MOUNTAIN-PLAINS CONSORTIUM

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RELATION BETWEEN THE DYNAMIC MODULUS OF ASPHALT MATERIALS AND ITS CRACKING TOLERANCE INDEX

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16. Abstract

This report documents the effort to develop a practical relation between the cracking tolerance index and portions of the dynamic modulus curves of asphalt mixtures. A review of practices used to create asphalt mixtures' dynamic modulus master curves, based on NCHRP reports and other relevant literature, indicates that the dynamic modulus used as input to the AASHTOWare Pavement ME® software can be generated based on four parameters. A review of data from 34 different projects indicates that the asphalt mixtures used in Utah have consistent patterns that define the ranges of the parameters used to generate the dynamic modulus master curve. Furthermore, an analysis that was conducted indicated that, theoretically, there should be some relation between the cracking tolerance index and the dynamic modulus. The relation was verified using nine different asphalt mixtures. Based on the literature review, theoretical analysis, and laboratory experiments, it was concluded that the feasibility of predicting portions of the dynamic modulus master curve using only the cracking tolerance index is reasonable and can provide more accurate results than simply using default values. It is recommended that the results be verified using a different set of asphalt mixtures and that an actual predictive relation be developed.

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Relation Between the Dynamic Modulus of Asphalt Materials and Its Cracking Tolerance Index

Pedro Romero-Zambrana, Ph.D., P.E.

Department of Civil and Environmental Engineering
The University of Utah
Salt Lake City, Utah

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ABSTRACT

This report documents the effort to develop a practical relation between the cracking tolerance index and portions of the dynamic modulus curves of asphalt mixtures. A review of practices used to create asphalt mixtures' dynamic modulus master curves, based on NCHRP reports and other relevant literature, indicates that the dynamic modulus used as input to the AASHTOWare Pavement ME® software can be generated based on four parameters. A review of data from 34 different projects indicates that the asphalt mixtures used in Utah have consistent patterns that define the ranges of the parameters used to generate the dynamic modulus master curve. Furthermore, an analysis that was conducted indicated that, theoretically, there should be some relation between the cracking tolerance index and the dynamic modulus. The relation was verified using nine different asphalt mixtures. Based on the literature review, theoretical analysis, and laboratory experiments, it was concluded that the feasibility of predicting portions of the dynamic modulus master curve using only the cracking tolerance index is reasonable and can provide more accurate results than simply using default values. It is recommended that the results be verified using a different set of asphalt mixtures and that an actual predictive relation be developed.

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EXECUTIVE SUMMARY

This report outlines the development of relations between the IDEAL CT test results and the dynamic modulus of asphalt mixtures. In this report, which follows up a previous study, the theoretical results previously obtained were validated by measuring dynamic modulus and cracking tolerance index values on nine different mixtures. Six of the mixtures were standard UDOT surface mixtures prepared with PG 64-34 asphalt binders. One of the mixtures was a base layer prepared with PG 58-28 asphalt binder. The last two mixtures were laboratory-produced with PG 64-34 binder prepared according to different specifications.

The asphalt mixtures were tested and, based on the test results obtained, two relations were developed between two parameters, beta and gamma, which define the shape of the dynamic modulus master curve. The beta parameter relates to the cracking energy (area under the force deformation curve) and the gamma parameter relates to the cracking tolerance (CT) index. These variables were chosen because they had a Pearson's correlation greater than 80%.

Using the developed relations, the dynamic modulus master curve was predicted based on IDEAL CT results. The prediction resulted in an average absolute difference of 17.2% with respect to the measured values in eight of the nine mixtures at intermediate temperature. Larger differences were observed for the mixture prepared with the PG 58-28 asphalt binder, indicating that adjustments need to be made for different types of mixtures. Similarly, larger differences were observed at high and low-temperature values.

The ability to predict the dynamic master curve of asphalt mixtures from index-type tests like the IDEAL CT is significant since it can reduce the effort needed to obtain inputs to AASHTOWare Pavement ME®. While measuring the actual dynamic modulus of asphalt mixtures continues to be the preferred option, the complexities and time demands of such a test make the use of simplified relations, albeit imperfect, a very attractive option to provide the required inputs without relying on averages or default values. Furthermore, such a relation also allows one to relate the pavement design properties to the mixture design, which can lead to more cost-effective pavements thanks to site-specific life-cycle analysis.

This work resulted in the following: theoretical relations were validated using nine different asphalt mixtures, a relation was developed that predicts the dynamic modulus of asphalt mixtures using IDEAL CT data, dynamic modulus master curves were simulated using IDEAL CT data and compared to actual dynamic modulus data.

The conclusion of this work is that there are relations between different tests and that the dynamic modulus of asphalt mixtures can be predicted within acceptable accuracy, especially at intermediate temperatures, using only the IDEAL-CT test for a specific type of mixture. However, further work is needed to expand the work to different mixtures and to different temperatures.

1. INTRODUCTION

1.1 Background

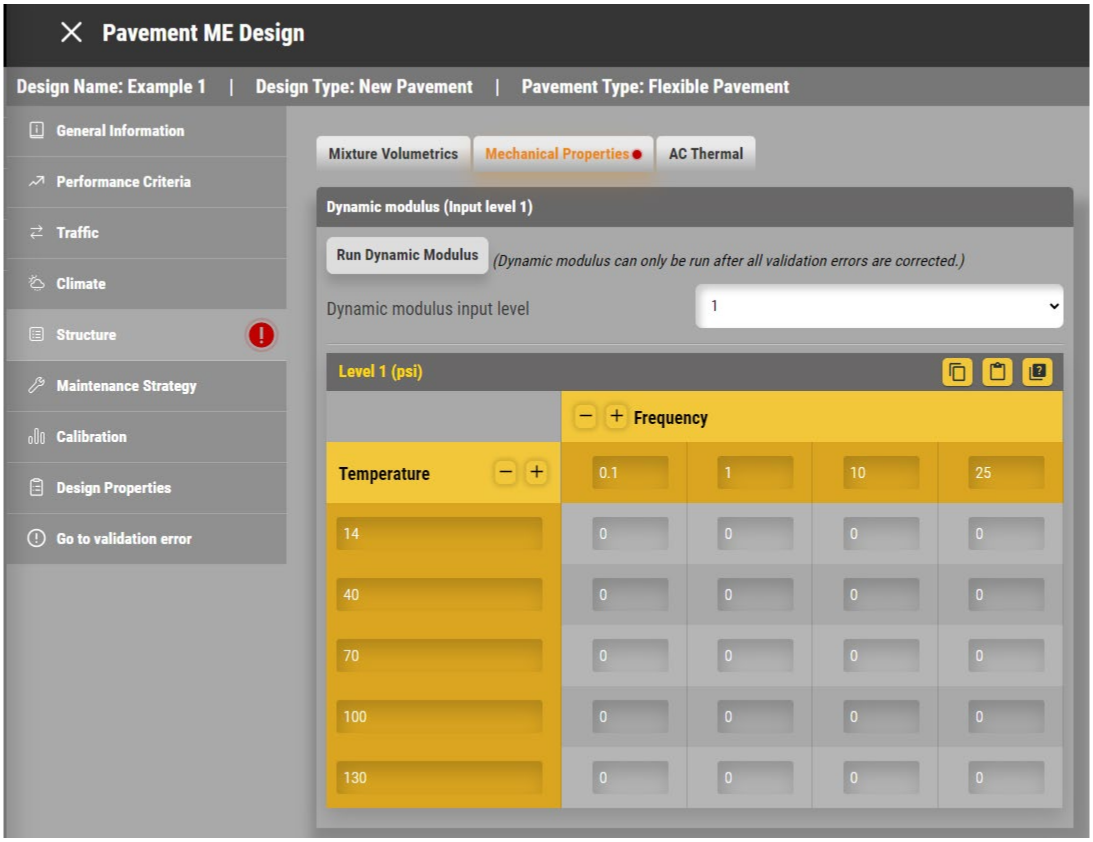
For more than a century, industry has sought a pavement design system that can, rationally and realistically, account for new and innovative use of materials, advanced construction practices, and a lower environmental footprint that incorporates recycled materials [1]. While there have been many advances throughout the years, there are still many unknowns requiring gross extrapolations. Perhaps no other quote best describes the process of pavement design as the one provided by Dr. A.R. Dykes: "The art of modeling materials we do not wholly understand, into shapes we cannot precisely analyze, so as to withstand forces we cannot properly assess, in such a way that the public has no reason to suspect the extent of our ignorance." [2] This limitation in the existing knowledge has led to conservative, overdesigned structures or, worse yet, premature failures.

The mechanistic-empirical pavement design process promises to close some of the gaps in knowledge in the structural (i.e., thickness) design process by incorporating both concepts of mechanics of materials and expected performance [3]. However, material characterization for mechanistic modeling requires knowledge of the material modulus (often referred to as stiffness) and Poisson's ratio at the conditions expected during the analysis. Asphalt concrete is a thermo-viscoelastic material, meaning that the response of the material depends on both the temperature and the loading rate (as related to traffic speed); therefore, characterization of material properties can be quite complex, and simplifications are often made.

Conceptually, there are many methods that can be used to obtain the required properties; however, most agencies involved in designing pavements follow the recommendations given as part of the Mechanistic Empirical Pavement Design Guide (MEPDG) [4]. The term MEPDG generally refers to both the procedure developed, including the software, and the documentation that describes the process. As part of the MEPDG, the asphalt concrete is characterized using its dynamic modulus.

The dynamic modulus is most likely obtained by using the Asphalt Mixture Performance Tester (AMPT). Once the properties of asphalt mixtures have been obtained using the AMPT, the dynamic modulus is modeled using a sigmoidal (i.e., s-shaped) equation and used as input in pavement design for AASHTOWare Pavement ME® [5], [6]. The required input for dynamic modulus in the latest version of the AASHTOWare Pavement ME ® is shown in Figure 1.1.

The process of pavement design contains many assumptions; most of them are related to the modeling process (mechanistic models, material characterization models, and damage models). These assumptions are well understood and common to most engineering processes. However, one important assumption that is often overlooked is the requirement that the material being tested in the AMPT, and used as input in the pavement design process, be the same material that is used to actually build the pavement. Pavement designs are done in advance of construction, making this a questionable assumption. Arguments are often made that the materials characterized for the design are "similar" to the one that will be used during construction. It is not clear what the term similar means but it should be evident that modeling a different material than the one actually used to build the pavement will result in meaningless performance predictions and flawed designs.



Design Name: Example 1 | Design Type: New Pavement | Pavement Type: Flexible Pavement

Dynamic modulus (Input level 1)

(Dynamic modulus can only be run after all validation errors are corrected.)

Dynamic modulus input level: 1

Level 1 (psi)

	Frequency			
Temperature	0.1	1	10	25
14	0	0	0	0
40	0	0	0	0
70	0	0	0	0
100	0	0	0	0
130	0	0	0	0

Figure 1.1 AASHTOWare Pavement ME Input Requirement for Dynamic Modulus

One possible solution to the discrepancy of having different materials used during the design and during the construction could be to force the contractor to use a material that is within certain limits of the one used in design. This would have to be verified by collecting and testing the materials during the construction process. Material can be collected from the construction site and brought to the lab where its properties can be quantified so the predictions can be adjusted and penalties or incentives assessed. In essence, this implies using the AMPT as a quality control test [7], [8]. While this is conceptually possible, the complexities of material characterization using the AMPT make such actions impractical. Fabrication of the asphalt concrete samples needed to perform the dynamic modulus test is time consuming and resource intensive. It requires compaction of the material to a known density, coring and cutting to obtain the right sample dimensions (100 mm diameter, 100 mm high), and instrumenting the cylindrical asphalt concrete sample. Once the samples have been instrumented, they have to be conditioned at the required temperature and, at each temperature, they are tested at different loading frequencies with the lower frequencies requiring a long time (frequency is the inverse of period or duration). This means that, even if agencies have the resources to test the material using the AMPT, the time and effort to do it makes the idea unrealistic to implement. Furthermore, AMPT machines are not readily available; for example, at present, there is only one functioning AMPT machine in the state of Utah since efforts at the University of Utah to upgrade another machine were unsuccessful.

The net result of these issues is that pavement design is done using average or default material properties (generally referred to as Level 3 inputs) that might or might not be the same as the material being used for construction. Besides the obvious consequences of inaccurate performance predictions, any opportunity for optimization or life-cycle analysis is lost. An alternative that balances rigor with practicality is desired.

1.2 Objectives

The objective of this research is to develop a relation that will allow the incorporation of mix-design/quality-control tests into the pavement design process and thus allow for more robust designs that can be optimized for specific, local materials. The incorporation of mix-design/quality-control tests into the pavement design process will be accomplished by developing a relation between single-point or index-type tests, such as the Hamburg Wheel Tracking (HWT) device, the IDEAL CT, and the Bending Beam Rheometer (BBR), which are used during mix design and/or quality control, and the parameters used to characterize a dynamic modulus master curve. While it is well understood that single-point or quality-control tests do not provide the same level of information obtained from the dynamic modulus, mix-specific relations would result in great improvement over current practices of using average or default values.

The specific objectives of this project are:

- Validate the theoretical and experimental results previously obtained using asphalt mixtures with different properties
- Develop a relation to predict the asphalt mixtures' dynamic modulus master curve using IDEAL CT data.
- Simulate dynamic modulus master curves from different mixtures using IDEAL CT data. Compare the simulated values to measured values.
- Propose a framework to incorporate tests at other temperatures.

1.3 Scope

Six asphalt mixtures were obtained as part of a previous study. All were tested using the IDEAL CT and three were tested to determine the dynamic modulus. All six mixtures were prepared with the same binder grade formulated based on Utah specifications.

The scope of this project is to determine the dynamic modulus of the remaining mixtures and test new mixtures that are different enough to provide a range of properties that will allow proper model development and validation of results.

2. RESEARCH METHODOLOGY

2.1 Overview

This chapter provides a summary of the research methodology associated with this work. It provides a short review and an overview of the proposed approach. A more comprehensive review of tests and procedures can be found in an earlier report [9].

2.2 AMPT Testing

As part of the MEPDG, the asphalt concrete is characterized using its dynamic modulus, E*. This property is most likely obtained by using the asphalt mixture performance tester (AMPT). This machine, shown in Figure 2.1, was developed through several NCHRP projects and is specifically designed to measure the E* of asphalt concrete [5], [6].

Figure 2.1 AMPT Machine

The AMPT applies a continuous sinusoidal (or haversine), stress-controlled loading at various frequencies and temperatures to a laboratory-prepared asphalt concrete cylinder. The results collected from the different frequencies and temperatures are fitted to an equation that represents the dynamic modulus master curve. This equation describes the modulus of asphalt concrete for any combination of temperature and loading rate. The construction of this equation was standardized in AASHTO PP61: Standard Practice for Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Using the Asphalt Mixture Performance Tester. The process of creating a dynamic modulus master curve is represented in Figure 2.2.

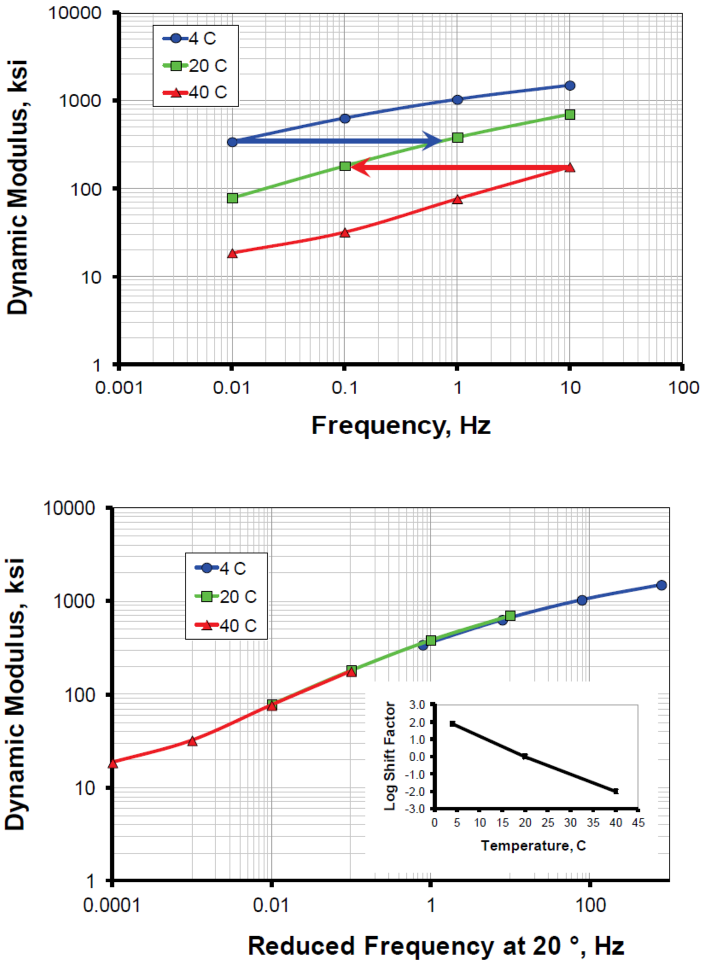


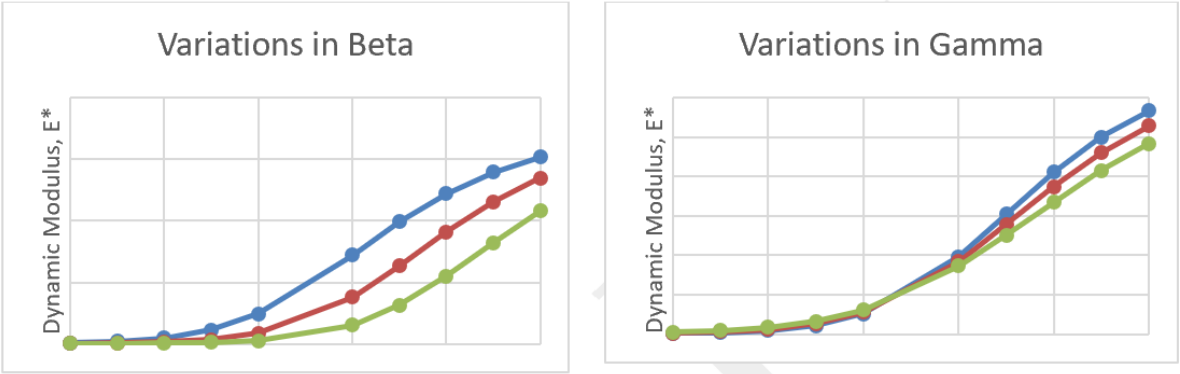
Figure 2.2 Schematic of Dynamic Master Curve Developed from Multiple Frequencies and Temperatures

2.2.1 Dynamic Modulus Master Curve

The material characterization for pavement design requires the dynamic modulus of compacted asphalt mixtures at a wide range of loading frequencies and temperatures. This is done by fitting the data obtained from AMPT testing to Equation 1 [6].

$$log|E^*| = \delta + \frac{(Max-\delta)}{1+e^{\beta+\gamma log\omega_r}}$$ Equation 1

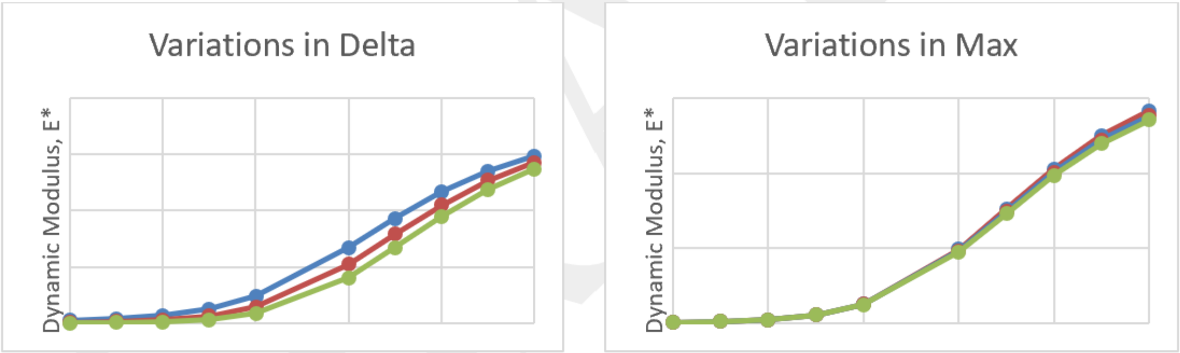
In this equation, the dynamic modulus, E*, is predicted as a function of reduced frequency, ω_r, based on four fitted parameters: δ (limiting minimum modulus), β, γ, and Max (limiting maximum modulus). In other words, the dynamic modulus master curve can be adequately described using only four parameters plus the time-temperature shift factor. The shift factor is used to obtain the reduced frequency from the test frequency through an equation based on the activation energy, ΔEA. The effect of each parameter of the dynamic modulus master curve equation is shown in Figure 2.3.


Variations in Beta

Variations in Gamma

a) Effect of beta parameter

b) Effect of gamma parameter


Variations in Delta

Variations in Max

c) Effect of minimum modulus parameter

d) Effect of maximum modulus parameter

Figure 2.3 Effect of Equation Parameters on the Shape of the predicted E* Master Curve.

The curves shown in Figure 2.3 were obtained by varying each parameter within ranges obtained from previous testing while keeping the other parameters fixed. The values of these parameters are not unlimited; previous testing done on asphalt mixtures obtained from 34 different projects in Utah indicated that the variation of the dynamic modulus master curve falls within specific ranges shown in Table 2.1 [9].

Table 2.1 Ranges in Master Curve Equation Parameters

Parameter	PG 70-28		-	PG 64-34		-
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
Max E* (ksi)	3384	3419	3409	3317	3438	3376
Delta (ksi)	2.26	5.31	3.09	0.58	19.27	4.71
Beta	-1.43	-0.83	-1.25	-1.02	-0.29	-0.76
Gamma	-0.52	-0.50	-0.51	-0.59	-0.40	-0.50
ΔEA	197113	211628	201180	183761	205113	195287

Figure 2.3 makes it clear that the variation in the parameter beta has a significant influence in the shape of the curve. Different values of beta result in different dynamic modulus at a given temperature and frequency. This parameter shows such significance because it is a shape factor with greater range in possible values in comparison with the other parameters. As shown in Table 2.1, for mixtures made with

PG 64-34 binders, the beta parameter can vary between -1.02 and -0.29 with an average of -0.76. In comparison, the gamma parameter only varies between -0.59 and -0.40 with an average of 0.50. The delta, or limiting minimum modulus, also seems to have a wide range but, due to the function characteristics, its influence in dynamic modulus is less significant.

In order to establish the dynamic modulus master curve, the five parameters listed on Table 2.1 need to be obtained. It is recognized that the parameters have some dependency on each other; nonetheless, each parameter relates to a specific characteristic (or portion) of the master curve. It can also be shown that, based on the time-temperature superposition principle, certain portions (i.e., frequencies) of the master curve are related to the behavior of the material at a specific temperature. For practical purposes this means that the HWT results, which are obtained at a temperature of 50°C, relate to the lower frequencies of the curve and thus to the delta, or minimum E*, parameter. Similarly, the CT index obtained at 25°C relates to the intermediate frequencies of the curve and thus the beta and gamma parameters. The creep modulus of the mixture obtained at temperatures below 0°C relate to the high frequencies of the curve and thus the Max E* and gamma parameters. Finally, any test property obtained at least at two different temperatures could help predict the shift factor, although other considerations are possible.

2.3 Material Design and Testing

The asphalt concrete used to construct pavements is a combination of aggregates and asphalt binder blended following some established specifications. These specifications are in place to ensure that the materials meet strength and durability requirements. Most specifications describe the process for determining the proportions of all materials but, more recently, they also incorporate some form of mechanical testing. The mechanical tests are meant to verify the ability of the material to withstand specific distresses such as excessive rutting at high in-service temperatures, cracking at intermediate temperatures, and cracking at low in-service temperatures. While some of these tests are based on a mechanical response, the analysis is often simplified, resulting in pass/fail indices. Also note that, even though the tests can be thought of as a verification step of the asphalt mix, the requirements needed to pass these tests affect the asphalt mixture design and optimization process (i.e., mixtures are formulated to pass the established test limits). Having different thresholds or limits would result in different mix formulations and novel designs with different dynamic modulus master curves. Three of these tests used for material specifications are the HWT device, the IDEAL CT, and the BBR on mixtures.

2.3.1 Hamburg Wheel Tracking Device

The HWT device is used to control the high in-service temperature performance of the asphalt mixtures. The test consists of a steel wheel that rolls back and forth over the submerged surface of a compacted asphalt mix specimen at a temperature of 50°C. As the rut caused by the wheel increases, the distance traversed across the path varies and the contact area between the wheel and the asphalt sample increases with the number of passes. This results in variable contact stress that is difficult to analyze using mechanics of materials (thus the pass/fail criteria). The specification allows for a maximum impression of the wheel (e.g., 10 mm) after a certain number of passes (e.g., 20,000) [10].

2.3.2 IDEAL CT and Cracking Tolerance Index

The IDEAL CT is an indirect tensile test that measures the force required to split a compacted cylindrical specimen and the corresponding displacement at 25°C. The area under the force-displacement curve and the post-peak slope are used to calculate the cracking tolerance index (CT Index) that is reported to be related to intermediate temperature cracking (often referred to as load-related or fatigue cracking) [11]. This test has gained popularity due to its simplicity, although questions still exist regarding its actual relation to field cracking.

2.3.3 Bending Beam Rheometer

The BBR tests on mixtures, often referred to as the "sliver test," measures the creep compliance of a thin asphalt concrete beam (i.e., sliver) at low temperatures (below 0°C). Higher compliance (lower modulus) results in better resistance to thermal cracking [12]. The creep compliance is a time-dependent property and can be related to frequency-dependent properties such as E* through either mathematical or semi-empirical relations.

2.4 Relation Between Single Point/Index Tests and Dynamic Modulus

As explained in the objectives, this work seeks to relate the different tests described in the previous chapter to the dynamic modulus of asphalt mixtures. While it is clearly understood that the mode and rate of loading of each test are different, work by Chen et al. and by Walubita et al. demonstrated that relations exist between different test modes [13], [14]. Furthermore, it was hypothesized, based on simplified assumptions, that the response of an object from the work done during a mechanical test is a way to transfer energy from one form to another. The transfer of energy can result in a new surface, material flow, heat, etc. Based on the assumption that the system losses are relatively small, the following relation, relating the results from the IDEAL CT tests and the dynamic modulus, was proposed [9].

$$\Delta W \propto \frac{sin(2\delta)}{E^*} \qquad \text{Equation 2}$$

In this equation, ΔW is the area under the load-displacement plot obtained from IDEAL CT tests, E* and δ are the dynamic modulus and the phase angle obtained from AMPT tests, respectively. In other words, it is reasonable to hypothesize that the results from IDEAL CT tests can be inversely related to dynamic modulus. This hypothesis was tested and encouraging results were obtained during previous work [9].

2.5 Summary

This chapter provides a summary of the research methodology that is being followed. It describes how the dynamic modulus is modeled using a sigmoidal (s-shaped) equation and how the different parameters that define the equation affect the dynamic modulus master curve. The chapter also describes the different tests used during mix design and explains how each test should relate to a specific frequency and temperature. While it is understood that different tests are based on very different modes of loading, there is no reason relations cannot exist. A mixture with high modulus at the relevant temperature and frequency should show less rutting, and a mixture with low modulus at the relevant temperature and frequency should show less cracking; monotonic/index-type tests should also follow similar patterns.

3. MATERIALS AND DATA

3.1 Overview

This chapter describes the materials used in this study and provides the results from testing done on them. Testing consisted of determining the dynamic modulus and the cracking tolerance index.

3.2 Materials

Seven plant-produced asphalt mixtures and two laboratory-produced mixtures were tested. The two laboratory-produced mixtures have binders produced based on different specifications.

3.2.1 Mixture Properties

The plant-produced mixtures (Mix #1 through Mix #6) came from different suppliers. The mixtures were prepared using PG 64-34 asphalt binders formulated according to UDOT specifications. Each mixture had a different aggregate source and different asphalt binder supplier. A different plant-produced mixture (Mix #7) was prepared using a PG 58-28 asphalt binder; the binder source was from Sinclair, WY. This mix was selected to evaluate the applicability of the models to a different binder grade. To further diversify the materials used in this study, two laboratory-prepared mixtures (Mix #8 and #9) were prepared using materials from Granite Construction (West Haven, UT) with aggregate imported from a variety of places. Of the two binders being used, the Peak PG 64-34 came from Idaho Asphalt (Blackfoot Terminal) and the Paramount PG 64-28 came from Fernley, NV, and was formulated based on Nevada DOT specifications. The properties of these mixtures are shown in Table 3.1.

Table 3.1 Description of Mixes Used

-	Mix #1	Mix #2	Mix #3	Mix #4	Mix #5	Mix #6	Mix #7	Mix #8	Mix #9
UDOT Pin	17230	17505	17307	16534	17305	15252	15688	N/A	N/A
Location	SR-10	SR-198	SR-150	SR-90	SR-302	SR-112	Base	N/A	N/A
Binder Grade	64-34	64-34	64-34	64-34	64-34	64-34	58-28	Peak 64-34	Paramt 64-28N
Binder Origin	Canada	Canada	Canada	Canada	Canada	Canada	Sinclair, WY	Idaho Asphalt	Fernley, NV
Total Binder	4.9%	4.9%	5.2%	5%	5.5%	5.3	5.0%	5.3%	5.3%
RAP Content	20%	20%	20%	20%	20%	20%	-	10%	10%
RAP Binder	1.13%	1.00%	1.15%	1.25%	1.38%	-	-	0.40%	0.40%

3.2.2 Mixture Gradation

All plant-produced mixtures, with the exception of Mix #7, are intended as 12.5-mm surface mixtures. The gradation for laboratory mixes #8 and #9 are meant to also represent surface mixtures. The gradation for all mixtures is shown in Figure 3.1.

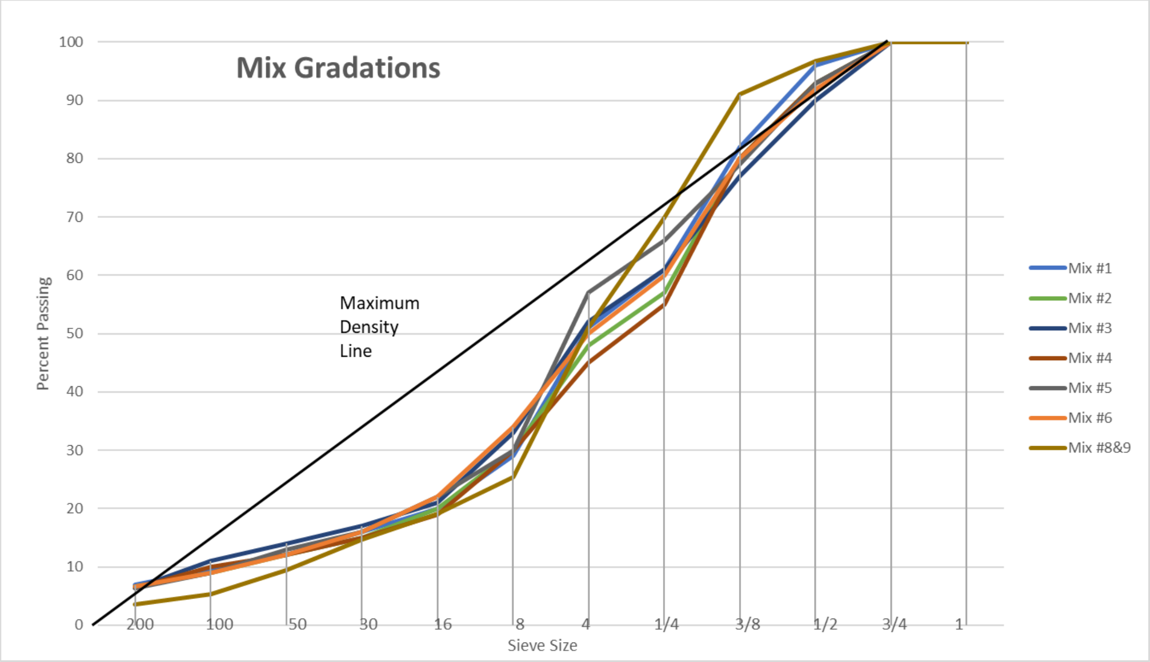


Figure 3.1 Aggregate Gradations for each Mixture

As Figure 3.1 shows, even though the mixtures were produced by different suppliers with different aggregate sources, the gradations are fairly close to each other, and they are the same "family" of mixes. This commonality reflects the specifications currently in place. Mixtures used in states other than Utah might have different gradation and different binder specifications resulting in different relations than the ones developed as part of this project. Care must be exercised in extending the results to different materials. Further research is needed to expand the results to other types of materials.

3.3 Results

The materials were compacted in the laboratory and prepared for testing according to standard procedures. The density of the prepared specimen was measured to ensure properties were within specified requirements. For IDEAL CT testing, no further manipulation was necessary; for AMPT testing, the samples were cored, and sensors were attached prior to testing.

Once the properties of the specimens were verified and instrumented as required, they were conditioned and tested at the relevant temperature. The data were electronically collected for analysis.

3.3.1 Quality Control

To ensure that the data are representative of the materials, a quality control process was applied to the data prior to the analysis. For the IDEAL CT, four specimens were tested, and the average and standard deviation of the CT-Index were determined. For the cases in which the standard deviation was greater than 25% of the mean (i.e., a coefficient of variation greater than 25%), an outlier analysis was conducted. If the highest value fell outside the interquartile range of Q3+1.5*IQR, it was highlighted as an outlier and removed from the analysis. No fewer than three data points per mix were analyzed.

For the dynamic modulus data, the data were collected for three specimens at three temperatures (4°C, 20°C, and 40°C) and three or four frequencies (10, 1, 0.1, and 0.01 Hz). An optimization routine was used to fit the parameters needed to describe Equation 1 using all data points. In all mixtures, the limiting dynamic modulus, Max, was fixed at 3,415.5 MPa since it is normally adjusted based on mixture volumetrics. The delta, beta, gamma, and ΔEA were obtained for each mix. The r-squared of the fit was determined, and in no case was the value below 0.99, indicating a satisfactory fit.

Directions to access the data are shown in Appendix A. Relevant results are shown in Table 3.2.

Table 3.2 Testing Results

-	-	IDEAL CT		Dynamic Modulus Parameters				
-	UDOT Pin	CT-Index	Fracture Energy J/m^2	Max E ksi	Min E Delta ksi	Beta	Gamma	ΔEA
Mix #1	17230*	94	8544	3415.5	2.6	-1.020	-0.490	177905
Mix #2	17505	75	7236	3415.5	5.1	-0.923	-0.522	198743
Mix #3	17307	61	6583	3415.5	4.3	-0.975	-0.530	195105
Mix #4	16534	72	6870	3415.5	2.3	-0.833	-0.519	193450
Mix #5	17305*	43	7659	3415.5	3.3	-0.999	-0.540	185238
Mix #6	15252*	105	6684	3415.5	2.2	-1.029	-0.509	184000
Mix #7	15688	28	6793	3415.5	3.1	-1.332	-0.498	199399
Mix #8	Peak	78	4797	3415.5	3.6	-0.493	-0.484	187284
Mix #9	Paramt.	116	5949	3415.5	2.6	-0.675	-0.437	191521
Average	-	74.6	6790.6	3415.5	3.06	-0.92	-0.50	190261

Tested as part of the previous study

4. ANALYSIS AND RESULTS

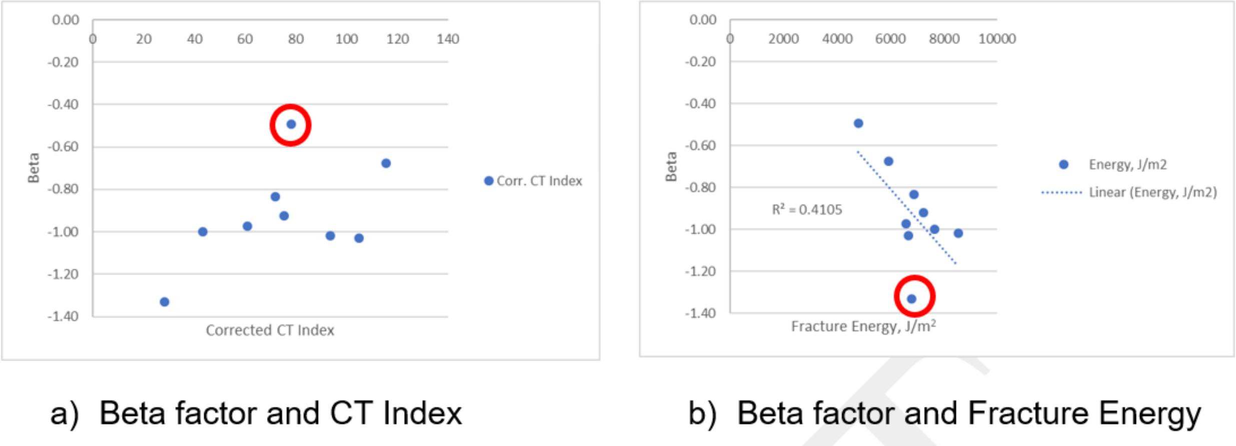
4.1 Overview

In this chapter, the data collected from nine different asphalt mixtures were analyzed to determine the relation between two different tests. Based on the analysis, some relations were developed that can predict the dynamic modulus master curve based on IDEAL CT tests. Comparisons between measured values and predicted values are shown.

4.2 Relation Between Variables

This work includes validation of previous results, development of a relation between specific parameters of the dynamic modulus master curve and the IDEAL CT results, and comparisons of the dynamic modulus master curve obtained from actual testing to the values obtained by simulating the parameters using IDEAL CT results.

It was established that the beta factor in Equation 1 played a significant role in the shape of the dynamic modulus master curve. Equation 2, developed during a previous study, indicates that the fracture energy obtained from the IDEAL CT tests is inversely related to the dynamic modulus of a material. Combining these two concepts, the first step was to evaluate the relationship between the CT Index and the beta factor and between the fracture energy and the beta factor values. The plot of these two variables is shown in Figure 4.1.



a) Beta factor and CT Index

b) Beta factor and Fracture Energy

Figure 4.1 Relation Between Beta Factor and IDEAL CT Results

Figure 4.1 shows that, as predicted, there is a trend between the beta factor and the IDEAL CT tests results. Note that in each plot there is one point, shown inside a red circle, which does not follow the pattern. Table 3.2 indicates that when looking at the CT Index (Figure 4.1a), that point corresponds to Mix #8. The asphalt binder used in this mix has a different formulation in comparison with the others and was reported to have different compaction behavior. Figure 4.1b shows that there is an inverse linear relation between fracture energy and the beta factor except for the point inside the red circle. That point corresponds to Mix #7, which is the only mixture prepared with a PG 58-28 asphalt binder and not intended as a surface mix. At this point in the research, it is reasonable to state that Mix #7 belongs to a different family of mixtures and will require more testing before it can be included in the relation.

Given that Mix #7 is a mixture "from a different family," it was not included in the Pearson's correlation analysis done on the remaining eight mixtures. These results are shown in Table 4.1.

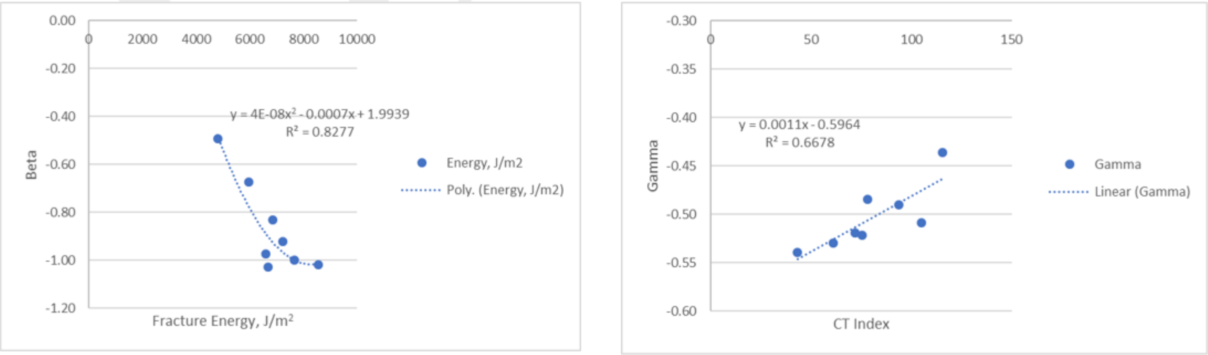
As seen in Table 4.1, the results are encouraging yet slightly different than what was observed during Phase I. The parameter beta has a correlation of -0.84 with the fracture energy (area under the load deformation curve of the CT Index) while the parameter gamma has a 0.82 correlation with the CT Index. These results are very encouraging.

Table 4.1 Pearson Correlation Between Variables

	CT Index	*Energy, J/m²*	*Post Slope*	*Max E* ksi*	*Min E* ksi*	*Beta*	*Gamma*	*ΔEA*
CT Index	1	-	-	-	-	-	-	-
Energy, J/m²	-0.19	1	-	-	-	-	-	-
Post Slope	-0.78	0.54	1	-	-	-	-	-
Max E*	-0.01	-0.60	-0.19	1	-	-	-	-
Min E*	-0.47	-0.09	0.06	0.42	1	-	-	-
Beta	0.22	-0.84	-0.71	0.64	0.02	1	-	-
Gamma	0.82	-0.41	-0.57	0.23	-0.37	0.60	1	-
ΔEA	-0.22	-0.29	0.23	0.82	0.52	0.20	-0.12	1

4.3 Development of Relation

There are many models that can be used in development of a predictive relation between the IDEAL CT tests and the parameters used to model the dynamic modulus master curve; however, given the relatively small dataset (eight mixtures), it was decided that a second-degree polynomial would be adequate. This decision was based on the simple observation, shown in Figure 4.1b, that for those mixtures with high fracture energy, the beta factor did not decrease linearly. Through a similar thought process, a linear relation was used to develop a relation between the CT Index and the gamma parameter. Obviously, as more data become available, other functional forms could be explored. These relations are shown in Figure 4.2.



a) Fracture energy and Beta Factor

b) CT Index and Gamma Factor

Figure 4.2 Relation Between Variables

Figure 4.2 shows that an r-squared greater than 0.82 is obtained when fitting a second-degree polynomial to the Fracture Energy – Beta values. An r-squared greater than 0.66 is obtained when fitting a linear relation to the CT-Index-Gamma values. The predicted equations are:

$$\text{Beta} = 4\text{x}10^{-8}(\text{Energy})^2 - 7\text{x}10^{-4}(\text{Energy}) + 1.9939 \qquad \text{Equation 3}$$

$$\text{Gamma} = 1.1\text{x}10^{-3}(\text{CT Index}) - 0.5964 \qquad \text{Equation 4}$$

Where "Energy" is the fracture energy in J/m^2 and CT Index is the cracking tolerance index, both obtained from the IDEAL CT test. Note that these are regression-based equations and thus units will not necessarily have any meaning outside the equations.

4.3.1 Prediction of Beta and Gamma Parameters

Using Equations 3 and 4 and the values shown in Table 3.2, the prediction of each of the parameters was made. The predicted values, as well as the fitted values from Table 3.2, are shown in Table 4.2.

As Table 4.2 shows, the beta parameter can be predicted using the fracture energy resulting, on average, in an error of 8.5% and less than 12.8%, while the gamma parameter can be predicted using the CT Index resulting, on average, in an error of 2.9% and less than 7.5%. As previously discussed, Mix #7 is from a different family (PG 58-34) and was not used in the equations development, thus predictions for this mix result in significantly higher error.

Table 4.2 Comparison of Beta and Gamma Factors Predictions

-	Beta			Gamma		
-	Fitted	Predicted	Error[1], %	Fitted	Predicted	Error, %
Mix #1	-1.020	-1.066	-4.6	-0.490	-0.493	-0.6
Mix #2	-0.923	-0.977	-5.9	-0.522	-0.513	1.6
Mix #3	-0.975	-0.881	9.7	-0.530	-0.529	0.2
Mix #4	-0.833	-0.927	-11.3	-0.519	-0.517	0.4
Mix #5	-0.999	-1.021	-2.2	-0.540	-0.549	-1.7
Mix #6	-1.029	-0.899	12.8	-0.509	-0.481	5.4
Mix #7	-1.332	-0.915	31.3	-0.498	-0.565	-13.4
Mix #8	-0.493	-0.443	10.0	-0.484	-0.510	-5.4
Mix #9	-0.675	-0.755	-11.8	-0.437	-0.469	-7.5
Absolute Average Error[2]			8.5	-		2.9

1. Difference with respect to Fitted values
2. Obtained by averaging the absolute value of the error excluding Mix #7

4.4 Modeling the Dynamic Modulus Master Curve

Equation 1 is used to represent the dynamic modulus master curve. As previously discussed, that equation requires four parameters, two of which can be predicted using results from the IDEAL CT tests. Other parameters should relate to tests performed at different temperatures. For this report, the average value of Max E and Min E was used along with the beta and gamma predicted using equations 3 and 4 to model the complete dynamic modulus master curve. To verify the models, the predicted E* was compared with the measured E* at 20°C. The temperature was selected since it is the reference temperature; therefore, there are direct comparisons not affected by the shift factors. The results are presented in Table 4.3.

Table 4.3 shows that, using only data from the IDEAL CT tests, it is possible to model the dynamic modulus of asphalt mixtures at one temperature with an average absolute difference of 17.2% when compared with actual measured values. The average absolute difference decreases to 14.3% if Mix #7 is excluded. Such a difference is considered reasonable for typical asphalt mixtures tests. These results support the assumptions previously discussed.

Table 4.3 Comparison of Measured and Modeled Dynamic Modulus at 20°C

-	Frequency Hz	Measured E* 20°C ksi	Modeled E* 20°C ksi	Difference
Mix #1	10	843.6	1010.2	19.7%
	1	457.5	566.7	23.9%
	0.1	221.7	272.4	22.9%
Mix #2	10	944.5	940.0	-0.5%
	1	528.9	501.2	-5.2%
	0.1	253.9	227.4	-10.5%
Mix #3	10	874.8	862.0	-1.5%
	1	485.8	437.1	-10.0%
	0.1	239.9	188.3	-21.5%
Mix #4	10	745.0	895.2	20.2%
	1	371.6	467.3	25.8%
	0.1	158.1	207.9	31.5%
Mix #5	10	908.4	1019.8	12.3%
	1	491.8	532.6	8.3%
	0.1	230.3	230.7	0.2%
Mix #6	10	930.7	832.5	-10.5%
	1	486.4	448.1	-7.9%
	0.1	222.6	210.4	-5.5%
Mix #7	10	1244.5	930.5	-25.2%
	1	755.4	459.5	-39.2%
	0.1	429.7	187.9	-56.3%
Mix #8	10	483.6	485.3	0.4%
	1	240.3	219.9	-8.5%
	0.1	108.2	91.0	-15.9%
Mix #9	10	526.0	693.6	31.9%
	1	281.9	362.3	28.5%
	0.1	140.1	168.2	20.1%

Underlined values have a difference greater than 25%.
The average absolute difference is 17.2%

To complete the predictions needed as input for the AASHTOWare Pavement ME® (Figure 1.1), the complete dynamic modulus master curve was modeled based on Equation 1. The measured data at the different temperatures were shifted to a reference temperature of 20°C using the average activation energy, ΔEA, in the Arrhenius equation as obtained from the different mixes tested (shown in Table 3.2). The data were compiled, and the results are shown in Figures 4.3 through 4.11.

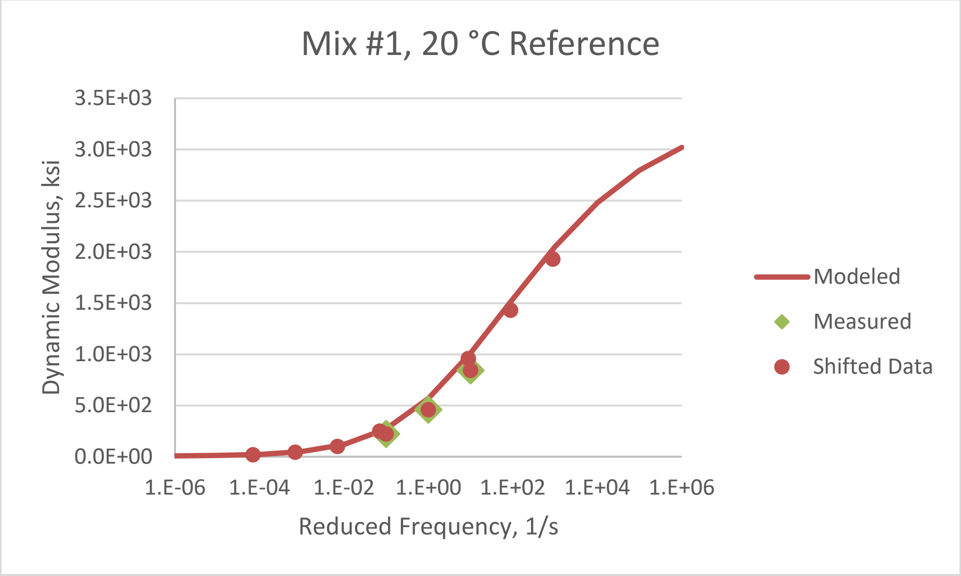


Figure 4.3 Dynamic Modulus Master Curve for Mix #1

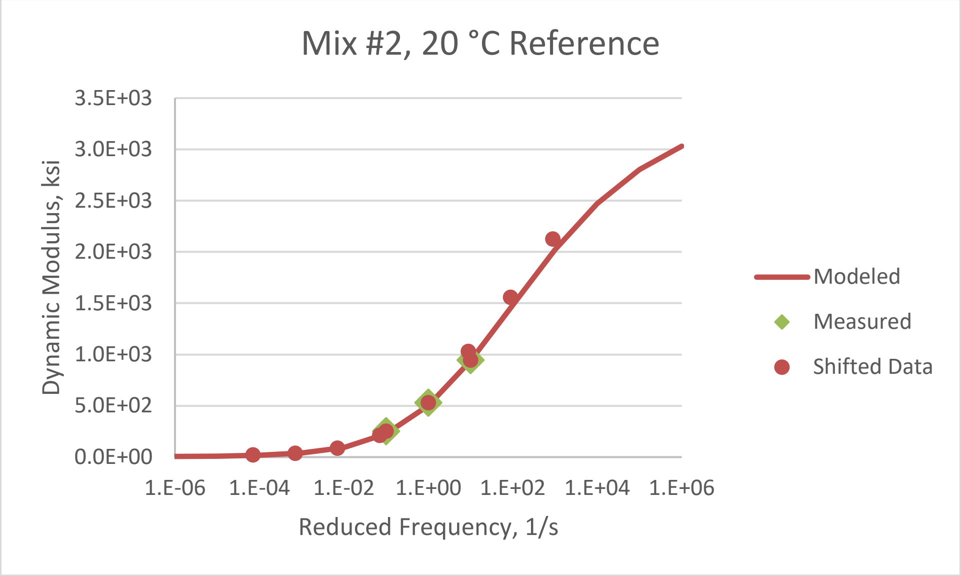


Figure 4.4 Dynamic Modulus Master Curve for Mix #2

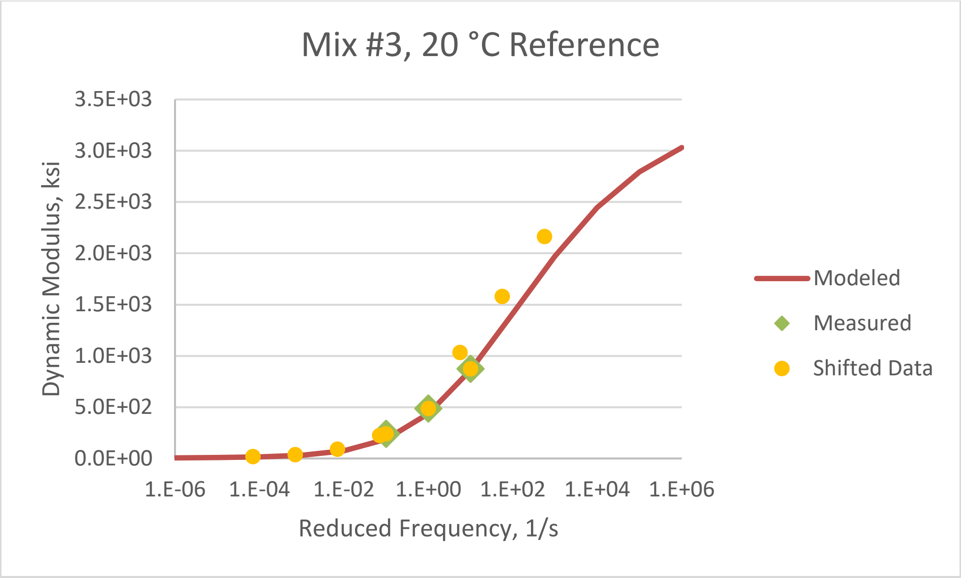


Figure 4.5 Dynamic Modulus Master Curve for Mix #3

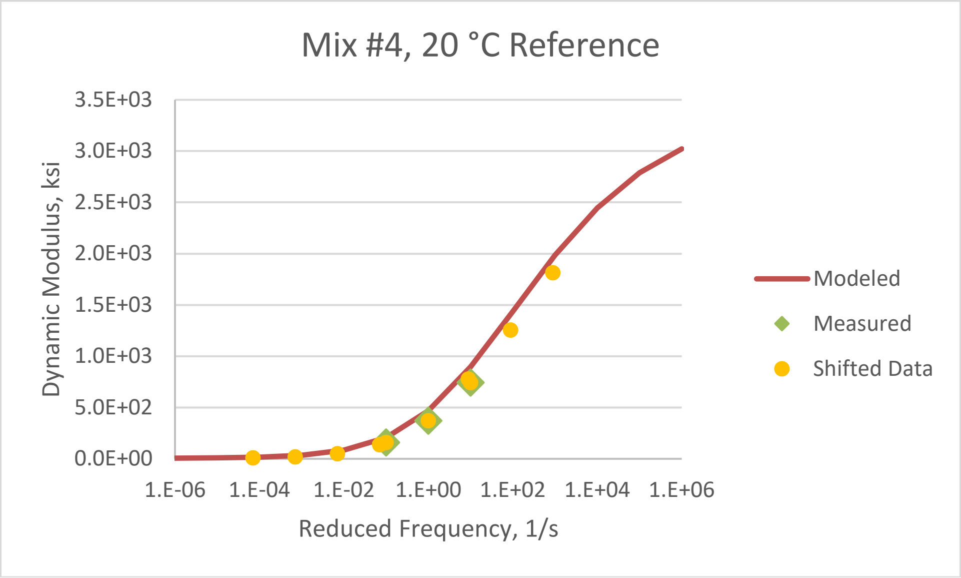


Figure 4.6 Dynamic Modulus Master Curve for Mix #4

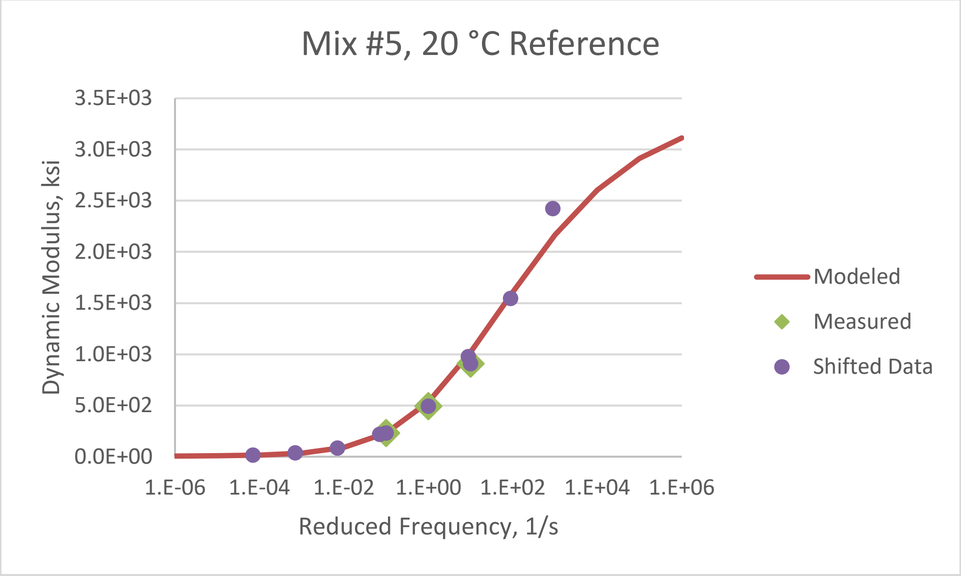


Figure 4.7 Dynamic Modulus Master Curve for Mix #5

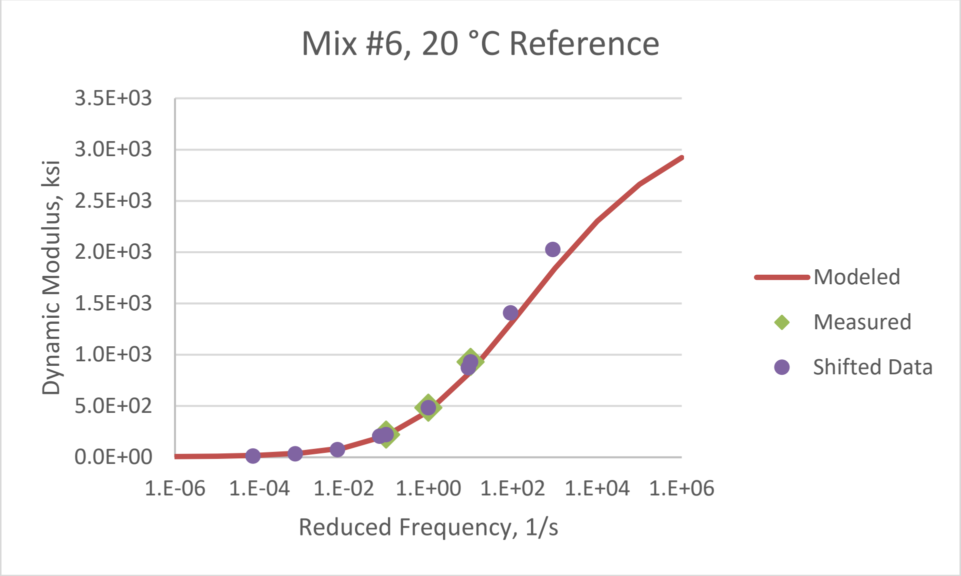


Figure 4.8 Dynamic Modulus Master Curve for Mix #6

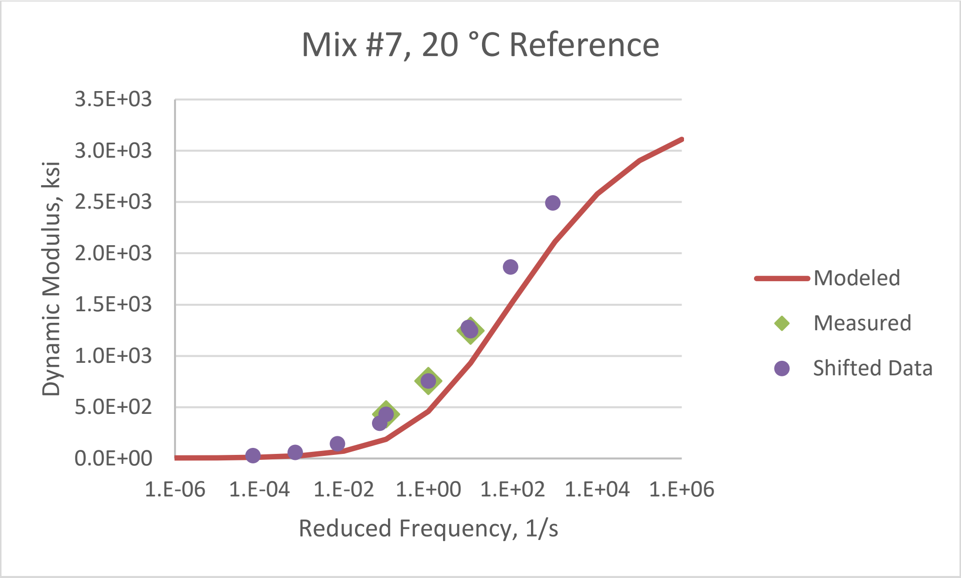


Figure 4.9 Dynamic Modulus Master Curve for Mix #7

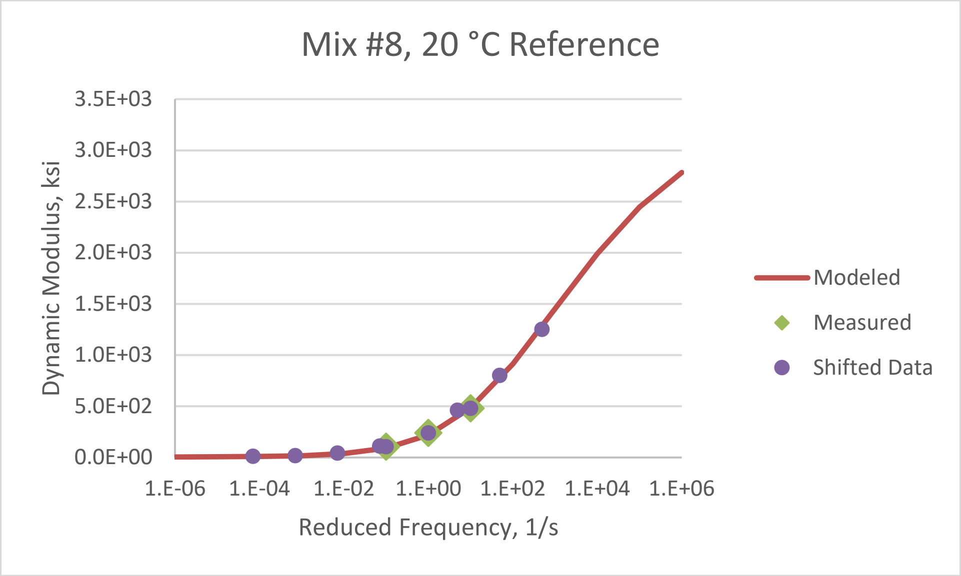


Figure 4.10 Dynamic Modulus Master Curve for Mix #8

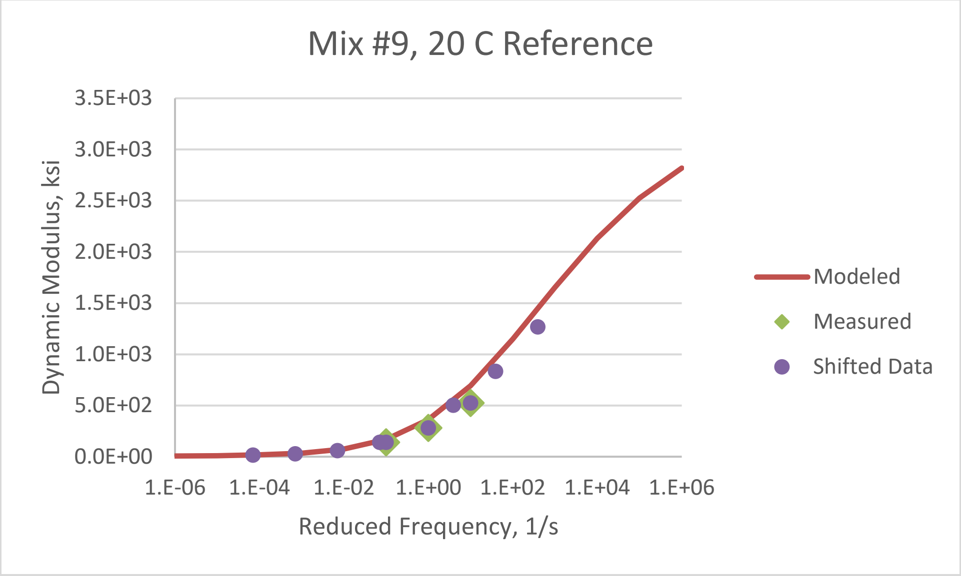


Figure 4.11 Dynamic Modulus Master Curve for Mix #9

As Figures 4.3 through 4.11 show, it is possible to model a complete dynamic modulus master curve using only IDEAL CT results and some default values with reasonable success at the intermediate temperature region. However, two issues are noted; the first one is the fact that the error in the model increases as the data deviate from the temperature at which the tests are conducted. This is not surprising given that the shift factor relation is not being measured in this project. The second issue is the questionable relations obtained from mixtures that are not part of the same family, namely Mix #7. Again, this is not a surprise considering that this mix was not used to develop the model. While more research is required to determine the behavior of different mixtures, it is notable that Mixtures #8 and #9 were designed using different binder formulations and yet they show good agreement between the measured values and the modeled ones.

4.5 Variability and Accuracy of Results

Table 4.3 showed that the prediction of the dynamic modulus using only IDEAL CT parameters results in an average error of 17.2%. This value must be put into perspective by comparing it with the accuracy of the actual AMPT test results. The average dynamic modulus data are obtained from testing three samples at different temperatures and frequencies. At low temperatures and high frequencies, the standard deviation is usually less than 10% of the mean (i.e., coefficient of variation); at high temperatures and low frequencies, this value is closer to 20%. This means that an error of 17%, while far from perfect, is within reason. As more tests are added to the model to include different temperatures, the accuracy of the results is expected to increase.

4.6 Summary

This chapter shows the development of relations between the results from the IDEAL CT and the dynamic modulus of nine different asphalt mixtures. The results support the hypothesis of this work given that the modeled values are within 17.2% of the measured ones. Furthermore, it was shown that complete dynamic modulus master curves could be developed for each mix.

While the relations are not perfect, the error observed is within values often observed in asphalt mixture testing. Furthermore, the predictions obtained are an improvement over default values often used. The implication of the results presented is also significant in terms of effort. As previously stated, at least three days of laboratory staff are needed to obtain the measured E* while the modeled E* requires, at most, a day of work. Furthermore, the results show that the tests used during mix design can be incorporated into the structural design of pavements.

Note that these results are only valid for the specific type of asphalt mixture structure used in the state of Utah and, to a limited extent, surrounding areas. The models apply to both field mixes and laboratory mixes and different binder formulations with the same performance grade. Further work will expand the prediction models to other types of mixtures and other asphalt grades.

5. SUMMARY AND CONCLUSIONS

5.1 Summary

The work presented as part of this research seeks to relate asphalt mixtures tests used during mixture design and quality control tests to tests used for the structural design of pavements based on AASHTOWare Pavement ME®. This is accomplished by developing relations between different tests. This phase specifically deals with the development of relations between the IDEAL CT test and the dynamic modulus of different asphalt mixtures.

5.2 Findings

The following was found as part of this work.

5.2.1 Validation of Theoretical Results

During previous work, a hypothesis was presented based on the fact that energy must be conserved; therefore, the work done during any tests must go into system losses, permanent deformation and flow, and creating a new surface. The usefulness of any test resides in its ability to isolate each effect. Preliminary work showed there was a reasonable relation between parameters that describe the dynamic modulus master curve and the results from the IDEAL CT test. This phase expanded on those results using nine different mixtures: six typical UDOT surface mixtures, two laboratory-prepared mixtures, and one base mixture. The relations held for one type of mixture; further testing is required to expand these relations to other mixtures.

5.2.2 Development of Relations

Based on test results from eight different mixtures, the following relations were developed:

$$\text{Beta} = 4\text{x}10^{-8}(\text{Energy})^2 - 7\text{x}10^{-4}(\text{Energy}) + 1.9939 \qquad \text{Equation 3}$$

$$\text{Gamma} = 1.1\text{x}10^{-3}(\text{CT Index}) - 0.5964 \qquad \text{Equation 4}$$

5.2.3 Comparison of Error and Accuracy

The equations developed have an R-squared greater than 80% for the prediction of the dynamic master curve parameters. The average error is 8.5% for the beta factor and 2.9% for the gamma factor. Using these parameters while holding the other parameters constant, the dynamic modulus at 20°C was predicted within an average absolute difference of 17.2% with respect to measured values. Better predictions were obtained for the mixtures made with PG 64-35 asphalt binders.

5.2.4 Framework

This work allows for the prediction of the dynamic modulus of asphalt mixtures by using data obtained from the IDEAL CT tests. While the predictions are not perfect, they are still an attractive alternative due to the shorter time and effort required to run the IDEAL CT test. The data can be obtained in approximately one day of work. Knowing the data, the parameters beta and gamma can be predicted and used in the sigmoidal equation to generate the inputs for the AASHTOWare Pavement ME® software. Futures projects will look to further improve the predictions by incorporating results from tests at other temperatures.

5.3 Limitations and Challenges

Six plant-produced asphalt mixtures were used during this work. Two lab-produced mixtures prepared with different binder formulations but the same performance grade were also used along with one base mix with a different binder performance grade. While these asphalt mixtures are typical of what would be encountered on Utah roads, they all belong to the same family, as was seen in Table 3.1 and Figure 3.1. Such lack of diversity represents a challenge since it was shown that the mixture with a different binder grade does not fit the relations well. Unfortunately, the lack of availability of different mixtures was a limitation of this study.

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7. APPENDIX A: Data Access

All of the data from testing were collected using electronic data acquisition of force, displacement, and temperature sensors. The data were collected in non-proprietary CSV format as generated by the data acquisition system. Spreadsheets were used to summarize and analyze the data. These spreadsheet data have been preserved and archived at Zenodo (https://zenodo.org/), an international repository/archive of research outputs from across all fields of research. Zenodo is listed as conforming to the USDOT Public Access Plan (https://ntl.bts.gov/ntl/public-access/data-repositories-conformant-dot-public-access-plan). According to Zenodo's policy, data entries remain accessible forever.

The data collected as part of this work can be found in the following link: https://doi.org/10.5281/zenodo.10501328

Romero, P. (2024). "Modeling the Dynamic Modulus of Asphalt Mixtures Using Single-value Test Results Phase II: Relation Between E* Parameters and CT Index" [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.10501328

A README file, including the metadata/information required to repeat the research, is included along with the data in the archive. Zenodo will provide proper citation for users to incorporate the data into their publications and will have a memorandum of understanding (MOU) stating that users may not re-release the data to a third party, but will direct them back to the repository.