12 SSS - IDT dynamic modulus curves & shift factors, sample failed after 2Hz testing at 30℃



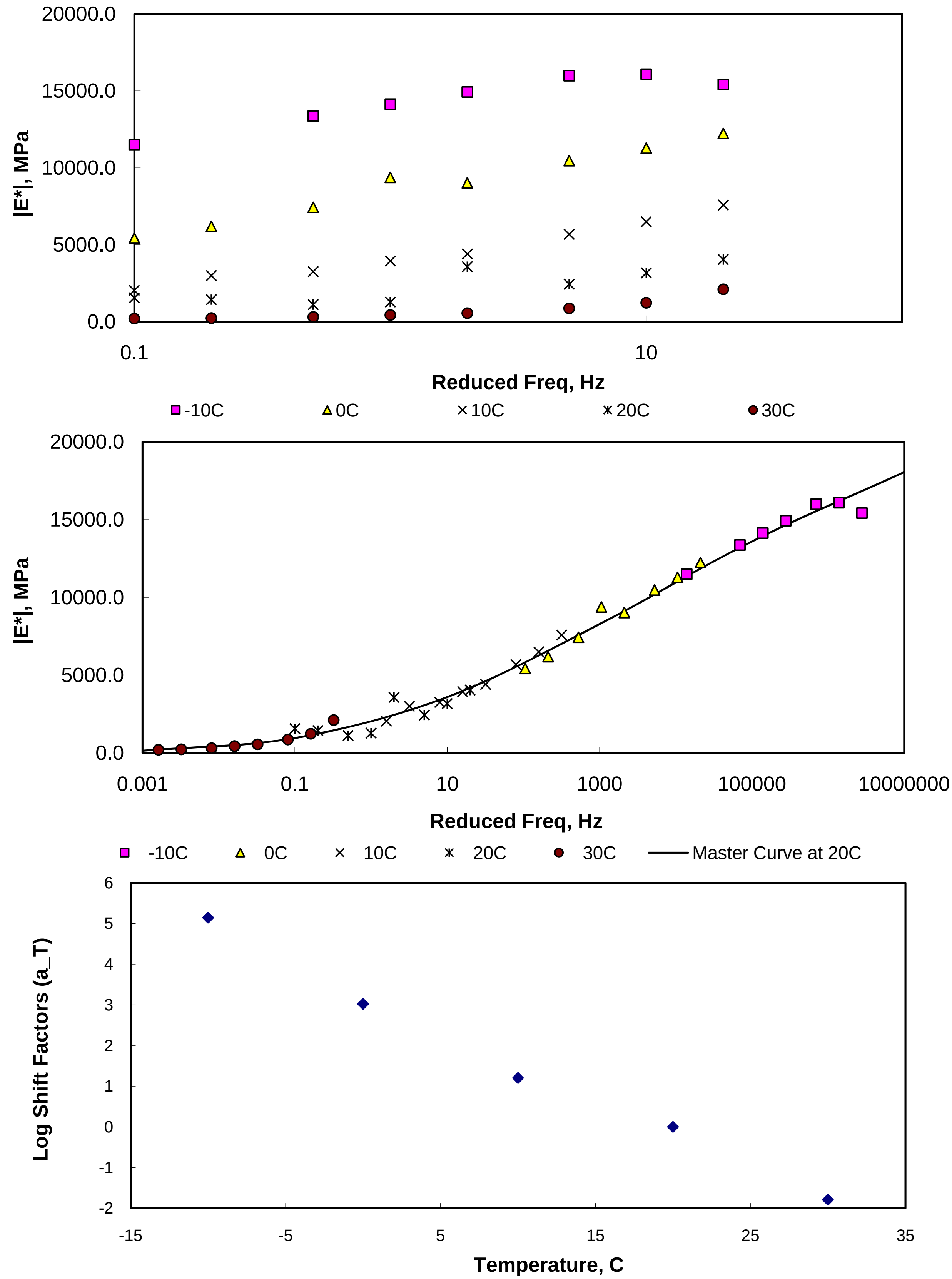
D19: PMTS5 SSS - IDT dynamic modulus curves & shift factors, sample failed after 2Hz testing at 30℃



D20: PMTS7 SSS - IDT dynamic modulus curves & shift factors



D21: PMTS8 SSS - IDT dynamic modulus curves & shift factors



D22: PMTS9 SSS - IDT dynamic modulus curves & shift factors

Appendix E – Mixture Properties used in MEPDG analysis

0% RAP Freq

Temp	0.1	1	10	25
10	2,084,867	2,381,550	2,581,071	2,638,912
40	707,807	1,183,970	1,668,998	1,843,327
70	92,156	242,114	539,656	701,219
100	15,384	40,512	112,548	166,351
125	6,709	14,910	39,101	58,769

15% RAP Freq

Temp	0.1	1	10	25
10	2,105,769	2,433,350	2,679,021	2,756,312
40	854,218	1,299,847	1,750,505	1,917,360
70	170,901	373,520	700,023	860,343
100	29,999	77,441	188,566	260,186
125	10,150	25,123	64,953	94,099

25% RAP Freq

Temp	0.1	1	10	25
10	2,264,062	2,643,936	2,946,819	3,046,846
40	846,059	1,312,959	1,799,150	1,984,949
70	151,765	367,804	714,347	883,343
100	21,583	79,795	224,544	315,902
125	6,503	29,723	103,193	156,928

40% RAP Freq

Temp	0.1	1	10	25
10	2,594,605	2,974,363	3,268,668	3,364,088
40	1,087,393	1,612,356	2,133,097	2,326,198
70	226,448	506,359	925,317	1,121,452
100	35,444	116,952	304,187	417,546
125	10,366	41,553	133,193	198,101

PMLC Freq

Temp	0.1	1	10	25
10	2,103,155	2,353,059	2,516,236	2,562,687
40	654,006	1,096,217	1,561,063	1,730,857
70	82,277	192,162	420,790	552,780
100	20,686	40,391	90,462	126,952
125	12,722	20,943	41,038	55,939

PMFC Freq

Temp	0.1	1	10	25
10	1,802,648	2,132,760	2,345,882	2,405,016
40	450,877	886,847	1,391,247	1,580,059
70	40,701	113,161	300,922	423,430
100	8,364	16,220	39,462	58,823
125	4,830	6,999	12,487	16,800