MOUNTAIN-PLAINS CONSORTIUM

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DEVELOPMENT OF DYNAMIC MODULUS PARAMETERS FROM SINGLE POINT TESTS

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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. Review of data from 34 different projects tested between 2007 and 2010 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 confirmed, theoretically, there should be some relation between the cracking tolerance index and the dynamic modulus. The relation was verified using asphalt mixtures from six different UDOT projects. 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. 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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Development of Dynamic Modulus Parameters from Single Point Tests

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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. Review of data from 34 different projects tested between 2007 and 2010 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 confirmed, theoretically, there should be some relation between the cracking tolerance index and the dynamic modulus. The relation was verified using asphalt mixtures from six different UDOT projects. 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. 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 documents the efforts to develop a relation between single-value performance-related tests and the dynamic modulus of asphalt mixtures. A review of the literature indicates that the dynamic modulus data used as input to the AASHTOWare Pavement ME® program is the result of testing and modeling based on mechanics-based principles. Ten data points are fitted to a sigmoidal equation that is defined by four fitted parameters. Knowing these parameters, the dynamic modulus of asphalt concrete can be predicted at any frequency and temperature combination, and thus provide Level 1 inputs to the structural design of pavements. Since each parameter defines a portion of the shape, a relation is expected to exist between single-point tests such as the IDEAL-CT and the dynamic modulus master curve.

A review of available dynamic modulus data obtained from 34 projects indicates that UDOT mixes show consistent patterns that might help in developing the relation between single point test parameters such as the CT Index and the dynamic modulus master curve E*. For example, there is consistency in the parameter that defines the shift factor, thus reducing the number of parameters that need to be predicted. Review of different reports also confirm that the dynamic modulus master curve has a relation with cracking and other pavement distresses.

A theoretical analysis was conducted based on thermodynamic principles in which it was hypothesized that some of the work done during testing was converted into the creation of a new crack. Even though not all system losses were accounted for, it was proposed that the fracture energy used in predicting the cracking tolerance of asphalt mixtures was inversely related to the dynamic modulus and directly related to the phase angle.

Finally, to verify if the theoretical analysis was reasonable, asphalt mixtures from six different UDOT projects were collected, and their cracking tolerance index was measured. Three asphalt mixtures were then selected for further testing to determine their dynamic modulus at different frequencies and four different temperatures. The results confirmed the theoretical analysis in that an inverse relation was found between the fracture energy at 25°C used to determine the cracking tolerance index and the dynamic modulus at 20°C (the closest temperature). The dynamic modulus at different frequencies and temperatures were used to create master curves based on the equation developed as part of the National Cooperative Highway Research Program (NCHRP). It was found that the parameters determining the equation have a high correlation (>0.95) with the cracking tolerance index.

While caution is recommended based on the fact that only a limited number of mixtures were tested, it was concluded that the approach of relating the cracking tolerance index to the dynamic modulus is feasible, and it is recommended that further testing be done to confirm the results and to develop an actual predictive relation.

1. INTRODUCTION

1.1 Problem Statement

The pavement structural design process and the asphalt materials used to build these pavements are currently disconnected in most highway agencies. Asphalt mixture properties obtained from adopted quality-control or mix design tests such as the Hamburg Wheel Tracking Device, IDEAL-CT, or Bending Beam Rheometer for mixtures are not used as input to the pavement structural design process. While AASHTOWare Pavement ME® has been adopted in the structural design, the actual material inputs required in the process are not always available, resulting in the use of average or default values that do not necessarily represent what is placed in the field (i.e., Level 3 inputs). This practice results in the AASHTOWare Pavement ME® process over/under estimating rutting, fatigue, and thermal cracking in pavement sections. Cost optimization opportunities are therefore being missed.

1.2 Background

One of the inputs for AASHTOWare Pavement ME® is the dynamic modulus obtained from the Asphalt Mixture Performance Tester (AMPT). However, due to the complexities of the test, the use of the AMPT to collect specific material data has been a less than palatable solution; thus, a standard-material model is being used in place of actual measured values. Using the Level 3 pavement design does not consider the unique material properties obtained from single point testing available today.

The AMPT is used on compacted asphalt cylinders to obtain the dynamic modulus, E*, of the material at different temperatures and different frequencies. The results from the different temperatures and frequencies are analyzed and can be combined, through some mathematical expressions, into a single curve called the dynamic modulus master curve. This curve can then be used to determine the material's response to loading at any rate and temperature. These values are some of the primary inputs in the structural design of pavement structures using the AASHTOWare Pavement ME® program.

The dynamic modulus master curve can be modeled using Equation 1, developed as part of NCHRP project 9-29.

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

Where:

$\|E^*\|$	= dynamic modulus, psi
ω_r	= reduced frequency, Hz
Max	= limiting maximum modulus, psi
δ, β,and γ	= fitting parameters

The resulting master curve is specific to a given material; therefore, so are the parameters that define the curve. In the AASHTOWare Pavement ME® program, the master curve is used by the software to determine the E* for any loading frequency and temperature. Based on the visco-elastic theory and the observed behavior of asphalt materials, it is known that a portion of the master curve relates to the high-temperature behavior (rutting), another portion relates to the intermediate-temperature behavior (fatigue cracking), and another relates to the low-temperature behavior (thermal cracking). This means that the results from tests currently used during asphalt mix design should be related to a specific portion of the master curve and thus provide the ability to “connect” material testing to the structural design process. This connection between dynamic modulus and simpler tests gives the ability for cost optimization that can benefit both the quality of materials and the structural design of pavements. Alternatively, a dynamic modulus curve can be approximated based on actual local material instead of using generic values, resulting in a more robust structural pavement design and performance predictions. Lastly, using data from existing tests can reduce the need for complex AMPT testing while still allowing a Level 1 pavement design.

1.3 Objective

The overall objective of this research is to develop a relation between material tests that are currently being used for mix design (Hamburg WTD at high temperatures, Bending Beam Rheometer for mixtures at low temperatures, and the IDEAL-CT at intermediate temperatures) and the dynamic modulus, E*, master curve values used as input to the pavement design software (i.e., Level 1 in AASHTOWare Pavement ME®). Understanding that a one-to-one relation is unlikely to exist, the expectation is that such a relation allows for selecting an E* master curve that is directly related to the asphalt mixture used in the pavement. Having this capability will improve the robustness of pavement design, allow for life-cycle analysis, and enhance cost optimization.

To accomplish this objective, a multi-phase approach has been proposed, with this report serving to evaluate the feasibility of the proposed work.

The specific objectives of this report are:

1. Establish a theoretical background regarding the relation between the CT Index from the IDEAL-CT and the portion of the dynamic modulus master curve from the AMPT that corresponds to intermediate temperatures (where most of the E* data are actually collected).
2. Demonstrate experimentally that data from both tests (AMPT and IDEAL-CT) relate to each other. Mixes with different CT indices should also result in different dynamic modulus master curves, and the relative ranking of these mixes should be similar (e.g., mixes with low CT indices will have high E* values or high slope).
3. Propose a framework that will allow the selection of dynamic modulus master curves as input to the AASHTOWare Pavement ME® program from IDEAL-CT data and eventually other tests.

1.4 Scope

The scope of this report is as follows:

a. A literature review was conducted to determine the characteristics of dynamic modulus, E*, data within the context of pavement design. This looked at the sigmoidal function used to model the E* master curve and how the function is obtained (i.e., identify the parameters that determine the shape of the master curve).
b. Previous test results were analyzed to determine the characteristics of the dynamic modulus master curve and the expected range of values obtained in mixtures produced in Utah. This provides the range of values that can be expected from this test and thus ensures that any predictions are valid.

c. The theoretical background of the approach was developed to justify the relation between the IDEAL-CT tests and the dynamic modulus master curve with extension to other tests.

d. Six asphalt mixtures were collected from field projects and tested using the IDEAL-CT tests. Based on the cracking index obtained, three of the six mixtures were tested using the AMPT. The data from the two tests were used to demonstrate the validity of the approach.

e. Finally, a framework is proposed to allow the selection of dynamic modulus master curves from IDEAL-CT data and eventually other tests.

2. LITERATURE REVIEW

2.1 Overview

This chapter summarizes relevant information from the literature and previous reports for the development of asphalt mixtures dynamic modulus master curves.

2.2 Development of AMPT

The process of asphalt mix design normally consists of the selection of asphalt binders, aggregates, and fillers or modifiers. The Superpave asphalt mix design method developed during the 1990s resulted in a procedure for selection of performance grade binders and volumetric mix designs. As the procedure evolved, the need for a mechanical test to complement the volumetric mixture design process was recognized. Over time, many mechanical tests have been proposed, with some still being evaluated. The Asphalt Mixture Performance Tester (AMPT) is one of such tests [1]. Initially, the AMPT was called the Simple Performance Test. However, as people started using it, they realized that such a designation was deceiving since, in reality, there is nothing "simple" about the test.

As the AMPT was being developed for asphalt mix characterization, the need arose to obtain time- and temperature-dependent mixture properties (i.e., stiffness or modulus) in support of the Level 1 pavement design process of the MEPDG (now called AASHTOWare Pavement ME®). Therefore, even though the adoption of the AMPT during the mix design process has not been universally accepted, the need for a test that provided the time- and temperature-dependent modus of the asphalt mixture has remained. This property is referred to as the dynamic modulus, E*, master curve [2]. The procedure for development of master curves from visco-elastic materials has been used by many industries, and the concepts are well understood. For the case of asphalt mixtures, a simplified procedure was developed as part of NCHRP 9-29 [3].

2.3 Creation of E* Master Curve

In order to evaluate the different loading rates and temperatures that the pavement is exposed to, AASHTOWare Pavement ME® uses the dynamic modulus, E*, obtained from a master curve at a reference temperature. A master curve is built by "combining" or "shifting" the dynamic modulus obtained at different frequencies and temperatures into a single curve that can be described using a smooth function [3]. In theory, this master curve can describe the response of asphalt mixtures for any loading rate at any temperature [4].

2.3.1 Dynamic Modulus

To obtain the dynamic modulus of asphalt concrete materials, a haversine axial compressive stress is applied to a cylindrical asphalt concrete specimen at a specified temperature and different loading frequencies. The applied stress and the resulting axial strain of the specimen are measured and used to calculate the dynamic modulus and phase angle. The dynamic modulus is defined as the peak stress divided by the peak strain at a specific frequency and temperature combination. This is the overall stiffness of the asphalt concrete mixture at that given condition. The phase angle is defined as the angle, in degrees or radians between a haversine applied peak stress, and the resulting peak strain in a controlled stress test [5]. The phase angle relates to the ability of the material to store or dissipate energy. Once the dynamic modulus values are measured over a range of temperatures and loading frequencies, they can be combined or shifted into a single curve. This curve is known as the dynamic modulus master curve. As previously mentioned, the master curve, along with the shift factors, provides information about the mechanical response of the specific asphalt mixture at any given load frequency and temperature [6].

2.3.2 AMPT Testing

Testing using the AMPT consists of preparing asphalt mixtures and compacting them into tall cylinders using the Superpave Gyratory Compactor (SGC). Four replicate samples are normally recommended to get a valid representation. From each sample, a 100-mm diameter core is obtained from the compacted cylinder and cut at the ends to obtain a specimen with final dimensions of 100-mm diameter and 100-mm height. The specimens are then instrumented and conditioned at a specified temperature. Once a specimen is at the correct temperature, testing is done at the temperatures and frequencies shown in Table 2.1. The overall process, from sample preparation to testing, is shown in Figure 2.1.

a) Preparing the mix

b) Compacting using the Gyratory Compactor

c) Coring sample to 100-mm diameter

d) Cutting sample to 100-mm high

e) Instrumenting sample

f) Testing in temperature-controlled chamber

Figure 2.1 Procedure for Testing Using the AMPT

Table 2.1 List of Temperatures and Frequencies for AMPT Testing

PG 58-XX and softer		**PG 64-XX & PG 70-XX**		**PG 76-XX and stiffer**	
Temperature (°C)	Loading Frequencies (Hz)	Temperature (°C)	Loading Frequencies (Hz)	Temperature (°C)	Loading Frequencies (Hz)
4	10, 1, 0.1	4	10, 1, 0.1	4	10, 1, 0.1
20	10, 1, 0.1	20	10, 1, 0.1	20	10, 1, 0.1
35	10, 1, 0.1, and 0.01	40	10, 1, 0.1, and 0.01	45	10, 1, 0.1, and 0.01

2.3.3 Creation of Master Curve

When all four replicate specimens have completed the required testing at the different temperatures and frequencies, the data are then compiled and prepared for the development of a dynamic modulus master curve. An example of the data is shown in Table 2.2 and plotted in Figure 2.2.

Table 2.2 Example of Dynamic Modulus Summary

Conditions		Specimen 1		Specimen 2		Specimen 3		Specimen 4		Modulus		Phase Angle	
Temperature	Frequency	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Modulus	Phase Angle	Mean	CV	Mean	Std. Dv.
C⁰	Hz	Ksi	C⁰	Ksi	C⁰	Ksi	C⁰	Ksi	C⁰	Ksi	%	C⁰	C⁰
4	10.00	1445	15.24	1484	16.91	1555	16.01	1496	16.9	1495.0	3.0	16.3	0.8
4	1.00	965.1	18.6	952.4	20.95	1021	19.82	961.9	20.93	975.1	3.2	20.1	1.1
4	0.10	626.3	21.3	578.6	24.14	640.8	23.11	581	24.15	606.7	5.2	23.2	1.3
20	10.00	638.1	24.06	630.4	26.18	573.5	26.66	598.6	26.16	610.2	4.9	25.8	1.2
20	1.00	361.3	26.34	333.9	28.66	301.4	29.18	314.9	28.47	327.9	7.9	28.2	1.3
20	0.10	199.9	27.25	167.7	29.39	154.3	29.91	158.1	29.35	170.0	12.2	29.0	1.2
40	10.00	172.8	29.39	128.3	32.82	144.6	33.22	129.9	33.21	143.9	14.3	32.2	1.9
40	1.00	77.8	29.53	53.4	32.9	55.8	34.65	48	35.17	58.8	22.3	33.1	2.5
40	0.10	41	27.63	29.7	29.19	28.3	32.06	23	33.53	30.5	24.8	30.6	2.7
40	0.01	25.3	24.87	21	24.77	19.2	27.33	13.8	29.71	19.8	24.0	26.7	2.3

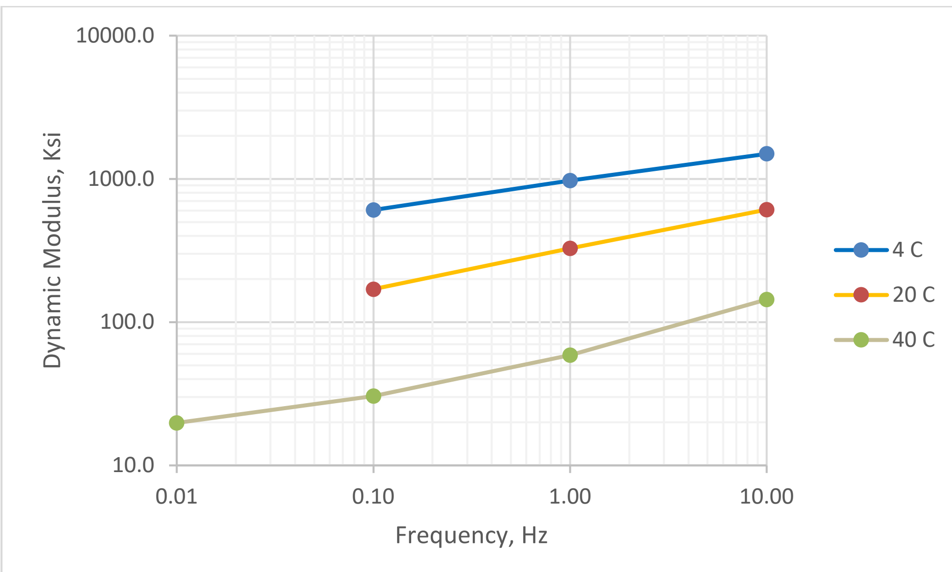


Figure 2.2 Plot of Dynamic Modulus Results

A dynamic modulus master curve is a composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis, as shown in Figure 2.3. The amount that a value is shifted is called the shift factor and the resulting frequency is called the reduced frequency.

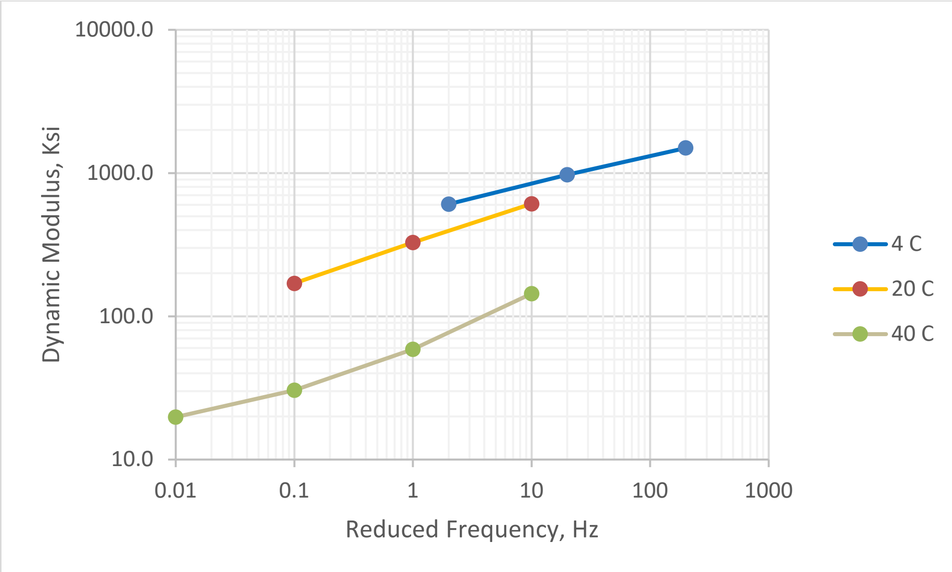


Figure 2.3 Plot of Dynamic Modulus with the 4 C Data Being Shifted

Once the data from all temperatures have been shifted, a smooth curve is formed. The curve is determined by Equation 1, developed as part of NCHRP Project 9-24 **[3]**. The general form of the equation is:

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

Where:

$|E^*|$ = dynamic modulus, psi
ω_r = reduced frequency, Hz
Max = limiting maximum modulus, psi
$\delta, \beta, and\ \gamma$ = fitting parameters

The reduced frequency is computed using the Arrhenius equation.

$$log\omega_r = log\omega + \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \text{Equation 2}$$

Where:

ω_r = reduced frequency at the reference temperature
ω = loading frequency at the test temperature
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as a fitting parameter)

The final form of the dynamic modulus master curve equation is obtained by substituting Equation 2 into Equation 1:

$$log|E^*| = \delta + \frac{(Max-\delta)}{1+e^{\beta+\gamma\left\{log\omega+\frac{\Delta Ea}{19.14714}\left(\left(\frac{1}{T}\right)-\left(\frac{1}{T_r}\right)\right)\right\}}} \quad \text{Equation 3}$$

The shift factors at each temperature are given by Equation 4,

$$log[a(T)] = \frac{\Delta E_a}{19.14714}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad \text{Equation 4}$$

Where:
a(T) = shift factor at temperature T
T_r = reference temperature, °K
T = test temperature, °K
ΔE_a = activation energy (treated as fitting parameter)

The maximum limiting modulus is estimated from mixture volumetric properties using the Hirsh model and limiting binder modulus of 1 GPa (145,000 psi), shown in Equations 5 and 6.

$$\left|E^*\right|_{max} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right) + 435{,}000\left(\frac{VFA \times VMA}{10{,}000}\right)\right] + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{435{,}000(VMA)}\right]} \quad \text{Equation 5}$$

Where:

$$P_c = \frac{\left(20+\frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650+\left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \quad \text{Equation 6}$$

Where:

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus, psi
VMA = voids in mineral aggregates, %
VFA = voids filled with asphalt, %

Using the average VMA and VFA of the specimens tested, the limiting maximum modulus is computed using Equations 5 and 6 [7]. The logarithm of the limiting maximum modulus is then computed and designated as Max. The next step is to select the reference temperature, T_r, for the dynamic modulus master curve. Most highway agencies have chosen a reference temperature of 20°C (293.15°K); however, other temperatures should yield similar results.

Substituting Max and T_r into Equation 3 and then then determining the four fitting parameters of the equation ($\Delta E_a, \delta, \beta, and\ \gamma$) results in a dynamic modulus master curve, as shown in Figure 2.4. This is done through numerical optimization routines.

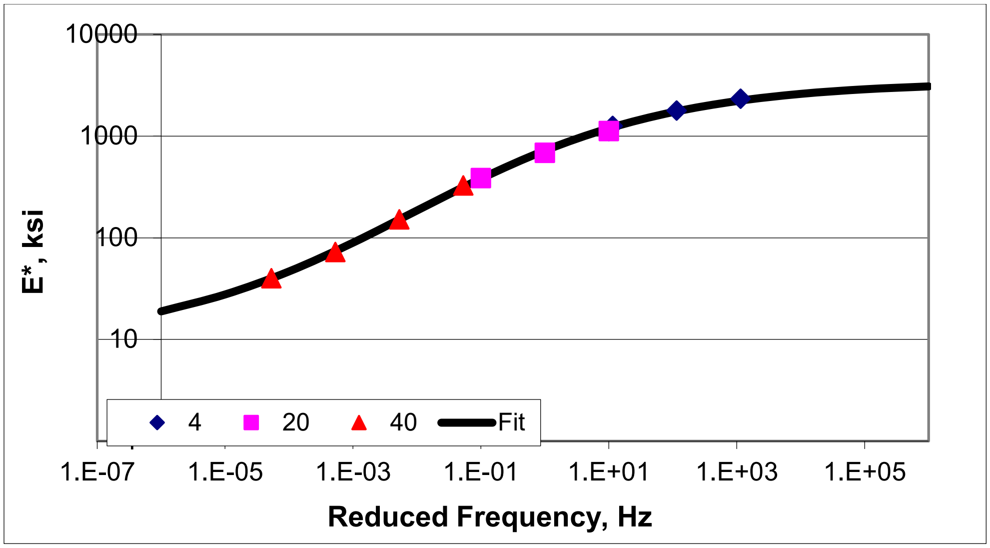


Figure 2.4 Master Curve (fit) Showing Individual Temperature Data

Users can develop their own optimization routine; however, in previous work, an Excel macro called Mastersolver, developed by Dr. Ramon Bonaquist, was used [5]. The Mastersolver version 2.3 uses the solver functions in Microsoft Excel for this numerical optimization. This is done by computing the sum of the squared errors between the logarithm of the average measured dynamic moduli at each temperature and frequency combination and the values predicted by Equation 3. The solver function is used to minimize the sum of the squared errors by varying the fitting parameters in the equation with the following initial estimates: $\delta = 0.5,\ \beta = -1.0, \gamma = -0.5, \Delta E_a = 200{,}000$. Finally, the standard deviation of the logarithm of the average measured dynamic modulus values for each temperature and frequency combination are computed. This value is designated as S_y.

The standard error of estimate is computed using Equation 7.

$$S_e = \left[\frac{1}{6}\sum_1^{10}\left(log\left|\hat{E}^*\right|_i - log\left|E^*\right|_i\right)^{0.5}\right] \qquad \text{Equation 7}$$

Where:

S_e = standard error of estimate
$log\left|\hat{E}^*\right|_i$ = value predicted by Equation 3 after optimization for each temperature/frequency combination
$log\left|E^*\right|_i$ = logarithm of the average measured dynamic modulus for each temperature/frequency combination

The explained variance, R^2, is computed using Equation 8.

$$R^2 = 1 - \frac{8{S_e}^2}{9{S_y}^2} \qquad \text{Equation 8}$$

Where:

R^2 = explained variance

S_e = standard error of estimate from Equation 3

S_y = standard deviation of the logarithm of the average dynamic modulus values

The fitted master curve is then evaluated for the ratio of S_e to S_y that should be less than 0.05 and the explained variance should exceed 0.99. The AASHTOWare Pavement ME® inputs are then determined by substituting the logarithm of the limiting maximum modulus (Max) and the fitting parameters (ΔE_a, $\delta, \beta, and\ \gamma$) into Equation 3 and computing the dynamic modulus at the specified temperatures and frequencies. An example of this is shown in Table 2.3.

Table 2.3 Sample AASHTOWare Pavement ME Input Values

This table may be copied directly into AASHTOWare. E* values in PSI						
Temperature (°F)	Frequency (Hz)					
	0.1	0.5	1	5	10	25
14	2237997.916	2518993.248	2623497.894	2828775.368	2902164.2	2986721.649
40	1192227.25	1560835.92	1719390.846	2069457.272	2208123.98	2377447.739
70	347684.1247	554711.9467	666740.7636	974846.4466	1123957.122	1330397.067
100	87071.5998	144146.7132	180091.0636	300458.0791	371593.799	486056.4273
130	31142.31662	45296.75541	54332.514	86347.84973	106891.6707	142881.8354

2.4 Summary

This chapter presented some basic background regarding the development of the AMPT and, specifically, the creation of the dynamic modulus master curve. Based on what was presented in this chapter, the following information is relevant to the project.

- Testing for dynamic modulus using the AMPT is a fairly involved process, which is perhaps the reason the test has not been universally adopted. In practice, only nine or 10 data points are collected for each mixture (3 or 4 testing frequencies and 3 temperatures). These 10 points are then used to create the dynamic modulus master curve.

- The master curve is based on visco-elastic theory and is fitted to a sigmoidal equation using curve-fitting techniques. The curve is described by only five parameters, one of which is related to mixture volumetrics, and the four others are fitted parameters. Knowing these parameters, the user can generate the dynamic modulus for any combination of frequency and temperature, thus providing inputs to the AASHTOWare Pavement ME® program.

3. HISTORICAL DATA

Between 2007 and 2010, the Utah Department of Transportation evaluated the feasibility of using the AMPT for mixture design. UDOT collected a significant amount of data that can be used as a starting point for this research. Looking at these historic data can complement any results obtained from the mixtures to be tested as part of this project.

3.1 Description of Data

Dynamic modulus data for 34 projects were analyzed. Some material was obtained from the field, and some was mixed in the lab. Each project consisted of four replicate specimens with a total of 136 individual specimens. These specimens were each subjected to 10 nondestructive testing cycles consisting of different combinations of frequency and temperature. This resulted in approximately 1,360 individual data points. The information regarding each project is presented in Table 3-1 on the next page. This table contains the project name and date as well as the binder grade and source, recycled asphalt pavement (RAP) content, asphalt content, air voids, bulk specific gravity, and identification code. In the far-left column, there is a check box used as part of the analysis. It creates a dynamic modulus master curve for the project using the MasterSolver program described earlier in this report.

3.1.1 Results

Using the results from the 34 projects described in Table 3.1, the dynamic modulus master curves were examined to determine if they corresponded to different mixtures or mixture properties. When the curves were coded for the binder used in the mix design, a distinct separation became clear. The mixtures made with PG 70-XX asphalt binder had overall higher dynamic modulus in comparison with the mixtures made with PG 64-XX binder. This result was expected due to the PG 70-XX binder having higher stiffness than the PG 64-XX. The AMPT appears to have the ability to group projects of the same binder grade together. This is shown in Figure 3.1.

Table 3.1 Information on Projects Analyzed

Check Box for Master Curve Evaluation		Project	Date (tested on)	Binder	RAP (%)	Asphalt Content (%)	Air Voids (%)	Gsb	Identification
☐ Check	1	US-6 MP 218.7 to Emma Park (Field Mix #2)	12/14/2010	C	15	4.65	3.5	2.758	1-C-R(15)
☐ Check	2	US-6 MP 218.7 to Emma Park (Field Mix #1)	12/8/2010	C	15	4.65	3.5	2.758	2-C-R(15)
☐ Check	3	US-6 MP 218.7 to Emma Park Road (Lab Mix #2)	5/11/2010	C	15	4.6	3.5	2.758	3-C-R(15)
☐ Check	4	US-6 MP 218.7 to Emma Park (Lab Mix #1)	5/10/2010	C	15	4.65	3.5	2.758	4-C-R(15)
☐ Check	5	Legacy Segment #2 (Field)	2/23/2010	A	15	4.6	3.5	2.693	5-A-R(15)
☑ Check	6	US-491, Monticello to MP 7 (Field Mix)	2/16/2010	E	0	4.8	3.6	2.396	6-E
☐ Check	7	I-80, Wahsatch to Wyoming State Line (Lab)	1/26/2010	D	0	4.75	3.1	2.626	7-D
☑ Check	8	US-491, Monticello to MP 7 (Lab Mix)	1/5/2010	E	0	4.8	3.6	2.396	8-E
☐ Check	9	Legacy Segment #1 (Field)	11/23/2009	B	15	4.6	3.5	2.693	9-B-R(15)
☐ Check	10	US-40, Clegg Canyon to Strawberry Valley (Lab Mix)	8/25/2009	D	15	4.6	3.3	2.412	10-D-R(15)
☐ Check	11	Legacy Segment #2 (Lab)	8/11/2009	B	15	4.6	3.5	2.693	11-B-R(15)
☐ Check	12	Legacy Segment #1 (Lab)	7/28/2009	B	15	4.6	3.5	2.693	12-B-R(15)
☐ Check	13	I-15, Arizona St. Ln. to Bluff Street (Field Mix #2)	7/14/2009	B	0	5	3.5	2.617	13-B
☐ Check	14	I-15, Arizona St. Ln. to Bluff Street (Field Mix #1)	6/29/2009	B	0	5	3.5	2.617	14-B
☐ Check	15	I-15, Arizona St. Ln. to Bluff Street (Lab Mix)	2/11/2009	B	0	5	3.5	2.617	15-B
☐ Check	16	Fort Pierce #2	2/11/2009	B	0	5	3.5	2.617	16-B
☐ Check	17	US-40, Clegg Canyon to Strawberry Valley (Field Mix #4)	10/28/2008	D	15	4.6	3.3	2.412	17-D-R(15)
☐ Check	18	Fort Pierce #1	10/27/2008	B	0	5	3.5	2.617	18-B
☐ Check	19	US-40, Clegg Canyon to Strawberry Valley (Field Mix #3)	7/2/2008	D	15	4.6	3.3	2.412	19-D-R(15)
☐ Check	20	US-40, Clegg Canyon to Strawberry Valley (Field Mix #2)	6/4/2008	D	15	4.6	3.3	2.412	20-D-R(15)
☐ Check	21	US-40, Clegg Canyon to Strawberry Valley (Field Mix #1)	5/29/2008	D	15	4.6	3.3	2.412	21-D-R(15)
☐ Check	22	I-80, Wahsatch to Wyoming (Field)	5/21/2008	D	0	4.75	3.1	2.626	22-D
☐ Check	23	I-80, Wahsatch to Wyoming (Field)	5/15/2008	D	0	4.75	3.1	2.626	23-D
☐ Check	24	I-80, Wahsatch to Wyoming (Field)	5/9/2008	D	0	4.75	3.1	2.626	24-D
☐ Check	25	I-80, Wahsatch to Wyoming (Field)	5/1/2008	D	0	4.75	3.1	2.626	25-D
☐ Check	26	I-80, Wahsatch to Wyoming (Lab)	4/27/2008	D	0	4.75	3.1	2.626	26-D
☐ Check	27	SPT #L1	3/5/2008	F	No Info	No Info	No Info	No Info	27-F
☐ Check	28	SPT #L2	3/3/2008	F	No Info	No Info	No Info	No Info	28-F
☐ Check	29	Geneva W-Pioneer	1/9/2008	F	No Info	No Info	No Info	No Info	29-F
☐ Check	30	Cox W-Crown	12/6/2007	F	No Info	No Info	No Info	No Info	30-F
☐ Check	31	Cox Pit W-Idaho (Field Mix #1)	10/12/2007	F	No Info	No Info	No Info	No Info	31-F
☐ Check	32	Cox Pit W-Pioneer	10/2/2007	F	No Info	No Info	No Info	No Info	32-F
☐ Check	33	Cox Pit W-Idaho (Field Mix #2)	9/13/2007	F	No Info	No Info	No Info	No Info	33-F
☑ Check	34	Echo TLA 2002 Samples	1/28/2007	F	No Info	No Info	No Info	No Info	34-F

Binder Reference		
	SEM PG 70-28 =	A
	Peak PG 70-28 =	B
	Paramount PG 64-34 =	C
	SEM PG 64-34 =	D
	Peak PG 64-34 =	E
	Assumed PG 64-34 =	F
	Wisconsin PG 58-28 =	G
	Wisconsin PG 70-28 =	H

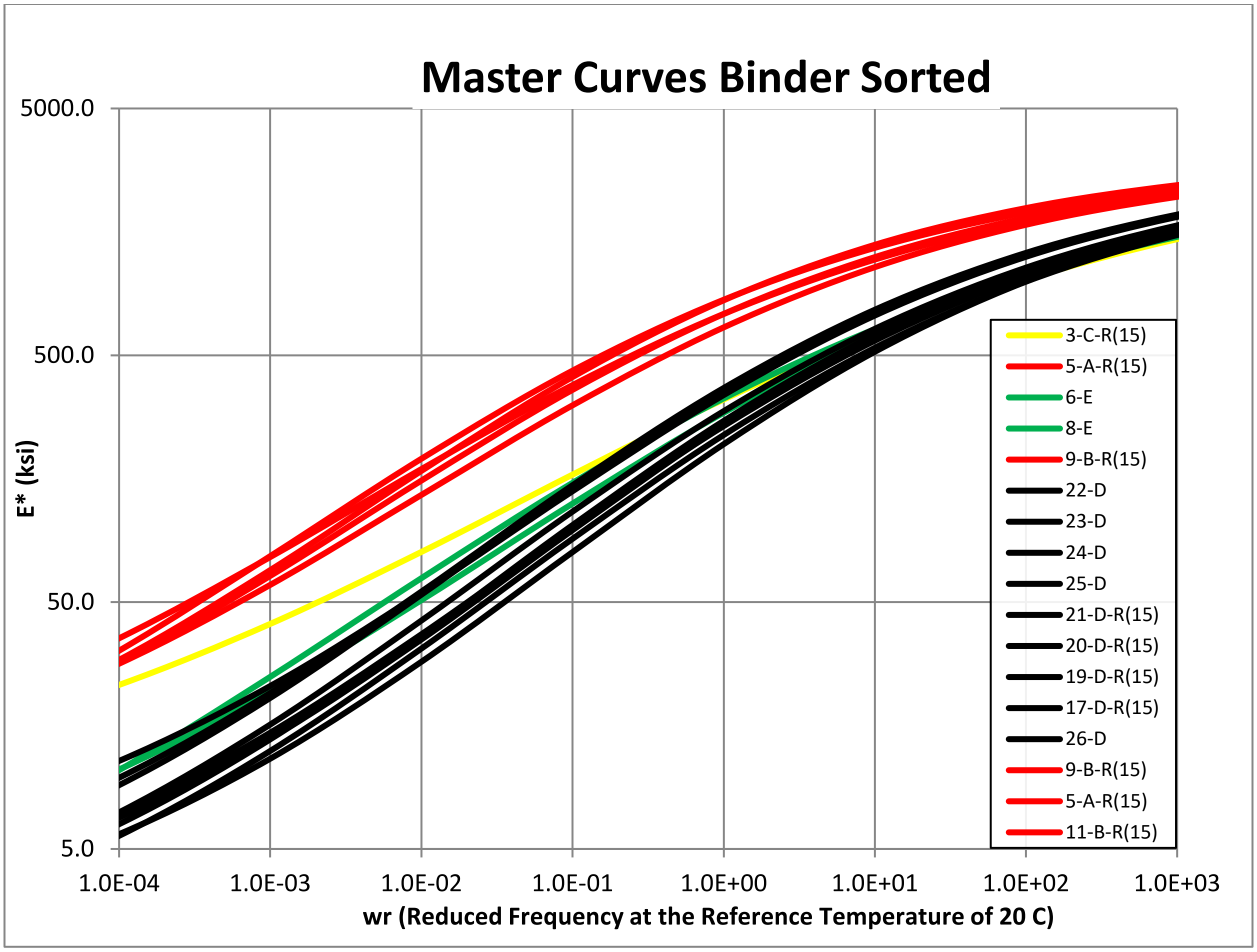


Figure 3.1 Dynamic Modulus Master Curves Sorted by Asphalt Binder Grade
(Red is PG 70-XX, black is PG 64-XX)

When the mixtures were sorted by volumetric properties, it was found there was not a significant enough difference in volumetric properties to establish any simple patterns in the master curves. As shown in Table 3.1, the range in asphalt binder content ranged from 4.6% to 5.0% and the RAP content was either zero or 15%. It is known that RAP has a more significant effect when added above 15%.

3.1.2 Parameters

As previously mentioned, five parameters are determined when creating a dynamic modulus master curve. These parameters are: Max, ΔEA, δ, $\beta, and\ \gamma$. Max is calculated directly from the volumetrics of the mix, so this is not considered a fitted parameter. Table 3.2 shows the ranges of each parameter separated by binder grade.

Table 3.2 Parameter Ranges for Each Binder Grade

Parameter	PG 70-28			PG 64-34		
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
Max E* (ksi)	3384	3419	3409	3317	3438	3376
Min E* (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

After examining the values shown in Table 3.2, it is seen that beta has the most sensitivity to capture high-temperature binder grade with an average of -1.25 for PG 70-28 and -0.76 for PG 64-34. The average value of gamma is essentially the same for both binder grades. It shows, however, a larger range of data values for the PG 64-34 binders than for the PG 70-28 binders, perhaps indicating an asymptote. The parameter ΔEA, which is used to generate the time-temperature shift factors, shows very little variation in values within all of the mixtures evaluated of the same binder grade. This implies that there is very little variation in the time-temperature shift factor of the mixtures evaluated. In other words, a value of 198,000 could be used for all mixtures without much loss in predictive capabilities.

The ranges shown in Table 3.2 represent the boundaries of the mixtures tested in Utah. To compare and ensure the validity of the data, a set of tests done on Wisconsin asphalt mixtures and reported by Bonaquist was also evaluated [8]. Using the reported data, the fitting parameters from Utah mixtures were compared with the Wisconsin mixtures. This is shown graphically in Figure 3.2. In general, the value of beta is slightly higher for the Wisconsin mixtures as compared with the Utah mixtures. This is consistent considering that some of the Wisconsin mixtures contain PG 58-34 binders, as it seems that high beta values imply lower high-temperature grade.

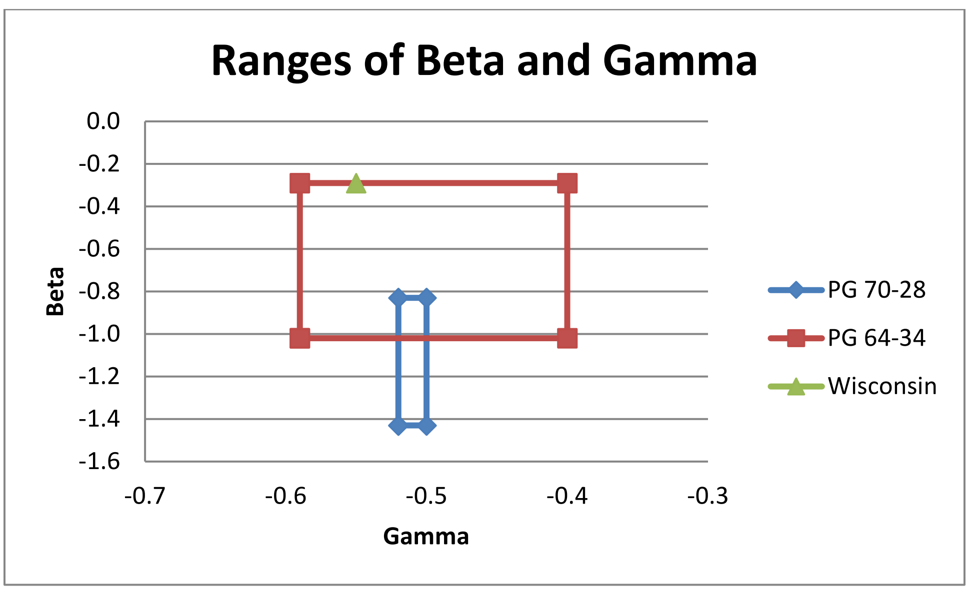


Figure 3.2 Ranges of Gamma and Beta for Utah Mixtures Evaluated with the Average for Wisconsin Mixtures

3.2 Comparison in Performance Prediction

As part of the original analysis, performance predictions were made using the MEPDG (as AASHTOWare Pavement ME® was formerly known) for two cases. In one case, the complete dynamic modulus master curve was used (Level 1 input). In another case, aggregate gradation and binder properties were used to estimate the properties (Level 2 input). This was done to illustrate the importance of having Level 1 input data. The resulting predictions for rutting at 20 years are shown in Figure 3.3.

As can be seen, there is a 50% decrease in predicted rutting over the life of this pavement when Level 1 input is used. This should be expected as there is a decrease in reliability when Level 2 input is used. This illustrates the importance of having a reliable way to predict the dynamic modulus master curve.

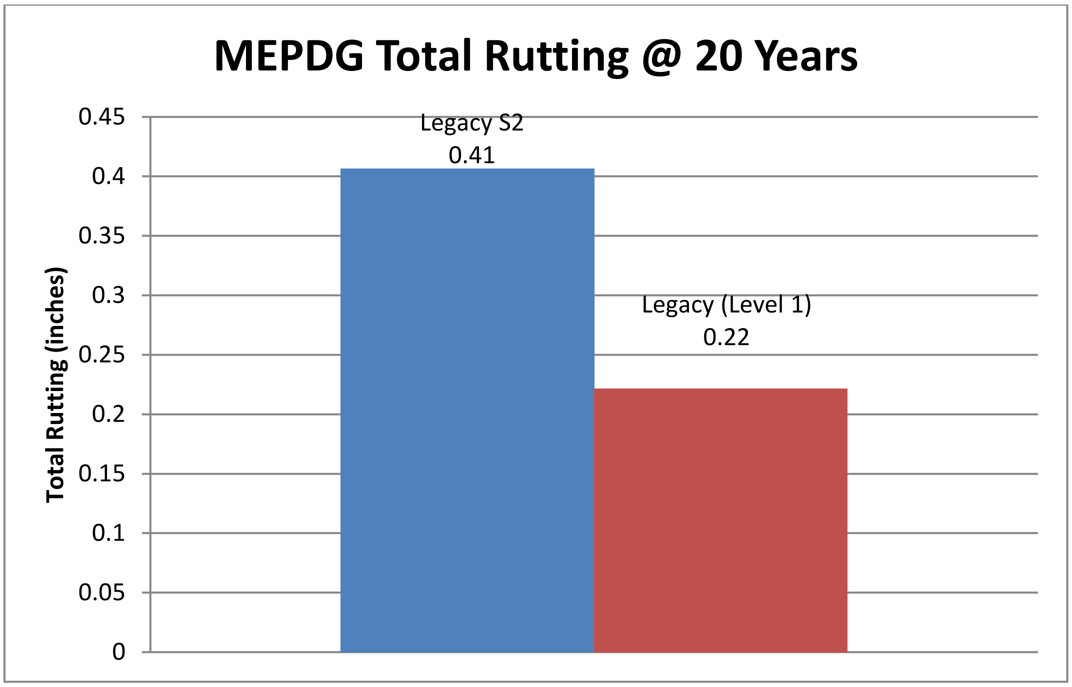


Figure 3.3 Comparison of Prediction for Level 1 and Level 2 Inputs

3.3 Summary

This chapter presented some historical data on 34 asphalt mixtures tested between 2007 and 2010. The data were used to determine the ranges of the four parameters used to create the dynamic modulus master curve.

Based on what was presented in this chapter, the following information is relevant to this project:

- Based on the data analyzed, it is evident that binder grade is a very significant contributor to the master curves. This would indicate that the AMPT has the ability to differentiate binder grades and should relate to other tests capable of doing so.
- It is unknown if the dynamic modulus follows a predictable pattern regarding volumetric properties. However, it is suspected that high RAP content might be detected. The lack of variation in the mix designs may be the reason that only binder grade affects the dynamic modulus values measured by the AMPT.
- There is a noticeable improvement in the reliability of the performance predictions when Level 1 inputs are used. This indicates the importance of having a reliable way to predict the dynamic modulus master curve.

This chapter demonstrated that there are certain characteristics in mixture components that affect the shape of the E* master curve, asphalt binder being the most significant so far. It is known that binder grade affects the mixture performance and that the IDEAL-CT tests are capable of capturing binder properties. Therefore, it is reasonable to think that the IDEAL-CT will relate to the E* master curve in some form or another.

Of interest is the parameter ΔEA, which showed very little variance in the historical data. This parameter is used to develop the temperature shift factors (see Equation 4). That means it should be possible to estimate the shift factors since they do not change between mixes. This should be verified when the new mixtures are tested.

4. THEORETICAL BACKGROUND

4.1 Overview

This chapter describes the theoretical background, based on energy principles, which justifies the development of a relation between the IDEAL-CT test at intermediate temperatures and the dynamic modulus. It is meant to show that the relation between the different mechanical tests is appropriate as long as the tests measure the mechanical response of the material.

4.2 Work and Energy

In physics, whenever a force acts upon an object while it is moving, work is said to have been done upon that object by that force. Work is the energy transferred to or from an object via the application of force along a displacement [9]. Work and energy are related; therefore, it can be argued, based on conservation principles of thermodynamics, that the response of an object from the work done during a mechanical test is the transfer of energy to another form. For example, the work done by the equipment during fracture testing is transferred to the creation of a new surface (minus typical system losses).

Other manifestations of energy transfer might include increased heat or material flow [10]. For the case of asphalt materials, the testing can become very complex due to the very different behavior of this material at different in-service temperatures or at different loading rates. At intermediate in-service temperatures, the behavior is even more complex since both solid and semi-solid characteristics can be simultaneously observed. The challenge of mechanical testing is isolating the specific energy transfer and then relating it to specific material distress and eventually to the expected performance. Most tests that have been adopted for asphalt mixtures claim such a relation to performance in one form or another.

This concept is represented graphically in Figure 4.1.

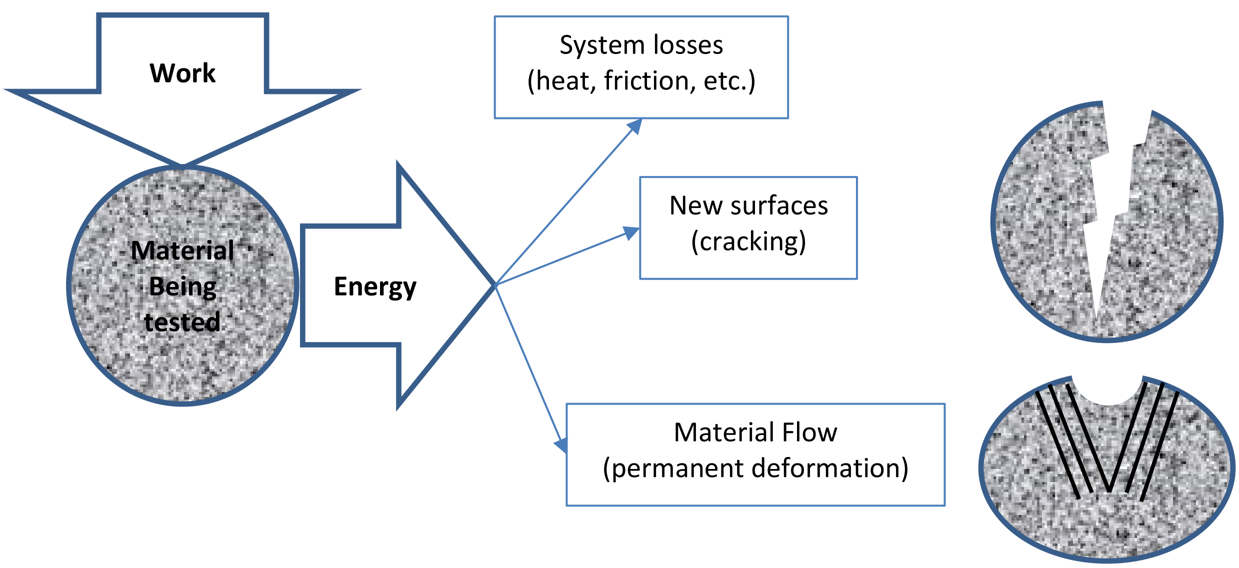


Figure 4.1 Representation of Work and Energy Transfer Concept

4.3 Dynamic Modulus

The dynamic modulus is defined as the peak stress divided by the peak strain at a specific frequency and temperature combination. This is the overall stiffness of the asphalt concrete mixture at that given condition. During the test, an asphalt concrete cylindrical sample is subjected to a steady-state haversine loading condition of a magnitude such that the material response remains within the linear range. The test is done at different frequencies which, based on the time-temperature correspondence principle, correspond to different conditions of both loading and temperature. The applied stress and the resulting strain of the specimen are measured and used to calculate the dynamic modulus and the phase angle.

The phase angle is defined as the angle, in radians, between the applied peak stress and the resulting peak strain in a controlled stress test. The phase angle is said to relate to the ability of the material to store or dissipate energy. Within one specific condition of temperature, the applied stress of constant amplitude is modeled by Equation 9.

$$\sigma_{(t)} = \sigma_0 \cdot sin^2(\omega t) \qquad \text{Equation 9}$$

Where:

$\sigma_{(t)}$ is the stress at time t

σ_0 is the stress amplitude

ω is the angular frequency

The response will be a strain of the same frequency but lagging behind by a time δ, and represented by Equation 10:

$$\varepsilon_{(t)} = \varepsilon_0 \cdot sin^2(\omega t - \delta) \qquad \text{Equation 10}$$

Where:

$\varepsilon_{(t)}$ is the strain at time t

ε_0 is the stress amplitude

δ is the time delay, called the phase angle, in units of radians.

In this case, the period is $T = 2\pi/\omega$ and the frequency is 1/T. Note that the sine squared function is used to represent the haversine wave applied during testing (i.e., no tension is applied to the specimen). This is represented in Figure 4.2.

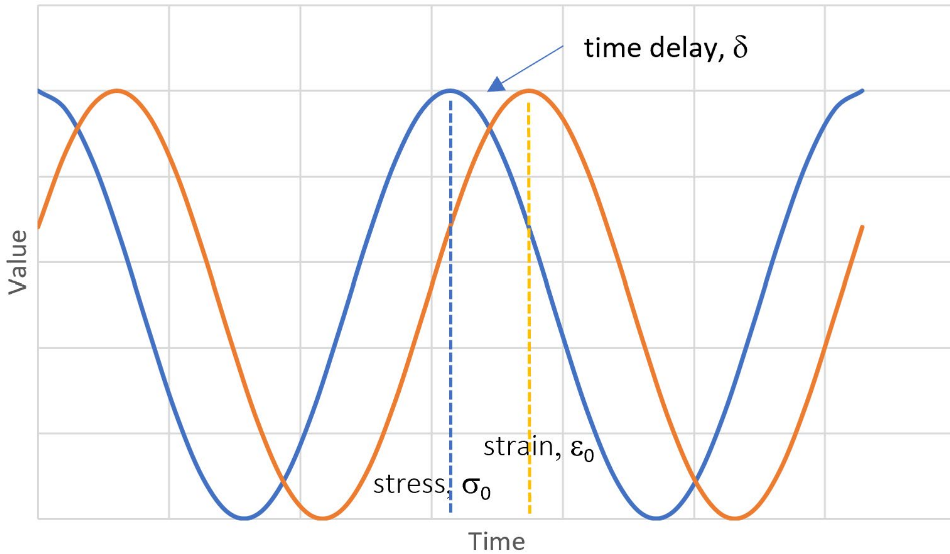


Figure 4.2 Representation of Haversine Loading and Corresponding Response

The dynamic modulus is defined as $E^* = \frac{|\sigma_0|}{|\varepsilon_0|}$. The work done by the stress over a cycle T is described in Equation 11.

$$\Delta W = \int_0^{\frac{2\pi}{\omega}} \sigma_{(t)} \frac{\delta \varepsilon_{(t)}}{\delta t} dt \qquad \text{Equation 11}$$

Equation 11 represents the area under the σ – ε curve during a given cycle; with some simple calculus and substituting the limits, Equation 12 is obtained.

$$\Delta W = -\pi \cdot \sigma_0 \cdot \varepsilon_0 \cdot sin(\delta) \cdot cos(\delta) \qquad \text{Equation 12}$$

Since $E^* = \frac{|\sigma_0|}{|\varepsilon_0|}$ and strain is the response, a substitution for ε_0 is done and the negative sign is ignored since the total energy magnitude is of interest, and Equation 13 is obtained.

$$\Delta W = \pi \cdot \frac{\sigma_0^2}{E^*} \cdot sin(\delta) \cdot cos(\delta) \qquad \text{Equation 13}$$

Using a trigonometric identity, Equation 14 is obtained.

$$\Delta W = \pi \cdot \frac{\sigma_0^2}{2 \cdot E^*} \cdot sin(2\delta) \qquad \text{Equation 14}$$

During a given test condition the stress is kept constant; therefore, it can be said that the work done per cycle is inversely proportional to the dynamic modulus, E*, and multiplied by the sine of 2δ. This is expressed in Equation 15.

$$\Delta W \propto \frac{sin(2\delta)}{E^*} \qquad \text{Equation 15}$$

The term "proportional" is used since, as shown in Figure 4-1, some energy is always lost in the system.

At conditions that represent low in-service temperatures, this work is the energy that relates to the relaxation of stresses and the creation of a new crack, resulting in a distress referred to as thermal cracking. At conditions that represent high in-service temperatures, this work is the energy that relates to flow, resulting in a distress referred to as permanent deformation or rutting. At conditions that represent intermediate temperatures, the work probably relates to both mechanisms; however, at high frequencies (fast loading), it is likely that a significant component of the energy flow relates to the material's ability to resist the creation of a new crack surface.

In the above discussion and derivation, it is assumed that the form of loading is stress-controlled; otherwise, the relation shown in Equation 15 would have the dynamic modulus in the numerator. In either case, it is argued that there is some proportionality between the material properties and the work done by the test, which can be related to expected material performance. The actual level of proportionality between test results and material performance is the subject of further research.

4.4 Intermediate-Temperature Mix Design and QC Tests

The characterization of asphalt mixtures for cracking at intermediate temperatures is normally done using two simpler, index-based tests, the IFIT and the IDEAL-CT, resulting, respectively, in the flexibility index (FI) or the cracking tolerance (CT) index. The first test evaluates the force-displacement curve of a semi-circular test loaded in bending with a notch in the middle. The second test evaluates the force-displacement curve in an indirect tension test. Both tests claim to relate to asphalt pavement fatigue cracking, an intermediate-temperature distress, by way of relating the area under the force-displacement curve to the energy spent in the creation of a new crack surface.

Of interest is that both of these tests apply forces to the specimen. Conceptually, an asphalt mixture specimen can have better field performance (i.e., not show excessive permanent deformation or prevent the formation a new crack surface) by resisting the forces applied during loading and "storing" as much energy as possible. As illustrated in Figure 4-1, once energy is released, it goes into the formation of a new crack surface or into flow (permanent deformation) depending on the temperature and other loading conditions.

Out of the two tests described, the IDEAL-CT is gaining popularity due to its simplicity, even though the mechanics of it are far from being clearly understood. The test requires minimal specimen preparation or instrumentation. It is meant as a quality control for routine use and not necessarily as a performance predictor [11]. The developers claim that it relates to the cracking of asphalt mixtures at intermediate temperatures. According to their analyses, which are based on Paris and Edogan's relation [12] and work done by Bazant and Prat [13], the cracking parameter named CI Index, shown in Equation 16, was derived.

$$CT_{index} = \frac{Gf}{|m_{75}|} \cdot \frac{l_{75}}{D} \qquad \text{Equation 16}$$

Where

Gf is the energy required to create a unit surface area of a crack, as shown in Figure 4-3

$|m_{75}|$ is the secant slope between 85% and 65% of the peak load point of the load-displacement curve after the peak

l_{75} is the deformation tolerance at 75% of maximum load

D is a normalization parameter.

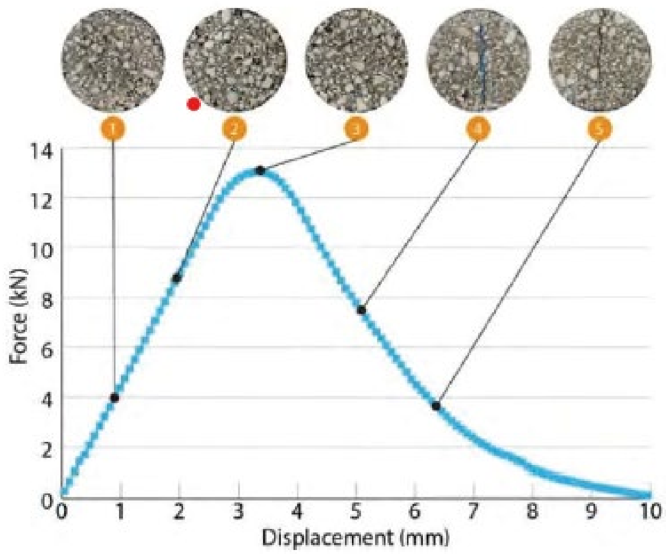


Figure 4.3 Relation Between Force-Displacement Curve and Crack Development (from Zhou **[11]**)

4.5 Relation Between Dynamic Modulus and CT Index

The development of both the dynamic modulus and the CT Index shows that the work done during testing is related to the response of the material. Such response will depend on several factors, including test temperatures and rate of loading. Furthermore, it must be understood that in both the dynamic modulus and the CT Index, more than one distress behavior is present at any time but each with different magnitudes (i.e., primarily cracking or primarily permanent deformation). In the case where the material's response results in some form of cracking, a portion of that energy must go into the creation of a new surface. Different materials will require different amounts of work to be done to develop a crack and thus, to some degree, there is a certain amount of energy that is a measurement of crack resistance. This is the basis of the IDEAL-CT. Since both the dynamic modulus and the CT Index provide some mechanical response, it is not too much of a stretch to hypothesize a relation, albeit not a direct one, between the parameters obtained from both tests. Based on Equations 15 and 16, Equation 17 is proposed.

$$Gf \propto \frac{sin(2\delta)}{E^*} \qquad \text{Equation 17}$$

The relation shown in Equation 17 shows that the fracture energy, Gf, is inversely proportional to the modulus. This is confirmed, albeit intuitively, by many practitioners who have known that high modulus mixtures usually lead to more cracking.

Finally, Equation 17, if shown to be correct, has many potential benefits. As previously alluded to, relating the dynamic modulus, a property used during the structural design of pavement, to the fracture energy, a property obtained during routine QC/QA testing, will allow us to develop "what-if" scenarios with materials of different properties resulting in true optimization. For example, a thinner pavement can be designed which specifies a minimum CT Index. Alternatively, a dynamic modulus curve can be approximated based on actual local materials instead of using generic values, resulting in a more robust structural pavement design and performance predictions.

4.6 Summary

This chapter describes a concept based on the conservation of energy. It is hypothesized, based on the work done by the equipment during the dynamic modulus tests, that the E* of a material is inversely related to the fracture energy as determined by the IDEAL-CT. Similar relations can also exist in other tests.

5. DATA TESTING AND ANALYSIS

5.1 Introduction

To evaluate the feasibility of relating E* data and fracture energy from the IDEAL-CT, field mixtures from six different projects were collected in 2021. These mixes will be used throughout the project to establish the proposed relations. Unfortunately, given the limited funding available on this project, only limited testing is possible; testing includes the determination of the CI Index and limited dynamic modulus. All six mixtures were tested to determine their CI Index. The mixtures with high and the low values were also tested in the AMPT to determine their dynamic modulus master curve.

5.2 Materials

Materials from six different projects were collected from across Utah. The materials were collected from the windrows and stored in sealed metal containers. The materials were brought to the University of Utah where they were stored indoors. The identification parameters and location for each of the projects are presented in Table 5.1.

Table 5.1 Mix Locations

Mix Designation	Route Number	Location
Mix 1	SR 10	I-70 to 200 E Emery
Mix 2	SR 198	1100 E Payson to 300 South Sp. Fork
Mix 3	SR 150	Bear River Service to Wyoming Line
Mix 4	SR 90	SR-13 to SR-91 Brigham City
Mix 5	SR 302	Rock Port State Park
Mix 6	SR 112	SR-138 to SR-36

A map of the state of Utah showing the location of these mixtures is shown in Figure 5.1. The projects for the mixtures used in this research are highlighted in red on the map.

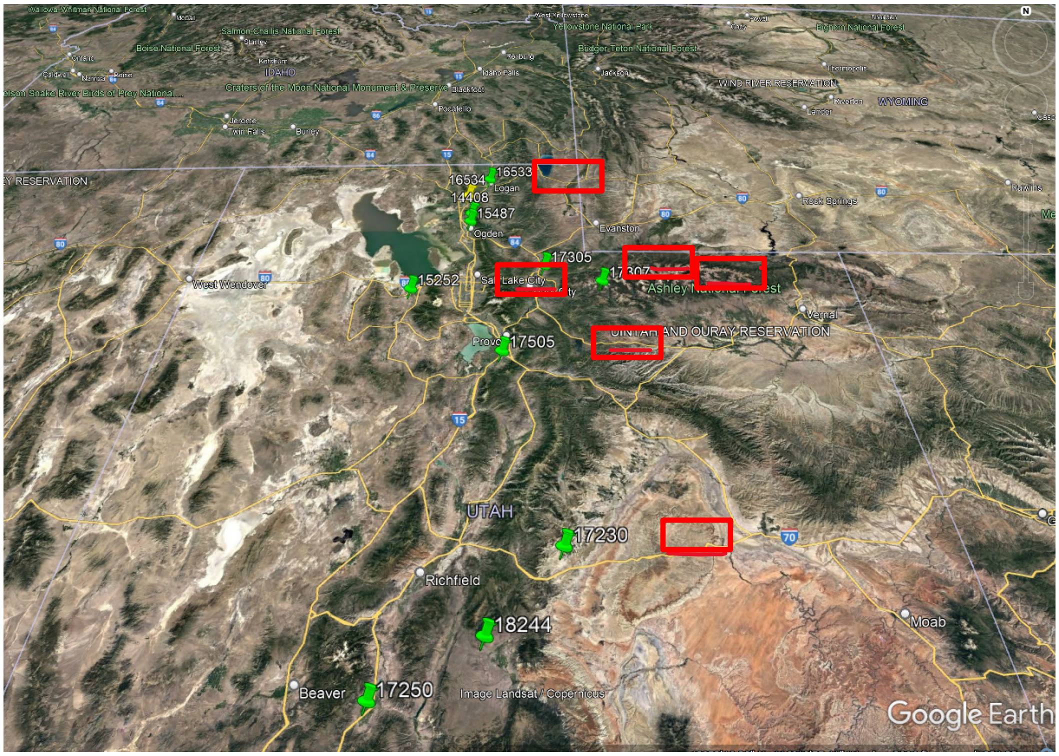


Figure 5.1 Location of all Projects

All of the mixtures were made with a PG 64-34 virgin binder and contained 25% RAP, by total weight. The general asphalt binder volumetric properties of each mixture are shown in Table 5.2.

Table 5.2 General Properties of the Mix (Virgin Binder PG 64-34)

Mix Designation	Total Binder Content, %	Virgin Binder Content, %	RAP Binder* Contribution, %
Mix 1	5.59	4.22	1.38
Mix 2	4.90	3.90	1.00
Mix 3	5.20	4.05	1.15
Mix 4	5.00	3.75	1.25
Mix 5	4.91	3.78	1.13
Mix 6	5.00	3.80	1.20

* all mixtures contained 25% RAP

5.3 IDEAL-CT Testing

All of the six mixtures were tested at the University of Utah to determine their cracking tolerance index. When the lab was ready for testing, the buckets with the asphalt mixture were heated overnight to a temperature of 120ºC while keeping the lid on to prevent further aging. Once the mix was pliable, enough material was sampled to measure its maximum specific gravity (Gmm). While it is known that slight differences between materials can exist due to segregation and sampling error, it was assumed that all of the material within a bucket and all of the buckets combined contained material with identical compositions.

Each asphalt mix was weighed based on the Gmm so that trial specimens could be compacted. The mix was heated to the appropriate compacting temperature and compacted to height using the Superpave Gyratory Compactor (SGC) following the procedures described in AASHTO T312: *Standard Method of Test for Preparing and Determining the Density of Asphalt Mixtures by Means of the Superpave Gyratory Compactor*. Once compacted, the air voids of each sample were determined following the procedures described in AASHTO T269: *Percent Air Voids in Compacted Dense and Open Asphalt Mixtures*. The number of gyrations to reach compaction and the air voids for each sample were recorded. Based on the trial samples, it was found that the number of gyrations required to reach compaction at a height of 62 mm exceeded 75 mm in all of the mixes. Therefore, it was decided to compact new samples to a height of 75 mm. Two sets of four samples were compacted and tested by two different operators to ensure reliability in the results. The results from both operators were consistent with each other; thus, only one set is presented here.

Testing was done based on ASTM D8225: *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. To ensure consistency, the samples were tested within eight to 20 hours after compaction.

The following data were measured for each set: air voids, fracture energy, tensile strength, and post-peak slope. The fracture energy and the post-peak slope were used to determine the CT Index based on Equation 16. These results are shown in Table 5.3.

Table 5.3 IDEAL-CT Test Results

Route Number	Average Number of Gyrations	Average Air Voids, %	Fracture Energy, J/m^2	Tensile Strength, kPa	Post-Peak Slope	CT Index
Mix 1	69	7.49	8544	978	-3.65	94
Mix 2	113	7.26	7236	854	-3.22	95
Mix 3	50	7.46	6583	859	-3.90	74
Mix 4	32	7.12	6870	845	-3.50	72
Mix 5	62	7.29	7902	1063	-5.35	52
Mix 6	75	6.97	6684	750	-2.71	105

All values in Table 5.3 represent the average of four or five samples. In the case where the coefficient of variation for the CT Index was above 25%, the data value furthest from the mean was eliminated. In all cases, this was a lower value resulting in a higher CT Index. The coefficient of variation for the fracture energy and the tensile strength was less than 7%, so no values were eliminated.

The values in Table 5.3 are shown in Figure 5.2.

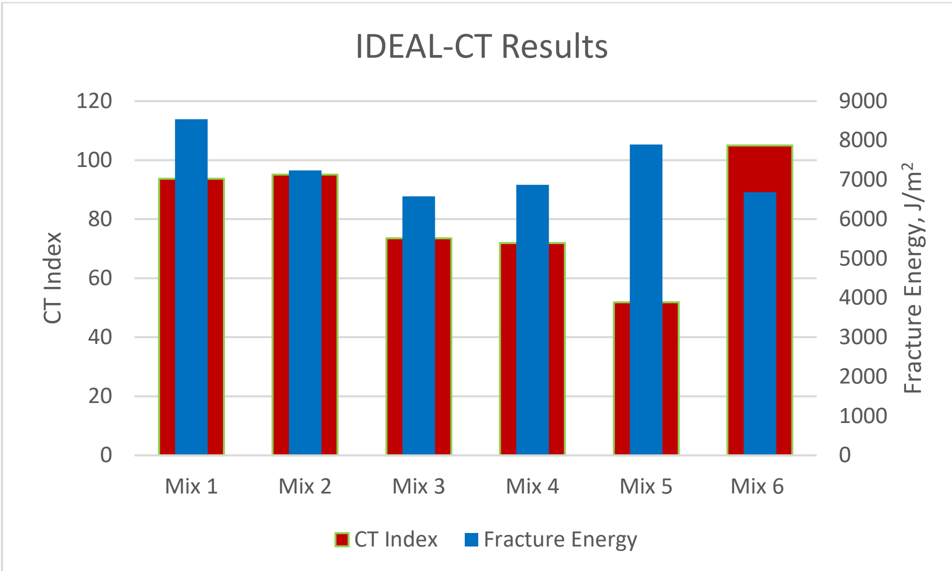


Figure 5.2 CT Index and Fracture Energy

Table 5.3 and Figure 5.2 show that, based on the CT Index, Mix 6 is expected to have the best cracking performance while Mix 5 is expected to have the worst cracking performance. It is noted that this ranking is not related to binder content. However, when looking at the fracture energy, the difference in expected performance is not as different. As seen in Table 5.3, the post-peak slope of Mix 5 is significantly lower (larger magnitude) than the rest, resulting in such a low CT Index. While evaluation of the IDEAL-CT test is not in the scope of this work, the behavior is seen as a testament to the complex behavior of asphalt materials where the strain tolerance, as represented by the post-peak slope, plays a role in its expected performance. Based on these results, Mix 1, Mix 5, and Mix 6, which represent the highest, lowest, and intermediate CT Index values, respectively, were selected for dynamic modulus testing.

5.4 Dynamic Modulus Testing

In order to validate the hypothesis presented in previous sections, many mixtures need to be tested. Unfortunately, that is not possible due to the limited funding available. Thus, only three of the six mixtures were tested.

Testing to determine the dynamic modulus of the mixtures was done following the procedures described in Figure 2.1. The test temperatures were selected based on Table 2.1; the frequencies were expanded by adding 25, 5, and 0.5 Hz. to better match the data input for the AASHTOWare Pavement ME® program.

For each mixture, three replicate samples were tested. As usual in this test, the data at the higher temperature were not as precise as the other temperatures, as the low modulus of the material decreases the signal-to-noise ratio. Nonetheless, the coefficient of variation of the three dynamic modulus replicates was less than 15% and often less than 10%. The phase angle has a lower value of less than 5%. Therefore, no values were eliminated. The complete results of the dynamic modulus and the phase angle are shown in Table 5.4.

Table 5.4 shows that the dynamic modulus decreases with increasing temperature and decreasing frequency. The opposite trend is observed with the phase angle. The table also shows that different relative behavior is observed at different temperatures (i.e., the relations at 4°C are different than the relations at 40°C). All of these are expected as the dynamic modulus covers a wide range of material behavior.

Table 5.4 Dynamic Modulus Test Results

		Mix 5		**Mix 6**		**Mix 1**	
Temp. °C	**Freq. Hz**	**Dynamic Modulus MPa**	**Phase Angle Degrees**	**Dynamic Modulus MPa**	**Phase Angle Degrees**	**Dynamic Modulus MPa**	**Phase Angle Degrees**
4	25	17281	10.00	15747	11.64	14711	10.05
4	10	16710	11.62	13986	13.24	13310	11.20
4	5	15012	16.38	12686	14.52	12294	12.16
4	1	10658	16.46	9712	17.95	9867	14.91
4	0.5	9204	17.55	8544	19.34	8861	16.24
4	0.1	6742	21.13	6044	23.13	6615	19.69
20	25	7704	21.33	8006	22.26	7177	20.57
20	10	6263	23.66	6417	24.57	5816	22.91
20	5	5323	25.00	5388	25.92	4927	24.33
20	1	3391	28.44	3353	29.15	3154	27.77
20	0.5	2772	29.09	2707	29.75	2592	28.45
20	0.1	1588	30.93	1535	31.11	1529	30.25
40	25	2243	31.28	2195	31.72	2470	30.29
40	10	1497	32.30	1437	32.65	1714	31.55
40	5	1137	31.81	1072	32.12	1321	31.37
40	1	571	30.91	528	31.01	684	30.85
40	0.5	444	29.53	410	29.57	533	29.67
40	0.1	259	27.02	248	26.03	305	27.42

A plot of the dynamic modulus as a function of frequency at 20°C is shown in Figure 5.3. The temperature of 20°C was selected since it is the closest one to the temperature used for the IDEAL-CT. As seen in the figure, the samples from Mix 6 had the highest E* while the samples from Mix 1 had the lowest E*. As noted, this relation is different at other temperatures.

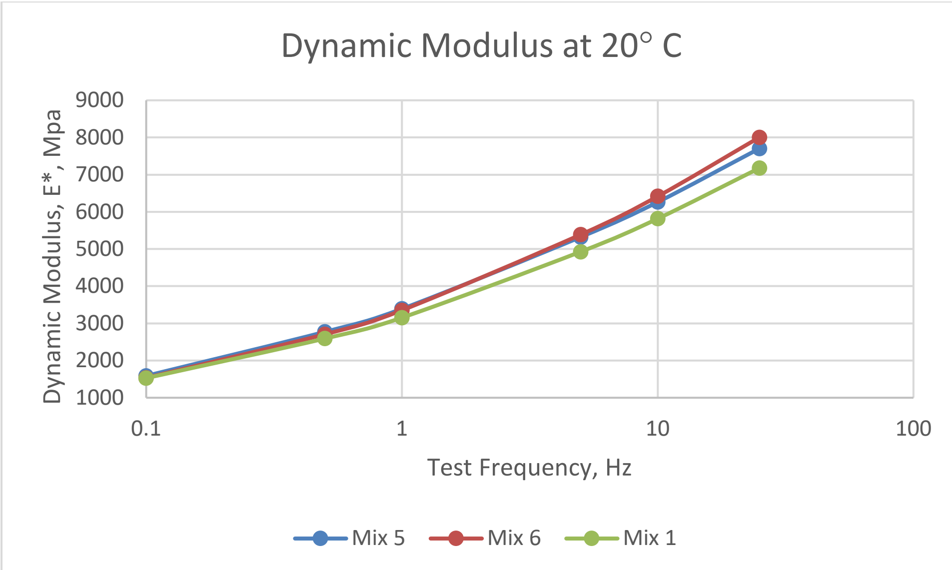


Figure 5.3 Measured Dynamic Modulus as a Function of Frequency at 20°C

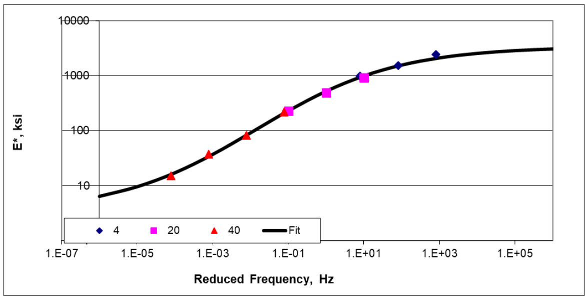
5.4.1 Master Curve Model

Based on the procedures described earlier in this document, a master curve, referenced at a temperature of 20°C, was created for each of the three mixtures tested. The resulting parameters, used for Equations 3 and 4, are shown in Table 5.5. As previously explained, these values define the master curve and are used to generate data at any temperature and frequency.

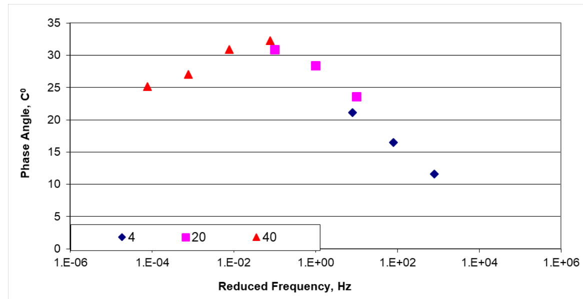
Table 5.5 Master Curve Fitted Parameters

	Mix 1	**Mix 5**	**Mix 6**
Parameter			
Max E*, ksi	3415.5	3415.5	3415.5
Min E*, ksi	2.6	3.3	2.2
Beta	-1.02009	-0.99896	-1.02943
Gamma	-0.49028	-0.53963	-0.50854
ΔEA	177905	185238	184000
R^2	0.992	0.994	0.998

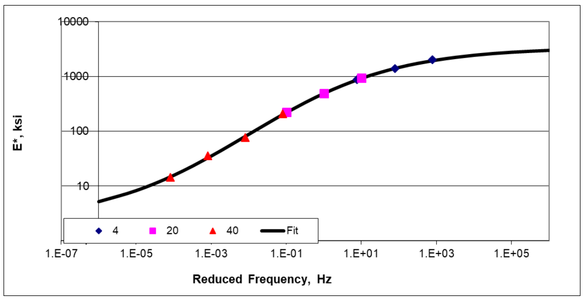
Comparing the fitted parameters in Table 5.5 with the averages previously shown in Table 3.2 shows that the parameters that characterize the materials are within the ranges previously determined for other Utah materials for a PG 64-34 binder. The value ΔEA for Mix 1 is the only one that fell outside the range. The parameters shown in Table 5.5 were used to generate dynamic modulus master curves and compare them to the measured values (converted to ksi). The results are shown in Figure 5.4 (a) through (f).



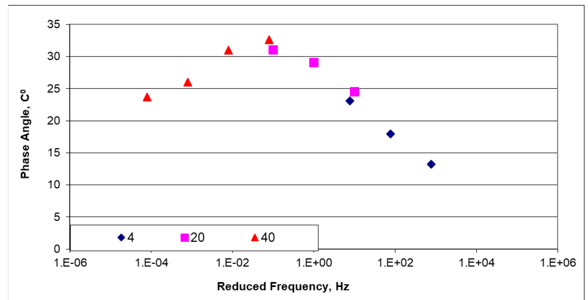
(a) Mix 5 Dynamic Modulus



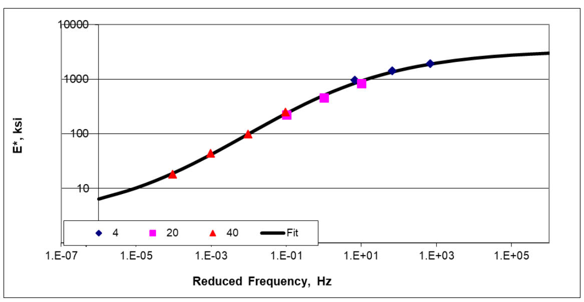
(b) Mix 5 Phase Angle



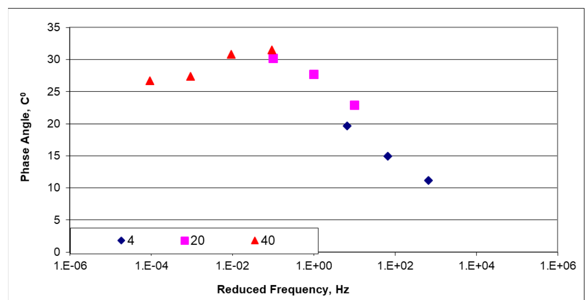
(c) Mix 6 Dynamic Modulus



(d) Mix 6 Phase Angle



(e) Mix 1 Dynamic Modulus



(f) Mix 1 Phase Angle

Figure 5.4 Fitted Master Curves and Phase Angle

Comparing the actual measured data shown in Figure 5.3 with the predicted data shown in Figure 5.4 indicates that the model did a good job in fitting the parameters to the master curve.

5.5 Analysis and Comparisons

The objective of this work is to determine if there is a relationship between the results from single-point tests like the IDEAL-CT with some portion of the dynamic modulus master curve based only on the actual measured data since modeling will be done in a separate study.

As shown in Figure 4.1, the response of the material can vary depending on the rate of loading and the temperature. At fast loading rates, the influence of flow should be small in comparison with cracking. Therefore, given the loading rate of 50 mm/min used during the IDEAL-CT test, the comparison between the IDEAL tests and the dynamic modulus is done at the highest test frequency of 25 Hz. As shown in Figure 5.3, other frequencies would result in similar comparisons. As previously discussed, the dynamic modulus should be inversely proportional to the fracture energy measured during the IDEAL tests. The modulus at 20°C is used for the comparison as it is the closest to the temperature of the IDEAL tests without requiring any modeling. The results are shown in Figure 5.5.

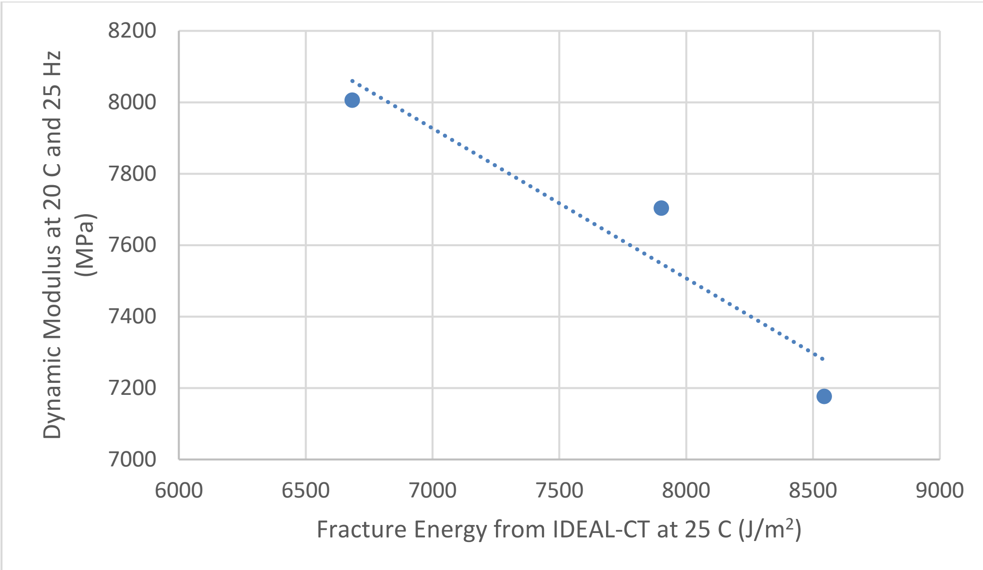


Figure 5.5 Relation Between the Dynamic Modulus and the Fracture Energy

As can be seen, the data show a reasonable inverse relation between the results from both tests. It is reasonable to assume that a material with higher modulus will act in a brittle manner, resulting in lower fracture energy.

Equation 17 predicts that the energy calculated from the dynamic modulus and the phase angle should relate to the fracture energy from the IDEAL test. This relation was evaluated using the measured values obtained at 20°C and 25 Hz. As seen in Figure 5.6, the relation is not linear but still reasonable. Values at other frequencies were also evaluated; however, the results were not as conclusive.

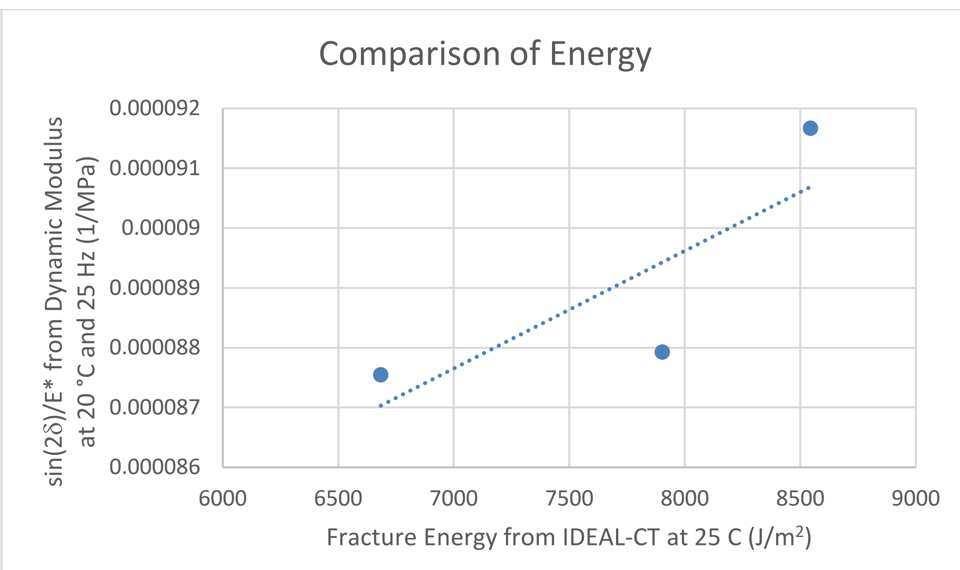


Figure 5.6 Relation Between Fracture Energy from the IDEAL Test and the Energy per Cycle from the Dynamic Modulus Test

5.6 Relation Between Dynamic Modulus IDEAL-CT Parameters

In order to eventually predict the complete dynamic modulus master curve, it is important to determine if the parameters that define such a curve relate to the values obtained from the IDEAL-CT tests. A high correlation might provide a strong argument that one can be used to predict the other. A correlation analysis was used between the values from Table 5.3 (from IDEAL-CT) and the values from Table 5.5 (from AMPT). The results are shown in Table 5.6.

The results shown in Table 5.6 show there is a high degree of correlation between the CI Index and the parameters that define the master curve (Min E*, Beta, and Gamma). These results, while encouraging, should be taken with caution since they are based on only three data points. Nonetheless, such a high correlation is encouraging and should be further explored.

Table 5.6 Correlation Between Test Parameters

	*Min E**	*Beta*	*Gamma*	*ΔEA*	*Fracture Energy*	*Slope*	*CT Index*
Min E*	1						
Beta	0.9980	1					
Gamma	-0.737	-0.779	1				
ΔEA	0.309	0.369	-0.871	1			
Fracture Energy	0.518	0.462	0.196	-0.653	1		
Slope	-1.000	-0.998	0.743	-0.317	-0.511	1	
CT Index	**-0.994**	**-0.999**	**0.807**	-0.412	-0.421	0.995	1

Note: Correlation based only on three tests

5.7 Discussion

The objective of this research is to evaluate the relation between the dynamic modulus, E*, and the single-point value obtained from the IDEAL test. As shown in Figures 5.5 and 5.6, there is a clear relation between the data obtained from both tests. Table 5.6 shows there is a strong correlation between the CT Index and the parameters that define the E* master curve. Further analysis is needed to validate those results using different asphalt mixtures.

6. Summary and Conclusions

6.1 Summary

This work has shown there is a clear relation between the IDEAL-CT test and certain parameters of the dynamic modulus master curve. Even though more analysis is needed, and only three mixtures were tested, the theoretically derived Equation 17 was shown to have merit, and the correlation between the parameters that define both tests is strong.

6.2 Conclusions

Based on the work performed as part of this research, the following is concluded:

1. A theoretical relation exists between the response of asphalt materials as determined using the IDEAL-CT tests (single-point, used for quality-control and mix verification) and the one determined by measuring the dynamic modulus (multiple-points, time-intensive tests). This relation was verified experimentally.
2. Parameters from the IDEAL-CT and parameters from the dynamic modulus tests have high correlation and, pending more data, could be used to predict one another.
3. While only limited data were available, using IDEAL-CT tests to predict the dynamic modulus and thus input to the pavement design software AASHTOWare Pavement ME® is considered feasible.

6.3 Suggestions for Future Work

The following suggestion are made regarding future work.

- Validate the results presented in this report by using different mixtures.
- Develop a framework that will allow the selection of dynamic modulus master curves as input to the AASHTOWare Pavement ME® program from IDEAL-CT data and eventually other tests.
- Verify intermediate-temperature cracking predictions by looking at actual field performance of the materials using Roadview Explorer®.

6.4 Limitations and Challenges

The results, while theoretically justified and experimentally validated, are based on limited materials. Mixtures with different properties should be tested.

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