RESEARCH

UDOT Keeping Utah Moving

Utah Department of Transportation - Research Division
4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

Report No. UT-22.18

MODELING THE DYNAMIC MODULUS OF ASPHALT MIXTURES USING SINGLE-VALUE TEST RESULTS

PHASE I: INITIAL RELATION WITH CRACKING TOLERANCE INDEX

Prepared For:

Utah Department of Transportation
Research & Innovation Division

Final Report
October 2022

DISCLAIMER

The authors alone are responsible for the preparation and accuracy of the information, data, analysis, discussions, recommendations, and conclusions presented herein. The contents do not necessarily reflect the views, opinions, endorsements, or policies of the Utah Department of Transportation or the U.S. Department of Transportation. The Utah Department of Transportation makes no representation or warranty of any kind, and assumes no liability therefore.

ACKNOWLEDGMENTS

The authors acknowledge the Utah Department of Transportation (UDOT) for funding this research, and the following individuals from UDOT on the Technical Advisory Committee for helping to guide the research:

- David Stevens
- Jason Simmons
- Lauriane Collins
- Howard Anderson

The following students from the University of Utah are an integral part of this work:

- Abdullah al Mamun
- Carlos Hermoza
- Beatriz Fieldkichner

Previous work cited in this report was also performed by:

- Ryan Ferrin
- Levi Roberts

The authors also acknowledge the financial support of the Mountain-Plains Consortium (MPC) that allowed this research to be possible.

TECHNICAL REPORT ABSTRACT

1. Report No. UT- 22.18	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle MODELING THE DYNAMIC MODULUS OF ASPHALT MIXTURES USING SINGLE-VALUE TEST RESULTS, PHASE I: INITIAL RELATION WITH CRACKING TOLERANCE INDEX		5. Report Date October 2022 6. Performing Organization Code N/A
7. Author(s) Pedro Romero, Ph.D., P.E. and Kevin VanFrank, P.E.		8. Performing Organization Report No. N/A
9. Performing Organization Name and Address The University of Utah Department of Civil and Environmental Engineering 110 South Central Campus Dr. Suite 2000 Salt Lake City, UT 84112		10. Work Unit No. 5H088 19H 11. Contract or Grant No. 22-8370
12. Sponsoring Agency Name and Address Utah Department of Transportation 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410		13. Type of Report & Period Covered Final Report October 2021 – October 2022 14. Sponsoring Agency Code PIC No. UT21.106

15. Supplementary Notes

Prepared in cooperation with the Utah Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

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 was conducted which confirmed that, 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, the theoretical analysis, and the 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.

17. Key Words Dynamic Modulus, asphalt mixtures, cracking tolerance index		18. Distribution Statement Not restricted. Available through: UDOT Research & Innovation Div. 4501 South 2700 West P.O. Box 148410 Salt Lake City, UT 84114-8410 www.udot.utah.gov/go/research		23. Registrant's Seal N/A
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 53	22. Price N/A	

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

UNIT CONVERSION FACTORS

Units used in this report and not conforming to the UDOT standard unit of measurement (U.S. Customary system) are given below with their U.S. Customary equivalents:

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

AMPT	Asphalt Mixtures Pavement Tester
BBR	Bending Beam Rheometer, refers to AASHTO TP-125
CT Index	Cracking Tolerance Index
E*	Dynamic Modulus
FHWA	Federal Highway Administration
HWTD	Hamburg Wheel Tracking Device
IDEAL CT	Indirect Tension Asphalt Cracking Test, refers to ASTM D8225
IFIT	Illinois Flexibility Index Test, refers to AASHTO TP-124
MEPDG	Mechanistic-Empirical Pavement Design Guide (Now AASHTOWare Pavement ME®)
NCHRP	National Cooperative Highway Research Program
PG	Performance Grade
RAP	Recycled/Reclaimed Asphalt Pavement
SGC	Superpave Gyratory Compactor
SPT	Simple Performance Tests (terminology no longer used)
UDOT	Utah Department of Transportation
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate

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 Utah Department of Transportation (UDOT) asphalt 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 confirms 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. Then three asphalt mixtures were 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 an NCHRP project. It was found that the parameters that determine 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.

1.0 INTRODUCTION

1.1 Problem Statement

The pavement structural design process and the asphalt materials that are used to build these pavements are currently disconnected in UDOT's practice. Asphalt mixture properties obtained from adopted quality-control or quality-assurance (QC/QA) 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/underestimating 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 Pavement Tester (AMPT). However, due to the complexities of the test, the use of the AMPT to collect specific materials 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 materials 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 being used for materials testing 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 QC/QA 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 approximately 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 by UDOT (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®). While it is understood that a one-to-one relation is unlikely to exist, the expectation is that such relation will allow for a selection of 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 cost optimization.

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

The specific objectives of Phase I 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 is 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 values of E* 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:

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 that is used to model the E* master curve and how it is obtained (i.e., what are 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 was 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.

1.5 Outline of Report

The outline of this Phase I final report is as follows,

- Introduction
- Literature Review
- Historical Data
- Theoretical Background
- Data Testing and Analysis
- Summary and Conclusions

2.0 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 was recognized for a mechanical test to complement the volumetric mixture design process. Throughout the years, many mechanical tests have been proposed, with some still being evaluated. The Asphalt Mixtures Pavement Tester, or AMPT, is one of such tests [1]. Initially, the AMPT was called the Simple Performance Test, SPT. However, as people started using it, they realized that such 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 modulus 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

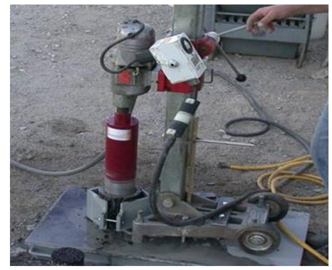
To obtain the dynamic modulus of asphalt concrete materials, a haversine axial compressive stress is applied to a cylindrical asphalt concrete specimen at a specified temperature and different loading frequencies. The applied stress and the resulting axial strain of the specimen are measured and used 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 given frequencies following the process described in Section 2.3.1. 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

The recommended temperatures and frequencies for different performance grade binders are shown in Table 2-1. In theory, other temperatures and frequencies can be used, resulting in the same predictions.

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 is 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 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.
C^0	Hz	Ksi	C^0	Ksi	C^0	Ksi	C^0	Ksi	C^0	Ksi	%	C^0	C^0
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

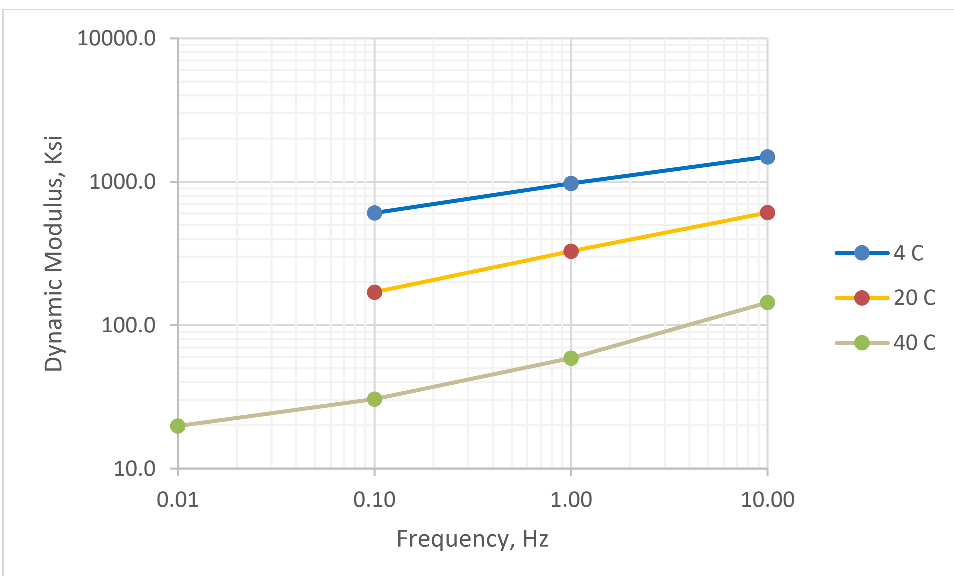


Figure 2-2 Plot of Dynamic Modulus Results

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.

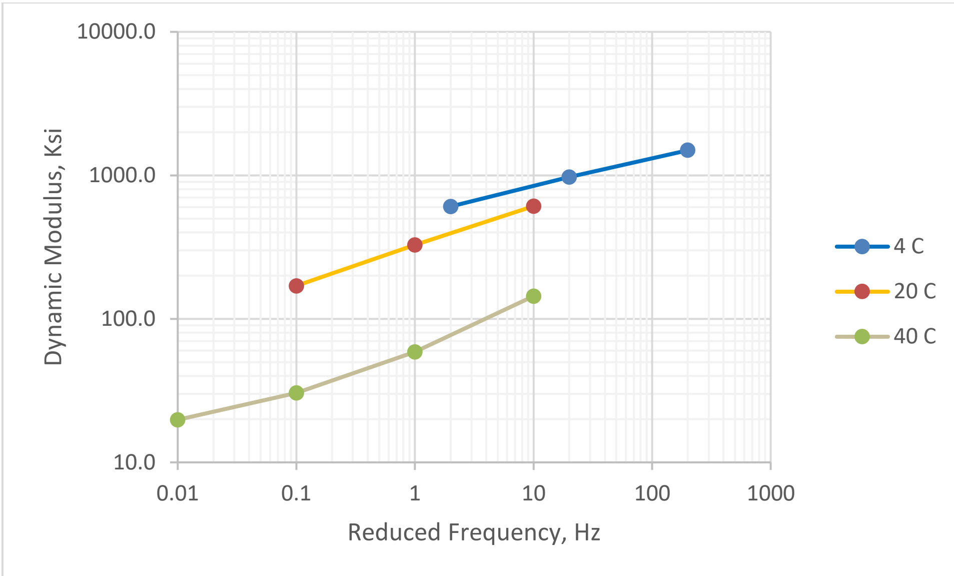


Figure 2-3 Plot of Dynamic Modulus with the 4 C Data Being Shifted

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:

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

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.

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

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:

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

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

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

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), Equations 5 and 6.

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

Where:

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

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. In the past, UDOT has chosen a reference temperature of 20 ℃ (293.15 °K); however, other temperatures should yield similar results.

Substituting Max and T_r into Equation 3 and then determining the four fitting parameters of the equation (ΔE_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.

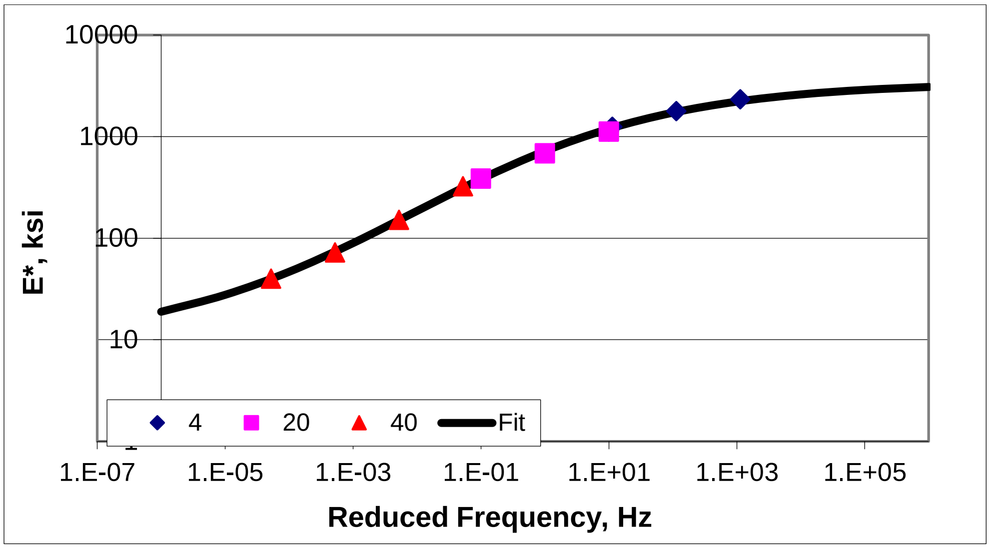


Figure 2-4 Master Curve (fit) Showing Individual Temperature Data

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 measure 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.

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

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.

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

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; that is perhaps the reason why the test has not been universally adopted. In practice, only nine or ten data points are collected for each mixture (3 or 4 testing frequencies and 3 temperatures). These ten 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.

3.0 HISTORICAL DATA

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

3.1 Description of Data

UDOT accumulated dynamic modulus data for 34 projects. Some material was obtained from the field and some was mixed in the lab. Each project consists of four replicate specimens with a total of 136 individual specimens. These specimens were each subjected to ten 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 in Section 2.3.3.

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 are coded for the binder used in the mix design, a distinct separation became clear. The mixtures made with PG 70-XX asphalt binder have overall higher dynamic modulus in comparison to the mixtures made with PG 64-XX binder. This result is 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

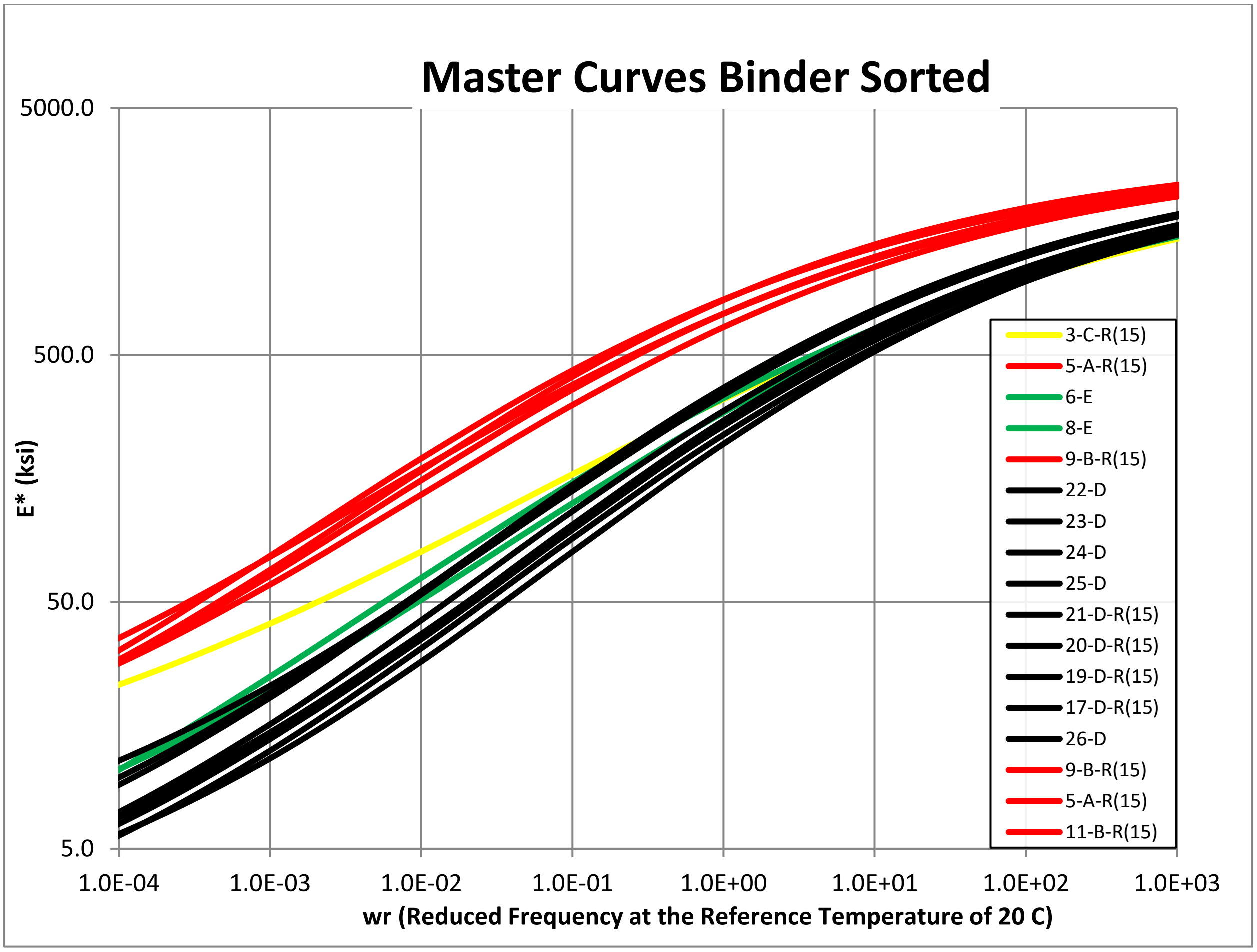


Figure 3-1 Dynamic Modulus Master Curves Sorted by Asphalt Binder Grade

(Red is PG 70-XX, black is PG 64-XX)

When the mixtures were sorted by volumetric properties, it was found that 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 percent, 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 mentioned in Section 2.3, there are five parameters that are determined when creating a dynamic modulus master curve. These parameters are: $Max, \Delta EA, \delta, \beta, and\ \gamma$. 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 198000 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 to 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 to 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.

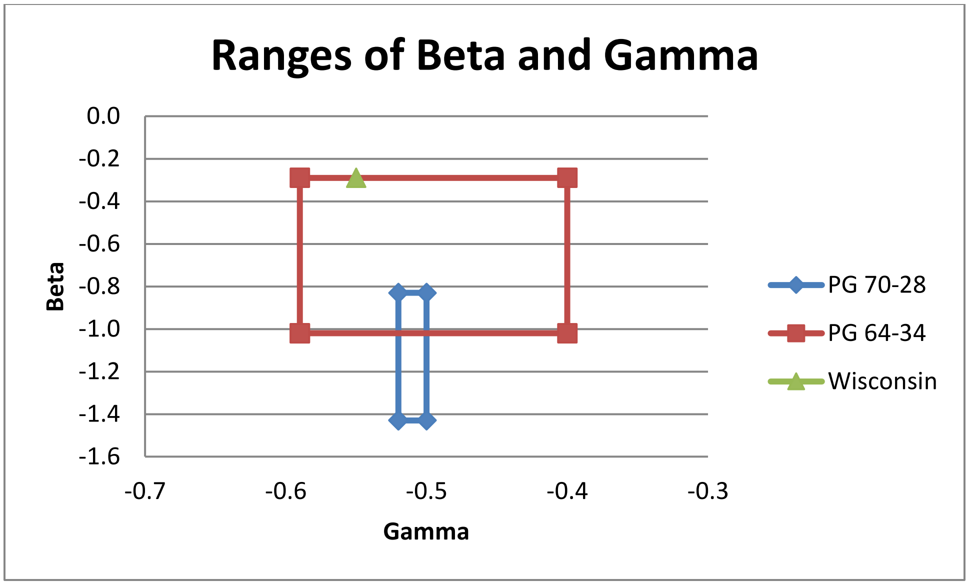


Figure 3-2 Ranges of Gamma and Beta for Utah Mixtures Evaluated with the Average for Wisconsin Mixtures

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 the reliability when Level 2 input is used. This illustrates the importance of having a reliable way to predict the dynamic modulus master curve.

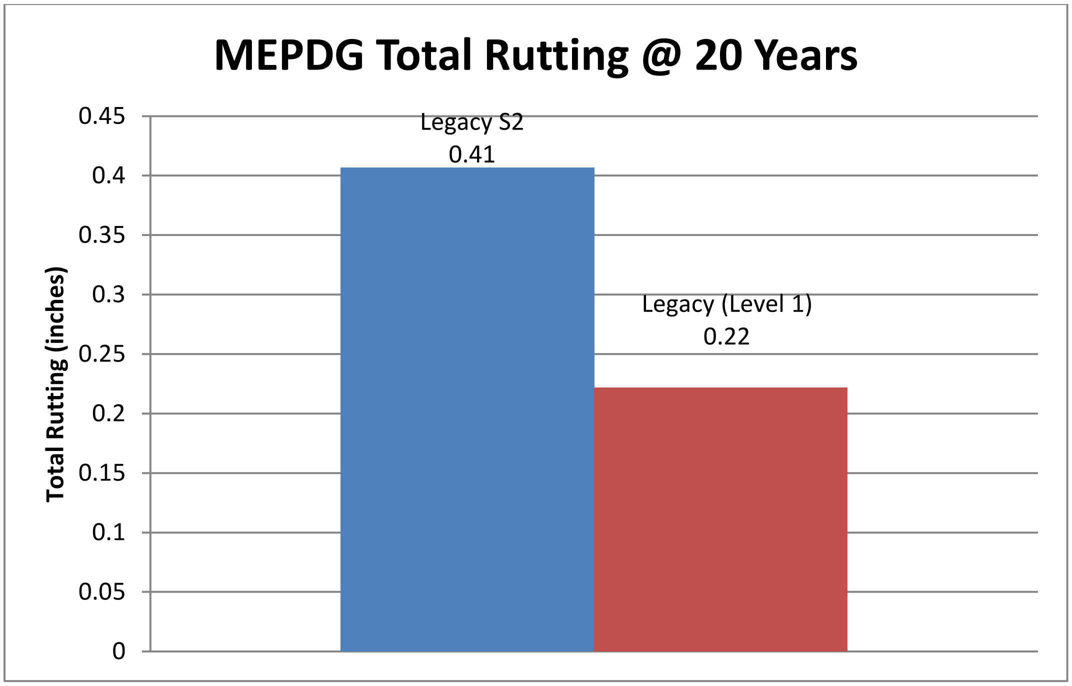


Figure 3-3 Comparison of Prediction for Level 1 and Level 2 Inputs

3.3 Summary

This chapter presented some historical data on 34 asphalt mixtures tested between 2007 and 2010. The data was 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, with asphalt binder being the most significant so far. It is known that binder grade affects the mixture performance and that the IDEAL CT test is 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 that 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.

4.0 THEORETICAL BACKGROUND

4.1 Overview

This chapter describes the theoretical background, based on energy principles, that 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.

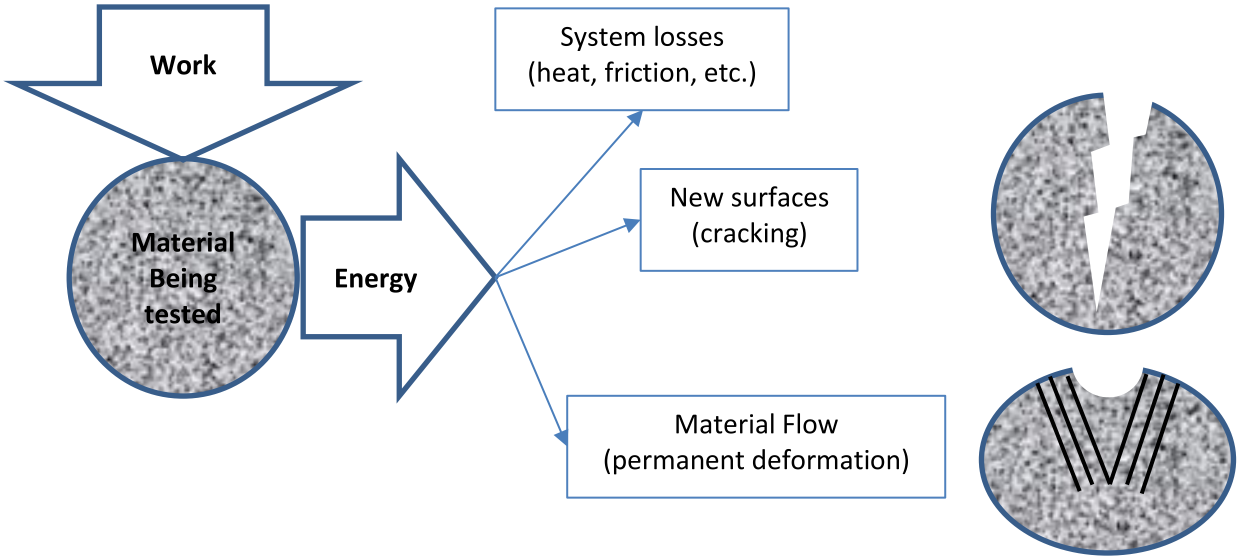


Figure 4-1 Representation of Work and Energy Transfer Concept

4.3 Dynamic Modulus

As explained in Section 2.3, 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.

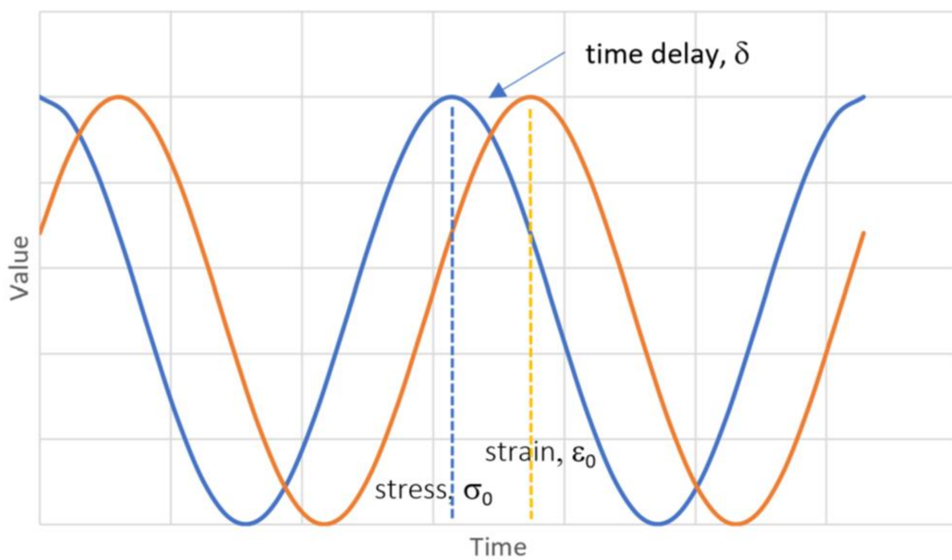


Figure 4-2 Representation of Haversine Loading and Corresponding Response

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 multiply 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. If that were not to be the case, then 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 much research.

4.4 Intermediate-Temperature QC/QA 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 the fact 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 of 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 hardly any 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 CT Index was derived as shown in Equation 16.

$$CT_{index} = \frac{Gf}{|m_{75}|} \cdot \frac{l_{75}}{D}$$ 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.

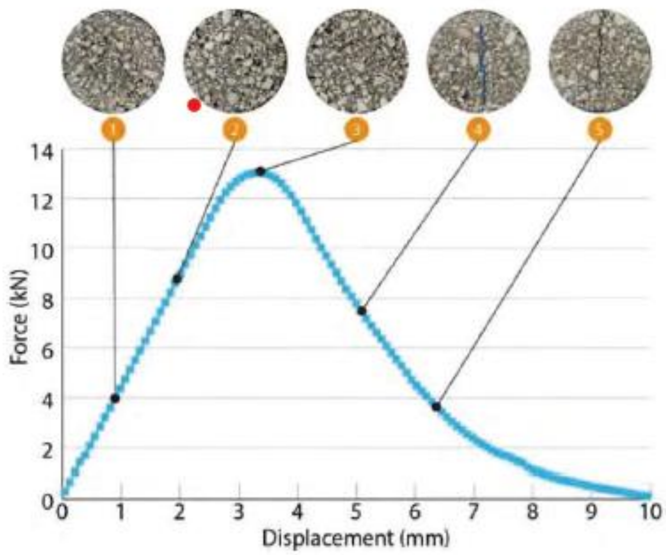


Figure 4-3 Relation Between Force-Displacement Curve and Crack Development (From Zhou [11]**)**

4.5 Relation Between Dynamic Modulus and CT Index

The development of both the dynamic modulus in Section 4.3 and the CT Index in Section 4.4 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 that 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, 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.

5.0 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 by UDOT 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 CT Index and limited dynamic modulus. All six mixtures were tested to determine their CT Index. The mixtures with the high and the low values were also tested in the AMPT to determine their dynamic modulus master curve following the process described in Chapter 2.

5.2 Materials

Materials from six different projects were collected from across the state of Utah. The materials were collected from the windrow 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 is presented in Table 5-1.

Table 5-1 Mix Locations

Route Number	UDOT Pin	Location	Begin MP	End MP
SR 302	17305	Rockport State Park	0	3.59
SR 198	17505	1100 E Payson to 300 South Sp. Fork	11.625	13.064
SR 150	17307	Bear River Service to Wyoming Line	15.961	25.399
SR 90	16534	SR-13 to SR-91 Brigham City	0	1.182
SR 112	15252	SR-138 to SR-36	0	8.217
SR 10	17230	I-70 to 200 E Emery	0	12.838

A map of the state of Utah showing the location of these mixtures is shown in Figure 5-1. The UDOT Pins (project numbers) for the mixtures used in this research are highlighted in red on the map.

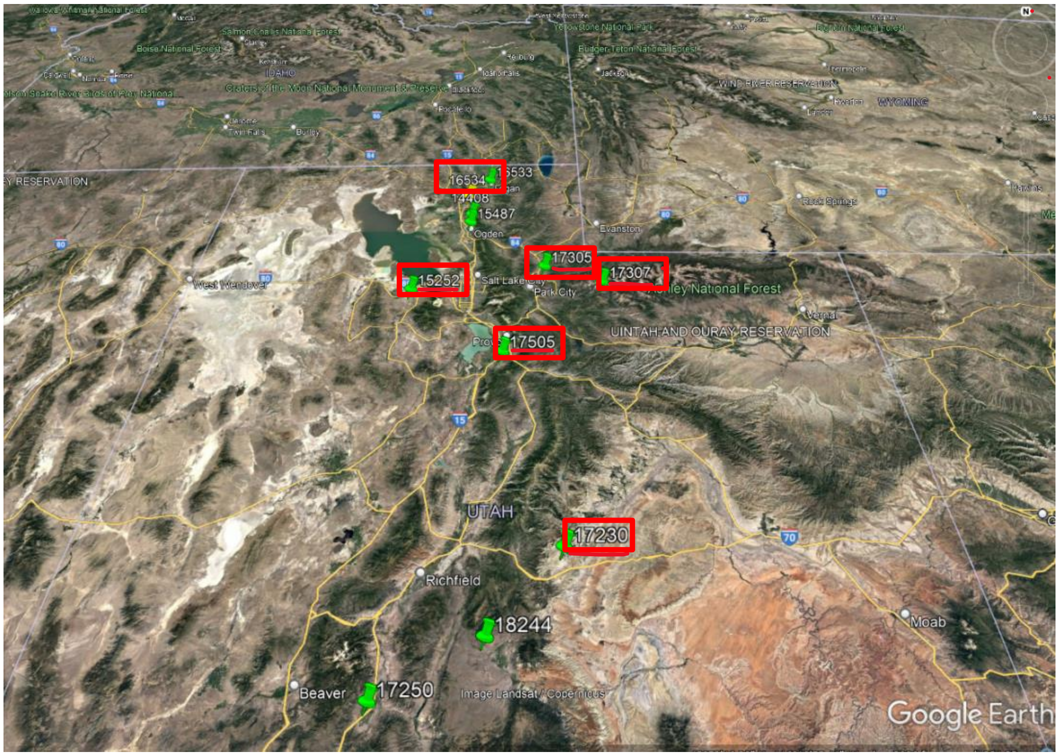


Figure 5-1 Location of All Projects

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)

UDOT Pin	Supplier	Total Binder Content, %	Virgin Binder Content, %	RAP Binder* Contribution, %
17305	Beck 12.5mm 64-34 2021	4.91	3.78	1.13
17505	Keigley 12.5mm 64-34 2021	4.90	3.90	1.00
17307	A141641R21_2021	5.20	4.05	1.15
16534	221074	5.00	3.75	1.25
15252	111-355510	5.00	3.80	1.20
17230	n/a	5.59	4.22	1.38

* 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 120 ºC 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 that all of the buckets, contained material with identical compositions.

Each asphalt mix was weighed based on the maximum specific gravity 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 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 8 to 20 hours after compaction.

The following data was 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

UDOT Pin	Average Number of Gyrations	Average Air Voids, %	Fracture Energy, J/m^2	Tensile Strength, kPa	Post-Peak Slope	CT Index
17305	62	7.29	7902	1063	-5.35	52
17505	113	7.26	7236	854	-3.22	95
17307	50	7.46	6583	859	-3.90	74
16534	32	7.12	6870	845	-3.50	72
15252	75	6.97	6684	750	-2.71	105
17230	69	7.49	8544	978	-3.65	94

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 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.

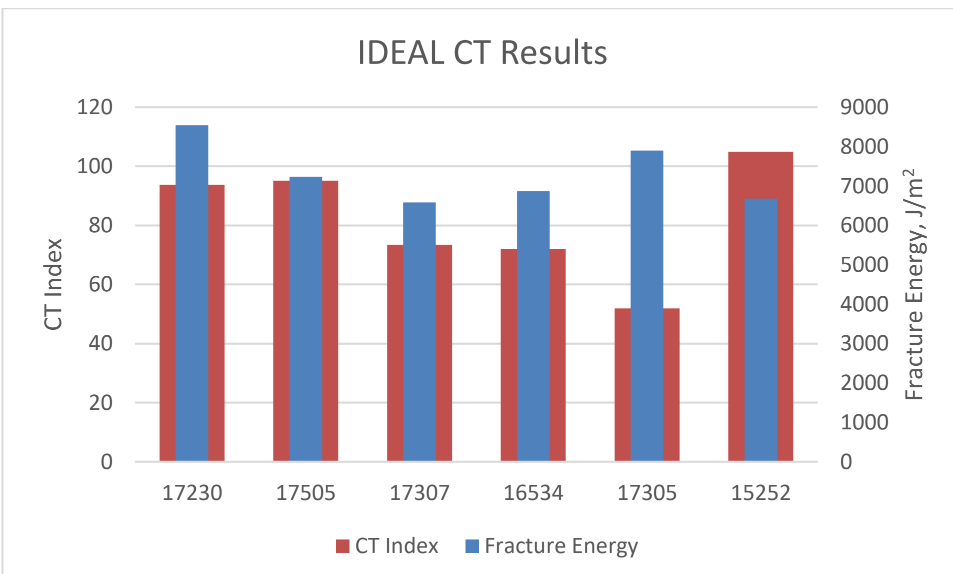


Figure 5-2 CT Index and Fracture Energy

Table 5-3 and Figure 5-2 show that, based on the CT Index, mix 15252 is expected to have the best cracking performance while mix 17305 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 17305 is significantly lower (bigger magnitude) than the rest, resulting in such a low CT Index. While evaluation of the IDEAL CT test is not part of the scope of this work, the behavior is seen is a testament of 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, mixes 15252, 17305, and 17230 which represent the highest, the lowest, and an intermediate CT Index value, respectively, were selected for dynamic modulus testing.

5.4 Dynamic Modulus Testing

In order to validate the hypothesis presented in Chapter 4, many mixtures need to be tested. Unfortunately, that is not possible due to the limited funding available. Thus, only three out 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 it is usual in this test, the data at the higher temperature was 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 percent and often less than 10 percent. 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

		Pin 17305		Pin 15252		Pin 17230	
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 can be seen in the figure, the samples from mixture Pin 15252 had the highest E* while the samples from mixture Pin 17230 had the lowest E*. As noted, this relation is different at other temperatures.

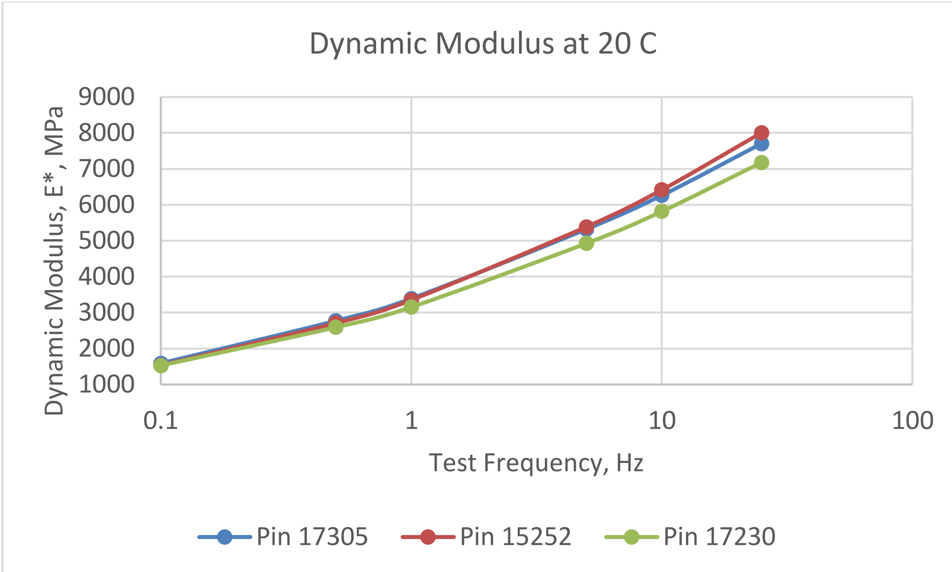


Figure 5-3 Measured Dynamic Modulus as a Function of Frequency at 20 °C

5.4.1 Master Curve Model

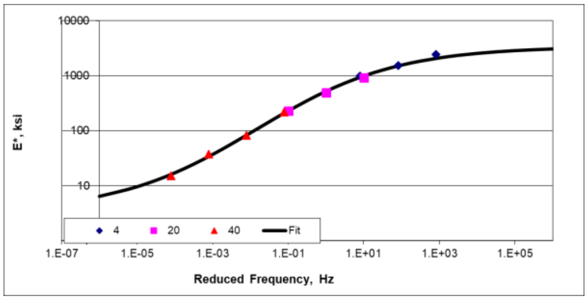
Based on the procedures described in Section 2.3.3, a master curve, referenced at a temperature of 20 °C, was created for each of the three mixtures tested. The resulting parameters, used for Equations 3 and 4, are shown in Table 5-5. As was previously explained in Chapter 2, these values define the master curve and are used to generate data at any temperature and frequency.

Table 5-5 Master Curve Fitted Parameters

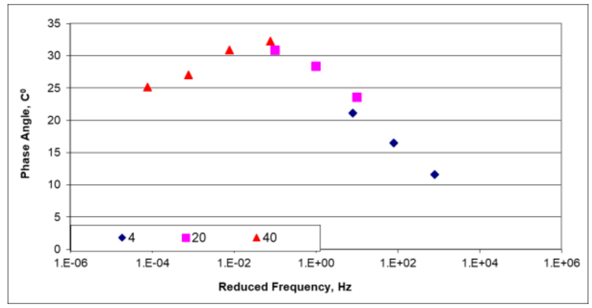
	Pin 17305	Pin 15252	Pin 17230
Parameter			
Max E*, ksi	3415.5	3415.5	3415.5
Min E*, ksi	3.3	2.2	2.6
Beta	-0.99896	-1.02943	-1.02009
Gamma	-0.53963	-0.50854	-0.49028
ΔEA	185238	184000	177905
R^2	0.994	0.998	0.992

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 Pin

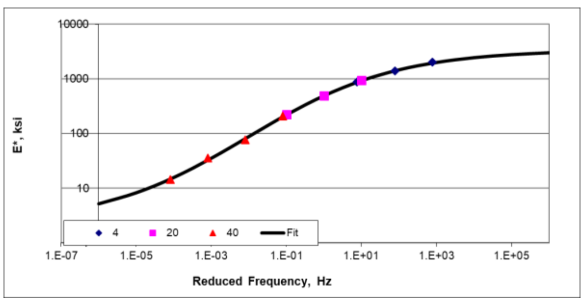
17230 is the only one that fell outside the range. The parameters shown in Table 5-5 were used to generate dynamic modulus master curves and compare them to the measured values (converted to ksi). The results are shown in Figure 5-4 (a) through (f).



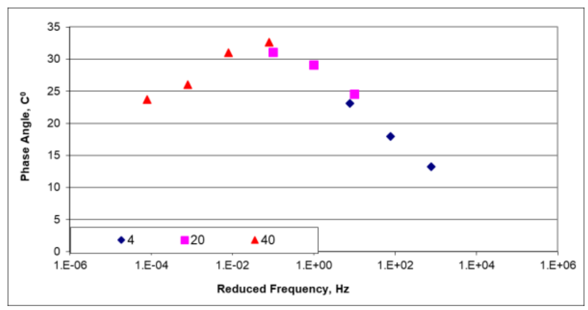
(a) Pin 17305 Dynamic Modulus



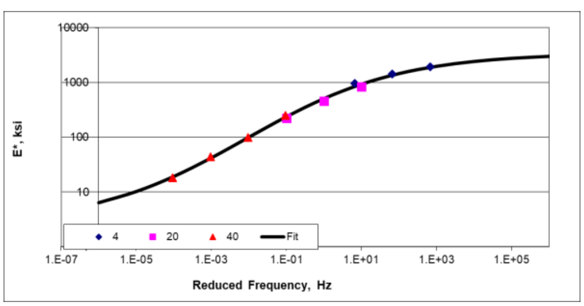
(b) Pin 17305 Phase Angle



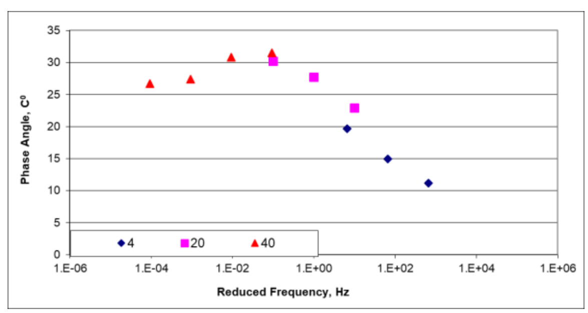
(c) Pin 15252 Dynamic Modulus



(d) Pin 15252 Phase Angle



(e) Pin 17230 Dynamic Modulus



(f) Pin 17230 Phase Angle

Figure 5-4 Fitted Master Curves and Phase Angle

Comparing the actual measured data shown in Figure 5-3 to 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 working relation between the results from a single-point test, like the IDEAL CT, to some portion of the dynamic modulus master curve. Based on the results obtained in Section 5.4, only the actual measured data is used in the comparisons. Modeling will be done on the next phase of this overall research project (not in this report).

As is 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 to cracking. Therefore, given the loading rate of 50 mm/min used during the IDEAL CT test, the comparison between the IDEAL CT tests and the dynamic modulus is done at the highest test frequency of 25 Hz. As is shown in Figure 5-3, other frequencies would result in similar comparisons. As discussed in Section 4.5, the dynamic modulus should be inversely proportional to the fracture energy measured during the IDEAL CT tests. The modulus at 20 °C is used for the comparison as it is the closest to the temperature of the IDEAL CT tests without requiring any modeling. The results are shown in Figure 5-5.

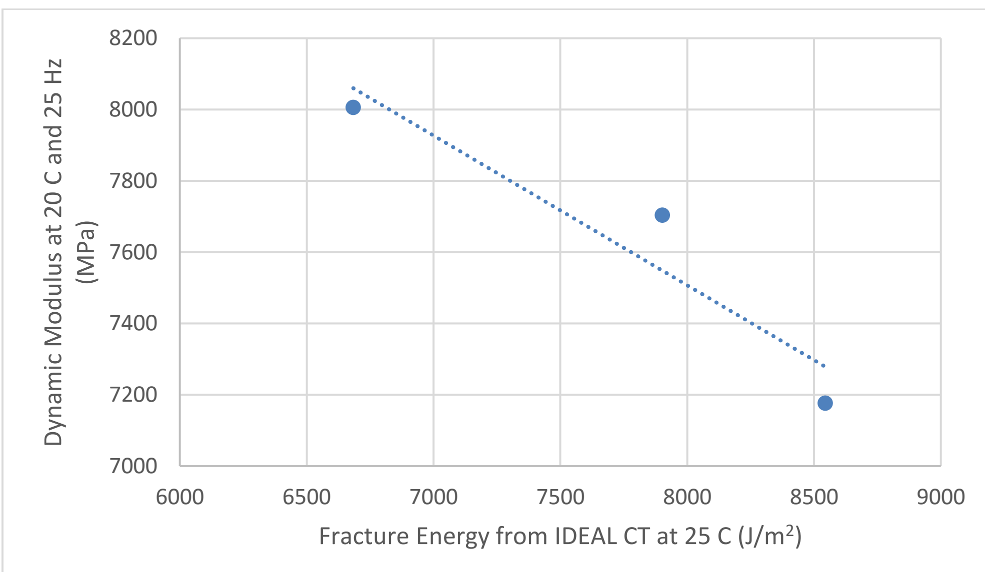


Figure 5-5 Relation Between the Dynamic Modulus and the Fracture Energy

As can be seen, the data shows a reasonable inverse relation between the results from both tests. As previously discussed, 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 CT test. This relation was evaluated using the measured values obtained at 20 °C and 25 Hz. As can be 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.

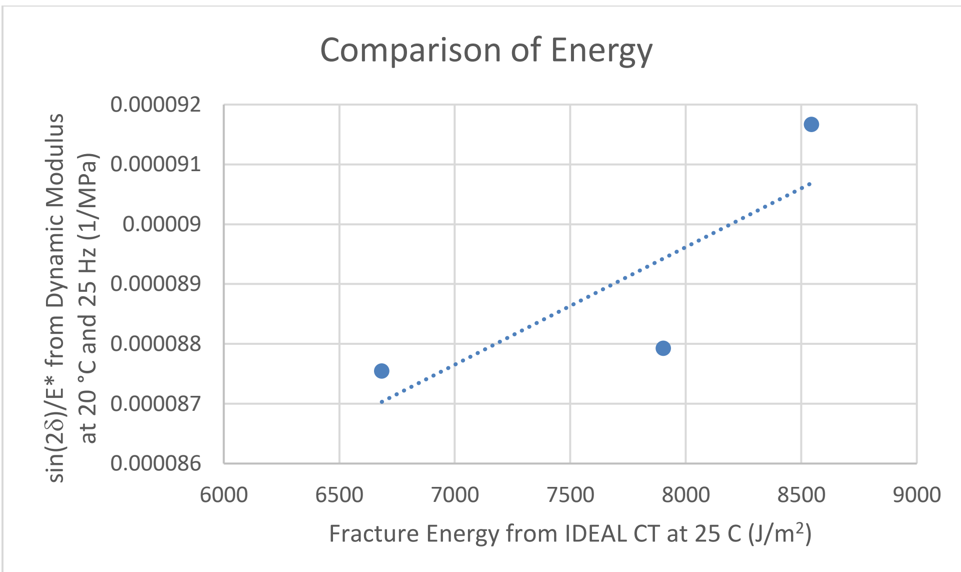


Figure 5-6 Relation Between Fracture Energy from the IDEAL CT test and the Energy per Cycle from the Dynamic Modulus Test

5.6 Relation Between Dynamic Modulus and 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 curve relate to the values obtained from the IDEAL CT tests. A high correlation might provide for 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 that there is a high degree of correlation between the CT Index and the parameters that define the master curve (Min E*, Beta, and Gamma). These results, while encouraging, should be taken with caution since it is based only on three data points. Nonetheless, such high correlation is encouraging and should be further explored.

Table 5-6 Correlation Between Tests 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 3 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 CT 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 that 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.

6.0 SUMMARY AND CONCLUSIONS

6.1 Summary

In Chapter 5 of this work it was shown that there is a clear relation between the IDEAL CT test and certain parameters of the dynamic modulus master curve. Even though more analysis should be done, 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 was 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 Next Steps

The following steps are recommended for the next phase of this overall research project:

- Validation of the results presented in this report by using different mixtures.
- Development of 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.
- Verification of 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.

7.0 REFERENCES

[1] M. Witczak, K. Kaloush, T. Pellinen, M. El-Basyouny and H. Von Quintus, "NCHRP Report 465: Simple Performance Test for Superpave Mix Design," National Academy Press, Washington, DC, 2002.

[2] L. Pierce and G. McGOvern, "NCHRP Synthesis 457: Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide Software," National Academy Press, Washington, DC, 2014.

[3] R. Bonaquist, "NCHRP Report 614: Refining the Simple Performance Tester for Use in Routine Practice," National Academy Press, Washington DC, 2008.

[4] P. Romero and A. Shenoy, "A standardized procedure for analysis of the dynamic modulus, E*, data to predict asphalt pavement distress," *Journal of the Transportation Research Record,* vol. 1789, pp. 173-182, 2002.

[5] R. Bonaquist, D. Christensen and W. Stump, "NCHRP Report 513: Simple Performance Tester for Superpave Mix Design," National Academy Press, Washington, DC, 2003.

[6] L. Roberts, P. Romero, K. VanFrank and R. Ferrin, "Evaluation of the Asphalt Mixture Performance Tester (AMPT): Utah Experience.," *Journal of the Transportation Research Board,* vol. 2296, pp. 69-79, 2012.

[7] D. Christensen, T. Pellinen and R. Bonaquist, "Hirsch Model for Estimating the Modulus of Asphalt Concrete," *Journal of the Association of Asphalt Paving Technologist,* vol. 72, pp. 97-121, 2003.

[8] R. Bonaquist, "Wisconsing Mixture Characterization Using the Asphalt Mixture Performance Tester on Historical Aggregatre Structures.," Wisconsin Highway Research Program, Madison, WI, 2010.

[9] H. Ohanian, Physics, New York: W.W. Norton and Co., Inc, 1985.

[10] A. Griffith, "The Phenomena of Rupture and Flow in Solids," *Philosophical Transactions, Series A,* vol. 221, pp. 163-198, 1920.

[11] F. I. A. a. H. S. Zhou, "Development and Validation of the IDEAL Cracking Test," *Transportation Research Circular* , Vols. E-C251, pp. 1-20, 2019.

[12] P. a. E. F. Paris, "A critical Analysis of Crack Propagation Laws," *Journal of Basic Engineering,* pp. 528-534, 1963.

[13] Z. a. P. P. Bazant, "Effect of Temperature and Humidity on Fracture Energy of Concrete," *ACI Materials Journal,* vol. 85, no. 4, pp. 262-271, 1988.

[14] T. Pellinen, "Investigation of the Use of Dynamic Modulus as an Indicator of Hot-Mix Asphalt Performance," Ph.D. Dissertation Arizona States University, Tempe, AZ, 2001.

[15] B. R., C. D. W. and S. W., "NCHRP Report 513: Simple Performance Tester for Superpave Mix Design: First Article Development and Evaluation," Washington D.C., 2003.

[16] D. Christensen and D. Anderson, "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements.," *Journal of the Association of Asphalt Paving Technologist,* vol. 61, pp. 67-116, 1992.

[17] A. Jamshidi, G. White and M. Hosseinpour, "Revisiting the Correlation Between the Dynamic Modulus and the Flexural Modulus of Hot Mix Asphalt," *Constructiona and Building Materials,* vol. 296, no. 123697, 2021.

[18] H. Ozer, I. Al-Qadi, P. Singhvi, J. Bausano, R. Carvalho, X. Li and N. Gibson, "Prediction of Pavement Fatigue Cracking at an Accelerated Testing Section using Asphalt Mixture Performance Tets," *International Journal of Pavement Engineering,* vol. 19, no. 3, pp. 264-278, 2018.

[19] M. Sayhaeifar, Y. Kim and P. Kabir, "New Predictive Models for the Dynamic Modulus of Hot-Mix Asphalt," *Construction and Building Materials,* vol. 76, pp. 221-231, 2015.

[20] M. Witczak, T. Pellinen and M. El-Basyouny, "Pursuit of the Simple Performance Test for Asphalt Concrete Fracture/Cracking," *Journal of the Association of Asphalt Paving Technologists,* vol. 71, pp. 767-778, 2002.