ISSN 1996-6814 Int. J. Pavement Res. Technol. 6(5):527-538

From Testing to Design: An Easy Way to Use and Interpret the Results from the Asphalt Mixture Performance Tester (AMPT)

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Abstract: While technologies available today allow the precise determination of material fundamental properties to be used in mechanistic pavement designs, these technologies are often confined to the realm of research and theoretical analysis at universities and research centers. A reason commonly cited to explain this situation is the scarcity of trained personnel to properly interpret the results obtained from these tests, often perceived as "too complex", "research grade", or "not practical".

In an effort to facilitate the use of perceived complex results from asphalt dynamic modulus tests into routine pavement engineering practice, a software application, identified as the HMA Analysis Tool (HMA AT), was developed to automatically generate the mixture's modulus master curve using the output files from the commercially available Asphalt Mixture Performance Tester (AMPT). The capabilities and applicability of the HMA AT software application were demonstrated using actual |E*| test results from unmodified and polymer modified asphalt mixtures evaluated by the University of Hawaii.

Examples of practical applications in which the results obtained from determining the dynamic modulus master curve from actual test data are utilized include Data Quality Control (DQC) procedures, an example of analysis of the effect of binder type and compaction level on the mechanical response of a mix, and the generation of input modulus values potentially useful as input in pavement design methods.

It is expected that the examples presented in this paper provide a glimpse of practical applications in which data generated with the AMPT can be used, and will hopefully contribute to generate ideas about how interested users could make the most out of the data generated with their AMPT systems.

DOI:10.6135/ijprt.org.tw/2013.6(5).527

Key words*: AMPT; Asphalt; Dynamic modulus; Master curve; Performance Testing.*

Introduction

Although the technologies available today allow the precise determination of material fundamental properties to be used in mechanistic pavement designs, these technologies are often confined to the realm of research and theoretical analysis at universities and research centres. A reason often cited to explain this situation is the lack of trained personnel in the road agencies (and in the practicing engineering community at large) to properly interpret the results obtained from these tests. There is a clear need to bridge the gap between proper material characterization and practicality in pavement engineering, in particular if the introduction of new materials and technologies is considered as a potential avenue to optimize scarce resources and reduce costs, while providing the necessary infrastructure for economic growth.

Background of the AMPT

Arguably, one of the major limitations for the widespread adoption of testing fundamental mechanical properties for asphalt mixtures has been the perceived high cost of the testing equipment needed, and the somewhat difficult set up and execution of the test protocols. Although one of the objectives of the Strategic Highway Research Program (SHRP) was to incorporate test procedures to evaluate mix performance within the Superpave asphalt mix design system, widespread adoption of the procedures initially developed was limited. As a result of NCHRP Project 9-19 "Superpave Support and Performance Models Management", Dynamic Modulus, Flow Number and Flow Time tests were proposed as suitable simple tests for the evaluation of the performance of HMA.

In order to articulate the proposed simple performance tests within the wider pavement engineering community, and to facilitate its widespread adoption and implementation, a major component of NCHRP Project 9-29 *Simple Performance Tester for Superpave Mix Design* was the design and manufacture of a simple performance tester capable of performing these tests.

Multiple equipment manufacturers from different parts of the world showed initial interest in developing a testing system within the strict budget and schedule requirements established in the project; however, only two manufacturers were able to meet the project objectives and deliver working systems during all the phases of the project. Although different reports were generated during the different phases of the NCHRP 9-29 project, details on the development of what is now known as the Asphalt Mixture Performance Tester (AMPT) can be found in Chapter 3 of [1]. The final equipment specification for the AMPT is included as Appendix E in [2].

Description of the AMPT

The AMPT is a purpose built bottom loading dynamic testing machine with a triaxial cell that doubles as environmental

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Note: Submitted January 15, 2013; Revised June 9, 2013; Accepted June 10, 2013.

conditioning chamber due to a fully integrated refrigeration and heating unit, a hydraulic dynamic actuator with its associated hydraulic power supply, and a high response control and data acquisition system (Fig. 1).

The loading frame, consisting of three vertical columns and two heavy-duty circular crossheads, is specifically designed to limit deflection and vibrations which might influence the accuracy of measurements during dynamic testing of Hot Mix Asphalt (HMA). The internal dimensions of the system allow the evaluation of 150mm tall specimens with a diameter of 100mm. The AMPT test specimens are usually obtained after coring and sawing mixes compacted with the Superpave Gyratory Compactor (SGC), although specimens obtained from field coring activities can also be used (Fig. 2).

The dynamic loading is applied to the HMA specimen by means of a low friction, double acting, high-speed hydraulic force actuator, which also includes a co-axial displacement transducer. Accurate dynamic performance is possible by means of an electrically controlled fast response hydraulic servo valve, which regulates the flow of oil from the AMPT's built-in high performance hydraulic power pack into the actuator.

A load cell mounted in line with the loading shaft is used to measure the axial force applied to the test specimen, as it is compressed by loading platens acting on its parallel faces. Depending on the particular test being performed (e.g., Dynamic Modulus |E*| or Flow Number), axial deformations are measured by means of specimen-mounted LVDTs (for |E*| determination) or using the co-axial actuator displacement transducer (for Flow Number tests).

Considering the particular characteristics of asphalt mixtures, the AMPT features a purpose-built environmental chamber with temperature control of ± 0.5℃ between 4℃ and 60℃ that doubles as a confining cell if triaxial testing of the specimens is required. Although dynamic modulus tests are sometimes performed under confined conditions, the ability to apply confinement to the specimens with the AMPT is particularly useful for permanent deformation testing, where stress levels that more closely replicate those observed in the field are required. Although the cell is tested to a pressure of 450 kPa, the confining stress levels required are normally well below this value (usually less than 220 kPa).

As required by the AASHTO TP79 specification [3], control of the systems and data acquisition and processing of all the relevant signals before and during the tests are performed electronically by means of fully automated pre-programmed routines. Although the AMPT was originally designed to perform both Dynamic Modulus (|E*|) and Permanent Deformation tests (Flow Number or Flow Time), in practice |E*| is arguably the more extensively performed these days. Results from dynamic modulus tests as determined with the AMPT provide a complete description of the mechanical behavior of the mix evaluated under a wide range of temperatures and loading frequencies, and can be used in multiple applications, ranging from pavement design to material characterization for QC/QA purposes.

Dynamic Modulus with the AMPT

A detailed description of the test is beyond the scope of the present document, and the interested reader is referred to the literature for in depth information on the subject [4-6]; however, a brief overview of dynamic modulus principles and testing with the AMPT is given in the following sections.

The primary mechanical property of interest for asphalt mixtures in mechanistic-empirical pavement design methods based on linear elastic principles is the time-temperature dependent dynamic

Fig. 1. Asphalt Mixture Performance Tester.

Fig. 2. HMA Specimen with LVDTs Attached for |E*| Test with the AMPT.

modulus |E*|. This parameter is defined as the absolute value of the complex modulus, *E** (for the interested reader, a very good explanation of the fundamentals of HMA’s *complex* modulus, *E**, can be found in [4]). To illustrate the concept of |E*|, the applied axial stress and corresponding strain response of a typical bituminous mixture during a dynamic modulus test is illustrated in Fig. 3.

In Fig. 3 above, the dynamic modulus |E*| is defined as the ratio of the amplitudes of peak stress and peak strain (i.e., $|E^*| = \sigma0/\varepsilon0$, where $\sigma0$ is the peak dynamic stress amplitude and $\varepsilon0$ is the peak recoverable strain amplitude). The term Δt is the phase lag between peak stress and peak strain (which is directly related to the phase angle), which is an indicator of the viscous properties of the material being evaluated. It is generally accepted that the dynamic modulus of bituminous mixtures is a function of temperature, rate of loading, age, and other characteristics such as binder stiffness, aggregate gradation, binder content, and air voids.

For a given asphalt mixture, the value of |E*| is dependent on the temperature and the frequency at which the stress is applied. Considering the wide range of temperatures and loading frequencies at which an asphalt concrete layer within a pavement structure will be exposed during its design life, it is necessary to establish the dynamic modulus at different combinations of the two variables, from where |E*| can be estimated for “any” given combination of frequency and time of loading. This is normally done by identifying the parameters of what is commonly known as the “dynamic modulus master curve”, which is a unique function describing simultaneously the dependency of the modulus to both the temperature and the time of loading (more on this later).

Although many variations of the test procedure to determine |E*| can be found worldwide, arguably the most common methods are the recently released AASHTO T342 [7] (which is based on the formerly known AASHTO TP62) and AASHTO TP79, which is the standard test procedure established specifically to determine the dynamic modulus of HMA with the AMPT [3].

The two test protocols are used to determine the dynamic modulus of asphalt mixtures in axial loading mode at various combinations of temperature and loading frequency. Although both methods are very similar, there are some key differences between the two. In both methods a dynamic compressive axial stress is applied perpendicular to the parallel flat faces of a cylindrical HMA specimen, producing a deformation small enough to ensure that the asphalt material behaves elastically.

AASHTO TP79 is based on NCHRP Report 629 [2], and although it is fundamentally based on AASHTO TP62, the test requirements established within AASHTO TP79 are meant for determining |E*| using the AMPT. From a testing point of view, the two procedures are very similar, except that a reduced number of temperatures and an expanded range of frequencies are prescribed in AASHTO TP79 (specifically, testing at temperatures of 4.4, 21.1, and 46.1℃ and at loading frequencies of 10, 1.0, 0.1, and 0.01 Hz). As reported by Bonaquist in [1], the use of a reduced number of temperatures and frequencies in developing a dynamic modulus master curve for asphalt mixtures was found to be appropriate.

In the AMPT, an HMA specimen with a diameter of 100mm and height of 150 mm is loaded at all required frequencies (from the highest to the lowest), at the lowest prescribed temperature level. Once the last (i.e., lowest) load frequency is applied, the specimen is brought up to the next temperature level, the load frequency sweep is repeated, and the complete process repeated until the modulus has been measured at the highest temperature level and lowest load frequency prescribed.

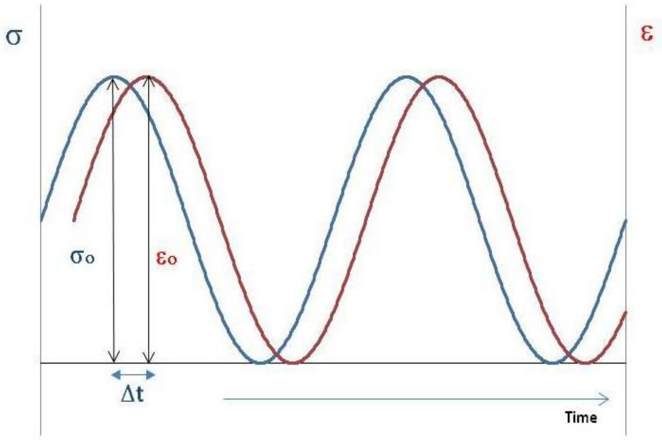


Fig. 3. Typical Applied Stress and Associated Strain Response of HMA During |E*| Test.

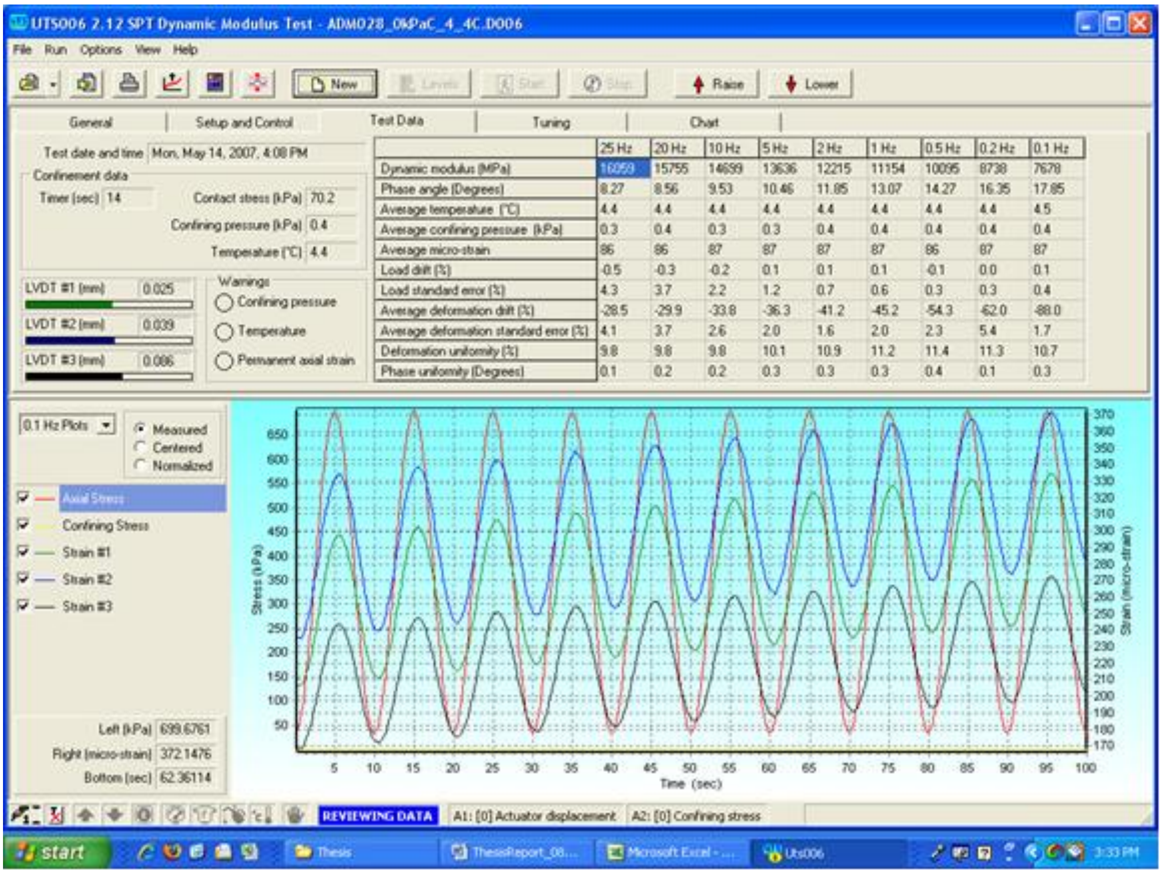
Vertical deformations produced during the dynamic modulus test with the AMPT are measured by means of three on-specimen linear variable differential transducers (LVDTs) separated 120 degrees from each other. The displacement transducers are secured in the proper positions using purpose built LVDT holders that easily attach to hexagonal gauge points previously glued to the faces of the specimen, as illustrated in Fig. 2.

Test frequencies, conditioning time, target temperature, target confining stress, initial modulus, axial gauge length, and specimen dimensions are defined in the setup menu. Some of these inputs, such as frequencies, are used directly for control of the test while others, such as the conditioning time, are included only for informational purposes. The applied stress, confining pressure (if any), temperature and resulting axial strain from the three on-specimen displacement transducers are measured as a function of time and then used to calculate the dynamic modulus and other required values, such as phase angle, average temperature, average confining pressure and a number of data quality measurements, as illustrated in Fig. 4.

|E*| Master Curve

The results of dynamic modulus testing on HMA consist of a set of dynamic modulus values obtained at different temperatures and different loading frequencies (or equivalent time of loading). For mechanistic pavement design, the dynamic modulus |E*| is needed for any given temperature and time of loading. Therefore, an interpolation model is required to predict |E*| for any condition. Such interpolation is achieved with the use of the time-temperature superposition principle, which allows superposition of a series of curves (each for a constant value of temperature and varying frequencies of loading) by horizontal shifts in the frequency domain to form a “Master Curve”.

The time-temperature superposition principle assumes that the effect of time of loading (or frequency) on the material properties



Test date and time: Mon, May 14, 2007, 4:08 PM

Confinement data

Timer (sec): 14

Contact stress (kPa): 70.2

Confining pressure (kPa): 0.4

Temperature (°C): 4.4

LVDT #1 (mm): 0.025

LVDT #2 (mm): 0.039

LVDT #3 (mm): 0.086

	25 Hz	20 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz
Dynamic modulus (MPa)	16059	15755	14699	13636	12215	11154	10095	8738	7678
Phase angle (Degrees)	8.27	8.56	9.53	10.46	11.85	13.07	14.27	16.35	17.85
Average temperature (°C)	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.5
Average confining pressure (kPa)	0.3	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.4
Average micro-strain	86	86	87	87	87	87	86	87	87
Load drift (%)	-0.5	-0.3	-0.2	0.1	0.1	0.1	-0.1	0.0	0.1
Load standard error (%)	4.3	3.7	2.2	1.2	0.7	0.6	0.3	0.3	0.4
Average deformation drift (%)	-28.5	-29.9	-33.8	-36.3	-41.2	-45.2	-54.3	-62.0	-88.0
Average deformation standard error (%)	4.1	3.7	2.6	2.0	1.6	2.0	2.3	5.4	1.7
Deformation uniformity (%)	9.8	9.8	9.8	10.1	10.9	11.2	11.4	11.3	10.7
Phase uniformity (Degrees)	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.1	0.3

Left (kPa): 699.6761

Right (micro-strain): 372.1476

Bottom (sec): 62.36114

A1: [0] Actuator displacement

A2: [0] Confining stress

Fig. 4. Dynamic Modulus Test Output from the AMPT.

can be replaced by the effect of temperature, and vice versa. In this way, the master curve can be defined as a function that describes simultaneously the dependency of |E*| on both the temperature and the time of loading.

Although estimation of the model parameters can be accomplished in a single step, it is easier to explain it and visualize it as a two-step process in which first, the curves obtained by varying frequency (or loading time) at each temperature are shifted horizontally until a smooth curve is obtained and second, a smooth function is fitted to the resulting data points. Fig. 5 illustrates the shifting and the resulting fitted |E*| master curve for a particular mix (reference temperature of 21℃).

The amount of shifting along the frequency axis (e.g., horizontal) is related to what is known as the *shift factor*, which is defined, in logarithmic terms by the equation:

$$log(t_r)=log(t)-log(a(T)) \tag{1}$$

In Eq. (1), *a(T)* is the shift factor (which is a function of temperature, as illustrated in Fig. 6), *t* is the time of loading at the desired temperature, t_r is the reduced time of loading at a reference temperature, and *T* is the temperature of interest. As can be seen in Eq. (1), the shifts shown in Fig. 5 are equal to the negative of the log(*a*(*T*)) (note that the time of loading is given in logarithmic scale in Fig. 5).

Although there are different continuous functions that could be used to fit the dynamic modulus test data to obtain a master curve for |E*|, the sigmoidal function presented in Eq. (2) is perhaps one of the more commonly used these days, as it is the form used in the current version of DarwinME, AASHTO's Mechanistic Empirical Pavement Design Guide (commonly known as AASHTO's MEPDG).

$$log_{10}|E^*|=\delta+\frac{\alpha}{1+e^{\beta+\gamma(log\,t_r)}} \tag{2}$$

In Eq. (2), t_r is reduced time of loading at reference temperature, α is the minimum value of log |E*|, $\delta+\alpha$ corresponds to the maximum value of log |E*|, and β and γ are parameters describing the shape of the sigmoidal function. This equation describes the time dependency of the modulus at the reference temperature whereas the shift factors describe the temperature dependency of the modulus; both are essential ingredients of the master curve.

Different approaches are available to establish the relationship between the shift factors and temperature (some of them involving the viscosity of the binder in the HMA). Considering that, in this instance, the objective is just to illustrate how the complete master curve can be developed, for brevity and simplicity only the polynomial approach is discussed in this document (i.e., the shift factors being modeled only as a function of temperature). The interested reader can find a detailed explanation of the different approaches available to determine the shift factors for |E*| master curve development in [4].

The parameters of the master curve can be estimated using Eqs. (1) and (2) along with the following equation, which for the

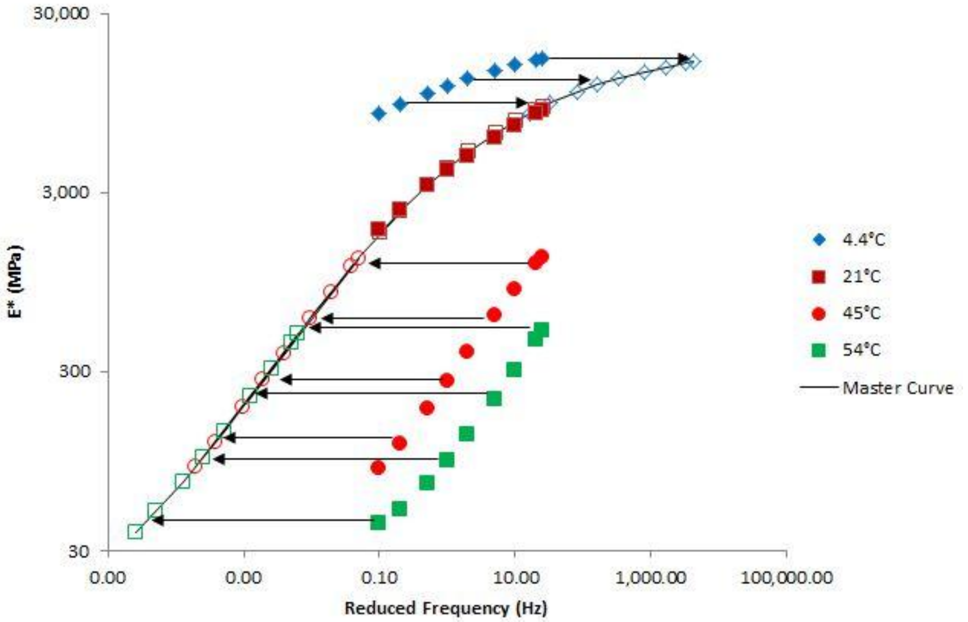


Fig. 5. Example of Shifting and Curve Fitting During the Development of Master Curve (T_{ref} = 21℃).

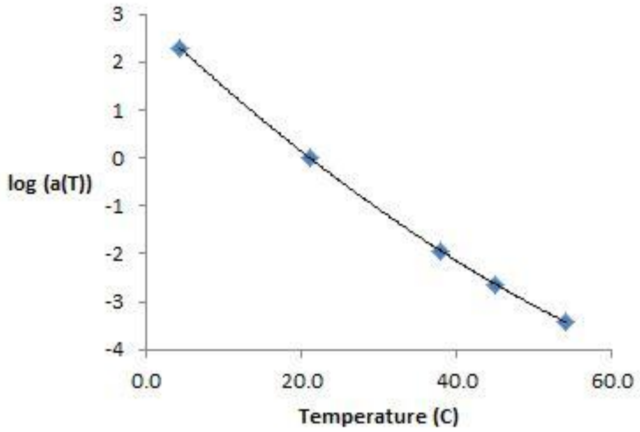


Fig. 6. Example of the Shift Factor as a Function of Temperature.

polynomial approach describes the shift factors as a function of temperature:

$$log(a(T)) = aT_i^2 + bT_i + c \tag{3}$$

In Eq. (3), a, b and c are model parameters and T_i is the temperature. All seven parameters (α, β, γ and δ in Eq. (2) and a, b, and c in Eq. (3)) are typically estimated simultaneously with the restriction that the values of a, b and c must yield a zero shift at the reference temperature. The only information required for their estimation is the dynamic modulus test results at the different temperatures and frequencies, which are directly measured by the AMPT.

Eq. (2) describes the time dependency of the modulus at the reference temperature, while the shift factors (Eqs. (1) and (3)) describe the temperature dependency of the modulus. Using the master curve makes possible the estimation of the dynamic modulus of the asphalt mixture over a wide range of temperatures and times of loading, which can be expected in the field, but would be impossible to simulate all in a laboratory setting.

Development of Dynamic Modulus Master Curves with HMA AT Software

Although the use of the AMPT has greatly simplified the execution of dynamic modulus tests on asphalt mixtures, the sometimes perceived complexity of the results and their applicability can make their widespread use difficult to implement. Considering the ever increasing trend towards the use of mechanistic-based pavement design principles (e.g., AASHTO's DarwinME Pavement Design Guide), and the increasingly common use of "new" technologies and materials (e.g., warm mix asphalt, modified binders, etc.), any efforts directed towards facilitating the understanding and adoption of fundamental material properties such as the dynamic modulus of asphalt mixtures by practicing engineers should be encouraged.

Different computer applications are available at the moment to process data from AMPT |E*| tests and generate master curves. Advanced dedicated software that can perform this task easily without significant training from the user include the licensed Rheology Analysis Software (RHEA) from Abatech [8]. Other software packages that can be used towards this end include Matlab and Excel, although it is important to note that users need accessibility to the software, and possess a basic understanding of programming macros within these particular applications. In addition, interested users can obtain the MasterSolver Excel worksheet, which was prepared as part of NCHRP Report 9-29, and is available for free from the Transportation Research Board website [9].

A software application called the HMA Analysis Tool software (HMA AT) was developed to automatically generate the mixture's modulus master curve using the output files generated by IPC Global's AMPT. This tool can potentially facilitate the use of perceived complex results from asphalt dynamic modulus tests into routine pavement engineering practice. The following sections describe some of the features and capabilities of the software. Readers interested in finding out details about the software package not described in this document can refer their questions directly to the developer, Dr. Ricardo Archilla, at archilla@hawaii.edu.

HMA AT – Software Overview

The main menu of the HMA AT Software contains a few simple commands that allow the user to import |E*| data, save master curve parameters to an external text file, copy a chart to the clipboard, and set threshold parameter values for data quality assessment.

When starting a new analysis, the first step is to import new |E*| test data into the program. When the command “Import Data Points” is activated in the main menu, a standard windows dialog box requesting the user to select the appropriate files is presented (the program has been designed to read directly the summary files in *.csv format generated by the AMPT manufactured by IPC Global).

An important feature of the program is that multiple summary test files can be imported simultaneously (Fig. 7), allowing the user to select several files corresponding to different specimens, which could be potentially useful for estimating an “average” master curve based on data from multiple replicate specimens.

Once the data is successfully imported, it is displayed in a data grid and presented in a chart form with Dynamic Modulus in the vertical axis and Frequency in the horizontal axis (Fig. 8). Among the features incorporated into the software, there is an option for excluding manually specific data points from further analyses if the user considers it necessary (for instance, if the user identifies values that do not meet data quality indicator requirements, or values that could be considered suspicious).

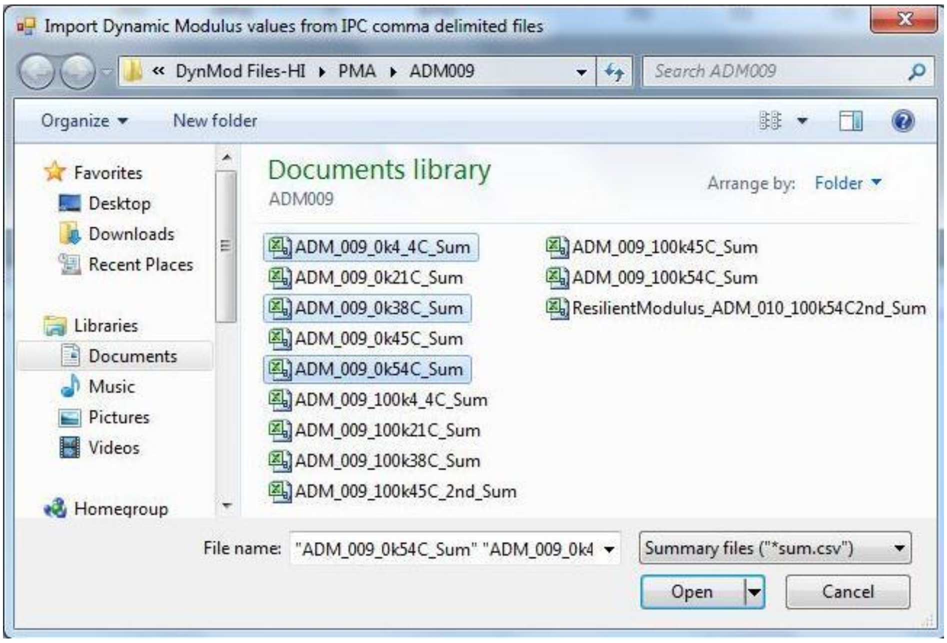
Master Curve Generation

As explained in the |E*| Master Curve section earlier in this document, both the sigmoidal function parameters (i.e., α, β, γ and δ) and the parameters defining the relationship between the shift factors and the temperature (e.g., *a*, *b* and *c* in Eq. (3)) are needed to fully describe the time of loading and temperature dependency of |E*|. The HMA AT allows the estimation of the shift factors both independently of the viscosity of the binder (as in Eq. (3)), or as a function of it, if the terms A and VTS that define the viscosity characteristics of the binder are known (as stated earlier, details about this model are not discussed in this document, and the reader is referred to [4] for details).

Once the AMPT dynamic modulus test data to generate the master curve has been imported and suspicious data has been selected for exclusion from the analysis, a dynamic modulus master curve at any user-defined reference temperature can be created with just two clicks. First, the user must click the “Initial Parameters” button so that initial reasonable values for the master curve parameters and shift factors are assigned. Then, after clicking the “Calc. Parameters” button, the HMA AT software determines the values of the parameters α, β, γ and δ of Eq. (2), along with the parameters describing the temperature dependency of the material (appropriate for the shift factor model selected) that achieve the optimum fit of the data to the dynamic modulus sigmoidal function incorporated within AASHTO’s DarwinME (i.e., Eq. (2)).

As shown in Fig. 9, after the master curve parameters have been estimated, the chart will be updated to show the newly generated master curve, the original data points, and the new location of the dynamic modulus original data points after shifted to fit the master curve.

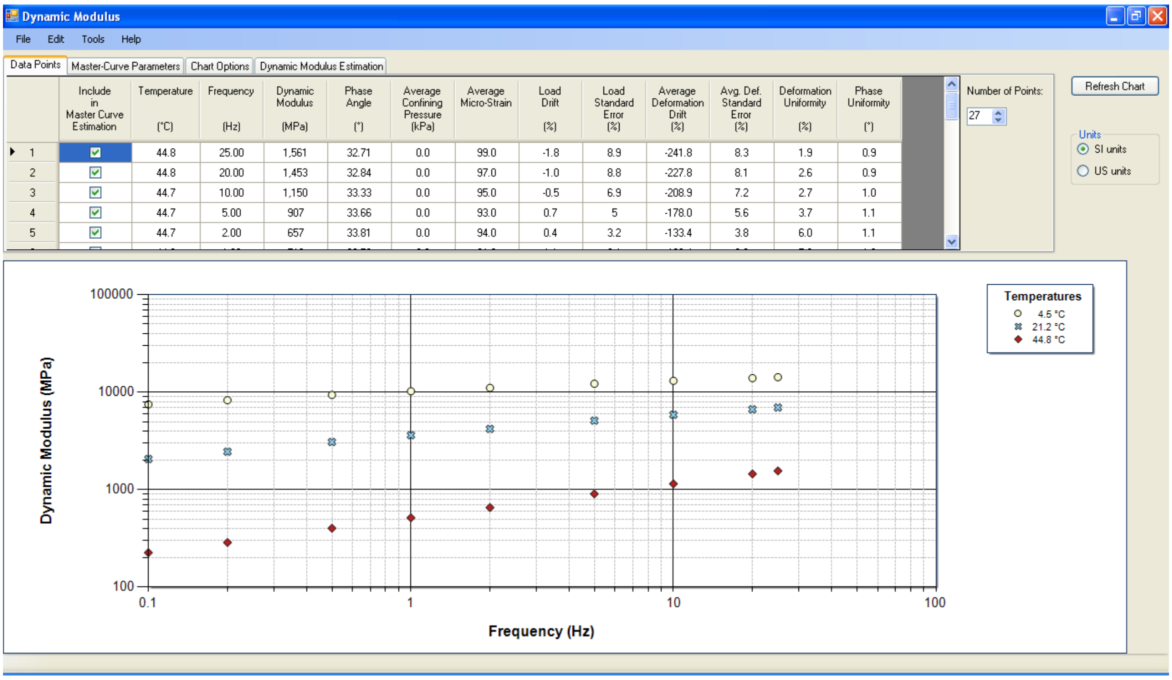
The HMA AT has some additional features that allow the user to manipulate the appearance of the master curve generated, including resizing of the chart, selecting the units in which the master curve data is displayed and plotted (i.e., International or English Units systems), changing the label titles and modifying the scales used in both the Frequency and Dynamic Modulus axes.



File name: "ADM_009_0k54C_Sum" "ADM_009_0k4

Summary files ("*sum.csv")

Fig. 7. Importing Dynamic Modulus Values from IPC Global’s Comma Delimited Files into HMA AT.

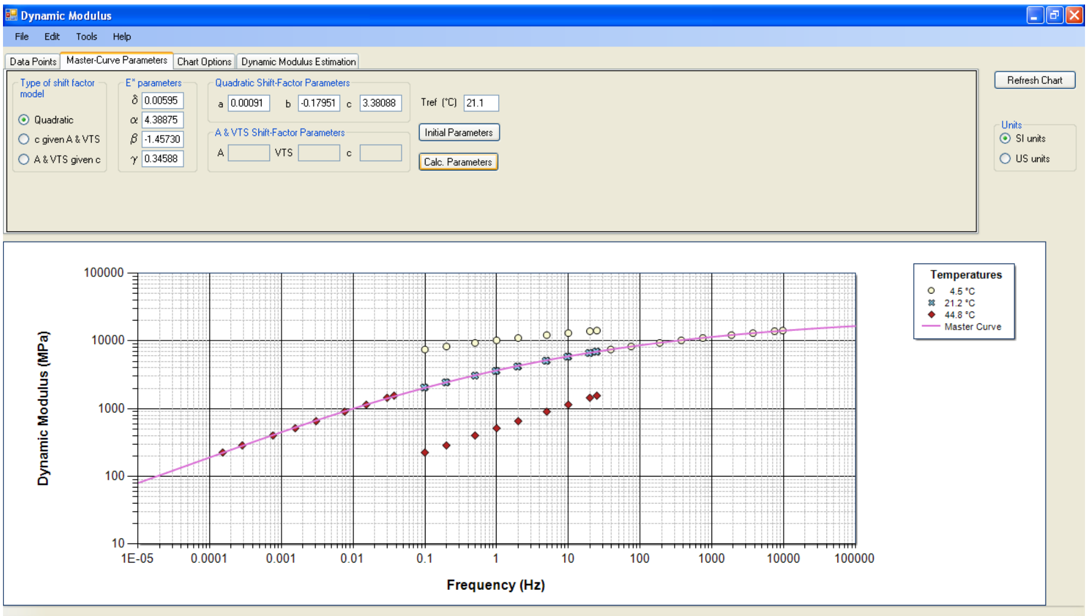


	Include in Master Curve Estimation	Temperature (°C)	Frequency (Hz)	Dynamic Modulus (MPa)	Phase Angle (°)	Average Confining Pressure (kPa)	Average Micro-Strain	Load Drift (%)	Load Standard Error (%)	Average Deformation Drift (%)	Avg. Def. Standard Error (%)	Deformation Uniformity (%)	Phase Uniformity (°)
1	☑	44.8	25.00	1,561	32.71	0.0	99.0	-1.8	8.9	-241.8	8.3	1.9	0.9
2	☑	44.8	20.00	1,453	32.84	0.0	97.0	-1.0	8.8	-227.8	8.1	2.6	0.9
3	☑	44.7	10.00	1,150	33.33	0.0	95.0	-0.5	6.9	-208.9	7.2	2.7	1.0
4	☑	44.7	5.00	907	33.66	0.0	93.0	0.7	5	-178.0	5.6	3.7	1.1
5	☑	44.7	2.00	657	33.81	0.0	94.0	0.4	3.2	-133.4	3.8	6.0	1.1

Number of Points: 27

Units
● SI units
○ US units

Fig. 8. Data Populated Data Grid and Chart Areas in HMA AT Software.



Type of shift factor model
● Quadratic
○ c given A & VTS
○ A & VTS given c

E* parameters
δ 0.00595
α 4.38875
β -1.45730
γ 0.34588

Quadratic Shift-Factor Parameters
a 0.00091
b -0.17951
c 3.38088

Tref (°C) 21.1

A & VTS Shift-Factor Parameters
A
VTS
c

Units
● SI units
○ US units

Fig. 9, |E*| Chart Updated after Master Curve Parameter Estimation in HMA AT.

The HMA AT application also allows the user to calculate the dynamic modulus |E*| for any frequency and temperature, based on the active master curve generated by the program. The table with the calculated Dynamic Modulus values can then be cut and pasted into other applications (e.g., Excel) to produce customized plots or for further analysis, or to be used as input within AASHTO's DarwinME Pavement Design Guide.

Practical Applications of HMA AT Software

Although the technologies available today allow the precise determination of material fundamental properties, these technologies are often confined to the realm of research and theoretical analysis at universities and research centres, with arguably one of the reasons most often cited being the lack of trained personnel in the practicing engineering community being able to properly interpret the results obtained from these tests.

To ensure that the benefits from advancements in materials and pavement technology actually materialize in practice, practical applications of the results obtained from proper material characterization tests need to be disseminated. As a contribution to achieve this, the following sections include specific cases in which AMPT dynamic modulus test data can be processed with the HMA Analysis Tool to facilitate routine tasks in pavement engineering.

Data Quality Control (DQC)

If the requirements established in AASHTO TP79-12 to perform dynamic modulus tests with the AMPT are to be fully satisfied, certain data quality indicator thresholds have to be met during the test. Specifically, data quality indicators include load drift, load standard error, average deformation drift, deformation uniformity and phase angle uniformity [3].

The HMA AT software can be readily used to review dynamic modulus test data for compliance with the specification, as when non-compliant events are present, the program will highlight the problematic values by changing their font to a red color. This allows for an easy identification of out-of-specification measurements in the data grid.

In addition to this feature being useful to check data quality indicators for large batches of test results, when the software is being used for developing a master curve for a particular mix, the non-compliant values can be easily excluded from the analysis, facilitating a more precise determination of the dynamic modulus master curve parameters.

This can be achieved by removing the tick mark in the check box under the column labeled "Include in Master Curve Estimation", as illustrated in Fig. 10.

The program provides a set of acceptable thresholds that can be accessed by selecting the "DM Test Settings" submenu in the "Tools" menu. When selecting that option, a dialog box will be displayed, and the user can edit the current values manually, if desired. After the "OK" button is pressed, the values are saved and used for data quality indicators evaluation from that point forward, until changed again. It is important to note that the new saved settings persist between sessions.

Both the submenu to invoke the "DM Test Settings", and the dialog box where the data quality thresholds can be altered, are illustrated in Fig. 11.

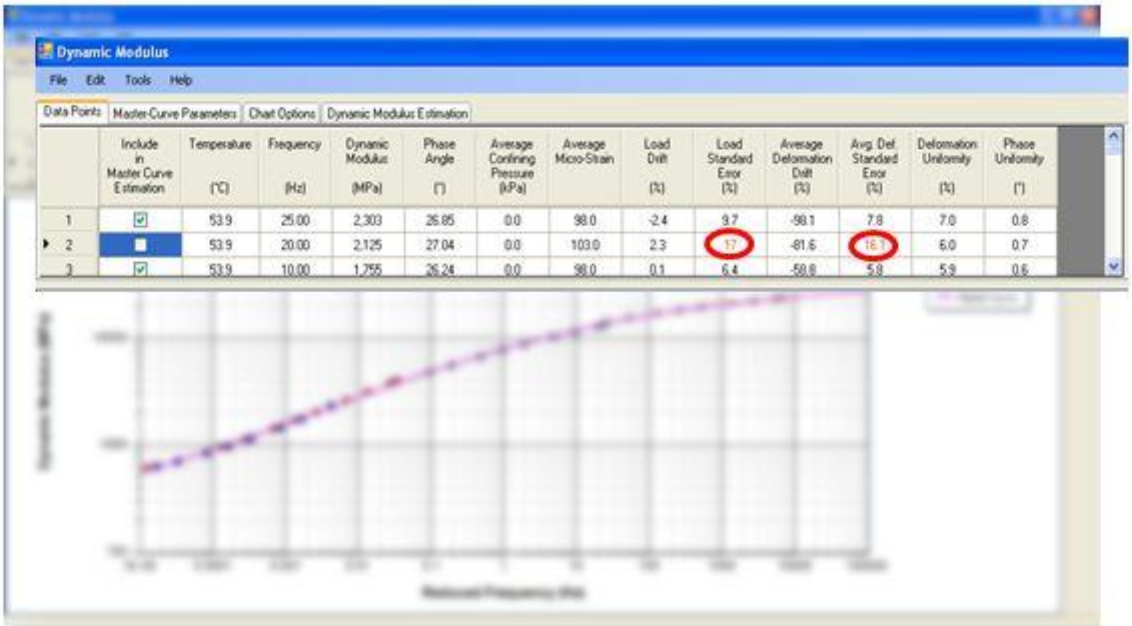
Generation of Master Curves and Modulus Data for Pavement Design

It is an established fact that asphalt modulus is dependent on the time of loading and the temperature at which the load is applied; however, in the name of simplicity, a generalized practice is to assume a "constant" or "single" value when a flexible pavement design using HMA is required. While this is already problematic by itself, to compound the issue it is quite common that actual modulus data not be readily available to designers, and in most cases, this constant modulus value is usually read from existing tables, calculated from existing models developed long time ago (and only applicable to materials that may not be relevant for the job at hand), or, in some instances, determined on the basis of educated guesses.

Although it has to be recognized that modulus values determined in this way are often corrected to account in some way for particular project conditions (e.g., temperature or speed of traffic), or for the particular characteristics of local materials by means of "correction" factors (usually based on limited monotonic testing or the concept of experienced local practitioners), it is important to highlight the fact that nothing can replace actual mix testing to understand the effect of time of loading and temperature on HMA.

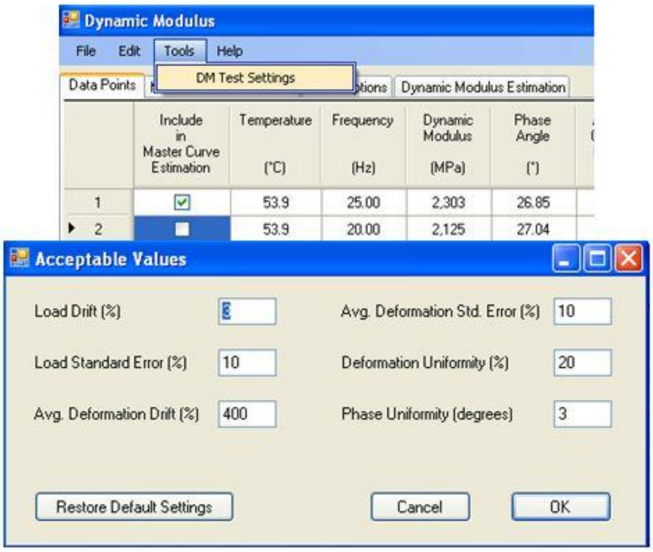
The implementation of more advanced pavement design methodologies is leading the way to incorporate the fundamental properties of asphalt mixes and their variability with time and temperature into the design procedures (e.g., AASHTO's DarwinME Pavement Design Guide), but to this day, numerous agencies and consulting firms still use the single modulus approach for pavement design. Regardless of the method being used, a significant, easy implementable step to reduce uncertainty and risk in the designs is to actually determine the modulus of the mixes being regularly used by an agency in its jurisdiction.

As an example of how the dynamic modulus test results obtained with the AMPT could be easily implemented and used regularly in practice, the HMA AT software was used to process actual test data to determine the master curve parameters from testing two different mixes with varying compaction levels at the University of Hawaii.



	Include in Master Curve Estimation	Temperature (°C)	Frequency (Hz)	Dynamic Modulus (MPa)	Phase Angle (°)	Average Confining Pressure (kPa)	Average Micro-Strain	Load Drift (%)	Load Standard Error (%)	Average Deformation Drift (%)	Avg. Def. Standard Error (%)	Deformation Uniformity (%)	Phase Uniformity (°)
1	☑	53.9	25.00	2,303	26.85	0.0	98.0	-2.4	9.7	-98.1	7.8	7.0	0.8
▸ 2	☐	53.9	20.00	2,125	27.04	0.0	103.0	2.3	17	-81.6	16.1	6.0	0.7
3	☑	53.9	10.00	1,755	26.24	0.0	98.0	0.1	6.4	-58.8	5.8	5.9	0.6

Fig. 10. Identification of Quality Indicators Outside Acceptable AASHTO TP79 Thresholds Using HMA AT.



	Include in Master Curve Estimation	Temperature (°C)	Frequency (Hz)	Dynamic Modulus (MPa)	Phase Angle (°)
1	☑	53.9	25.00	2,303	26.85
2	☐	53.9	20.00	2,125	27.04

Load Drift (%) 3
Load Standard Error (%) 10
Avg. Deformation Drift (%) 400
Avg. Deformation Std. Error (%) 10
Deformation Uniformity (%) 20
Phase Uniformity (degrees) 3

Fig. 11. Data Quality Indicators Threshold Values Settings in HMA AT.

Although multiple specimens were tested during the execution of the project, only |E*| data from four specimens, manufactured at low and high air void content levels using the Superpave Gyratory Compactor, were included in this particular example (additional information about these and the other mixes evaluated during the research undertaken at the University of Hawaii can be found in [5] and [10]). The specimens selected consisted on a 12.5 mm Superpave mix design with identical aggregate gradation and included both polymer modified and unmodified binders, as summarized in Table 1.

Different plots could be constructed with the information generated with the AMPT; in this particular example, two plots were constructed to illustrate the type of information that could be obtained with actual test data. The master curve parameters were first used to construct |E*| master curve plots, and then used to generate charts where the modulus of the mixes can be easily read directly under different conditions of temperature and time of loading, providing a quick reference for making an educated guess about the modulus of a mix with similar characteristics, if actual dynamic modulus data is not available.

In the first plot (Fig. 12), the |E*| master curves of all four specimens at a reference temperature of 21.1℃ are shown, based on the model parameters for Eqs. (2) and (3) obtained with the HMA AT software.

It is immediately evident that the graphical representation of the master curves can provide very useful information.

For example, the results suggest that when properly compacted

Table 1. Details of Specimens of Modified and Unmodified HMA Mixes Used for Examples.

Specimen ID	Binder	Va [%]	Pb [%]	Pbeff [%]	VMA [%]	Master Curve Parameters from HMA AT Software (Eqs. (2) and (3))						
						α	β	γ	δ	a	b	C
PMB-LVa	PG70-XX	3.0	5.7	12.3	13.4	2.536	-0.987	0.453	1.959	672E-6	-0.154	2.957
PMB-HVa	PG70-XX	9.8	5.7	11.6	19.4	4.380	-1.426	0.351	0.003	823E-6	-0.173	3.281
STD-LVa	PG64-16	2.7	5.7	12.2	13.0	2.527	-1.024	0.594	1.923	933E-6	-0.177	3.324
STD-HVa	PG64-16	9.3	5.7	11.3	18.9	3.633	-1.417	0.553	0.688	473E-6	-0.145	2.843

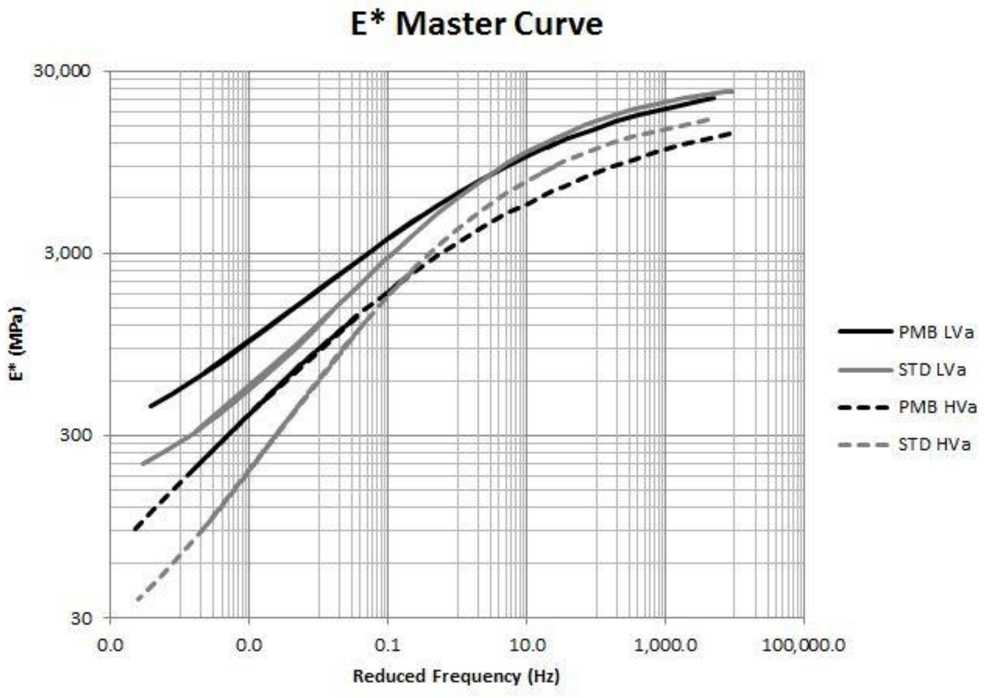


Fig. 12. |E*| Master Curves for Modified and Unmodified HMA Based on Parameters Estimated with the HMA AT.

(LVa mixes), the modulus for both modified and unmodified mixes is very similar at high reduced frequencies (which are associated with lower temperatures), but as the reduced frequency decreases, the modulus of the unmodified mix (i.e., STD LVa) decreases significantly faster. This could be explained by considering that when the mix is highly compacted, its modulus is mostly affected by the aggregate structure (note that although both binders will be stiff at low temperatures, their contribution to the stiffness of the mix is lower relative to that of the aggregate).

As reduced frequency decreases (temperature increases), the softening of the binder will have a greater effect on the overall stiffness of the mixes, and consequently, the modulus of the unmodified mix will decrease at a greater rate than that of the modified mix, following the stiffness drop rate of the unmodified binder. The same effect is observed in the modified mix, but due to the lower temperature susceptibility of its binder, its reduction in modulus can be expected to be less dramatic, as seen in the series identified as PMB LVa in Fig. 12.

Similar phenomena can be observed for the mixes with high air voids (i.e., dramatic decrease in modulus as temperature increases, but more pronounced for the unmodified binder); in this case, however, at low temperatures most of the stiffness of the poorly compacted mixes is driven by the stiffness of the binders, as the aggregate has not achieved the proper interlock (this is evidenced by a major difference in modulus for mixes PMB HVa and STD HVa at the higher reduced frequencies in Fig. 12). As at low temperatures the unmodified binder can be expected to be stiffer than the modified binder, the modulus of the unmodified mix will be greater than that of the modified mix; however, as temperature increases, the stiffness drop will be more dramatic for the unmodified binder due to its higher temperature susceptibility, reversing the situation exhibited at lower temperatures (i.e., greater modulus exhibited by the modified mix at higher temperatures).

Although |E*| master curve plots can be very useful for comparing mixes relative to each other and for certain analyses, reduced frequency is not something that lends itself for straight forward interpretation and comparison (reduced frequency needs to be converted “back” to frequency and temperature if one wants to determine the conditions at which the particular mix exhibits certain modulus). To this end, a chart where the effect of temperature on |E*| is illustrated for the mixes evaluated at both low and high frequencies was created with the master curve parameters generated with the HMA AT software, and is reproduced in Fig. 13.

Although this chart is more cluttered than the one showing the master curves for the mixes (i.e., Fig. 12), and omits information for intermediate frequencies (only shows frequencies of 10 Hz and 0.2 Hz to represent high and low frequencies, respectively), it would prove to be highly applicable, as it is straight forward to understand, and could be useful to determine specific HMA modulus values under given project conditions of temperature and loading frequency for known mixes, with potential applicability by designers to generate inputs for use in readily available multi-layered linear elastic analysis (MLLEA) programs, with the objective of checking the appropriateness of flexible pavement structural sections.

As a practical example in this case, the modulus of the highly compacted polymer modified mixture (identified as PMB LVa in Table 1) is estimated in Fig. 13 at around 3,000 MPa for high frequency loading (assumed to be 10 Hz), and at around 1,000 MPa for low frequency loading (assumed to be 0.2 Hz), both at a temperature of around 41℃.

It is important to remember that the values used to create the chart above were obtained from |E*| testing with the AMPT (i.e., they are laboratory based) and, consequently, the appropriate temperature and frequency values to be used for estimating a modulus value for design, which are beyond the scope of this document, should be the ones applying for the design temperature and frequency determined by the design engineer.

Additional interesting information could be drawn from the master curves in Fig. 12 and from the trends exhibited in Fig. 13;

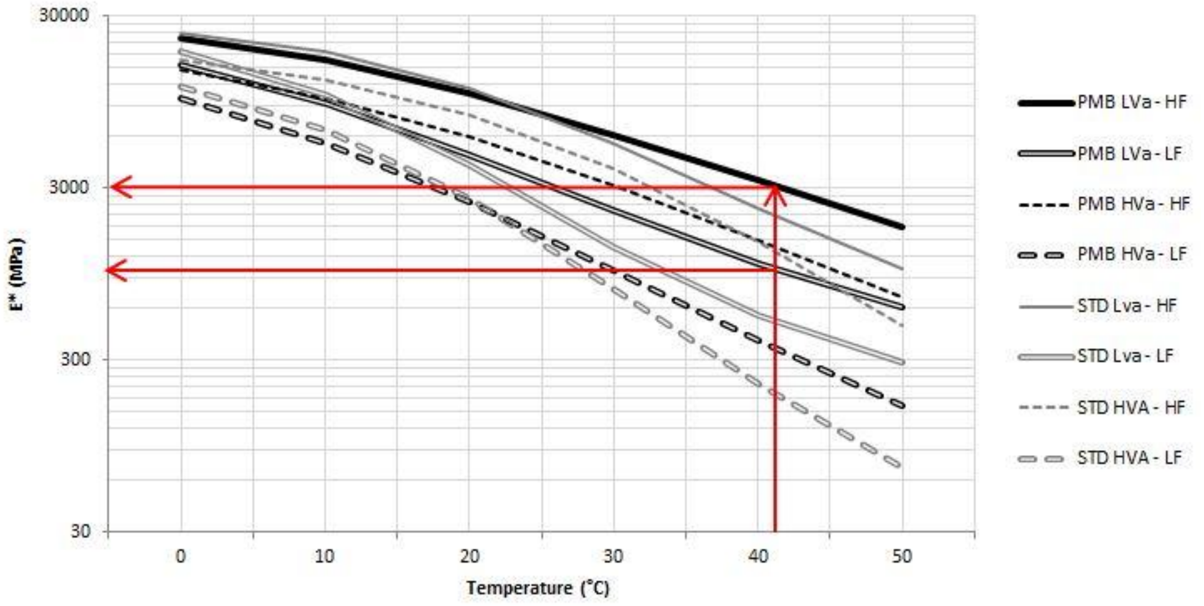


Fig. 13. Effect of Temperature on |E*| at High (10 Hz) and low (0.2 Hz) Frequencies.

however, recall that the objective of the exercise was to show practical applications of what could be done with the information generated from processing AMPT |E*| test data with the HMA Analysis Tool, and therefore an in-depth analysis of the data plotted in these charts is beyond the scope of this document.

The HMA AT can also be used to generate dynamic modulus data to be used with the strict format requirements prescribed in AASHTO's DarwinME Pavement Design Guide at the highest input level (i.e., Level 1). Due to the nature of certain asphalt mixes (e.g., a combination of extremely high air voids and very high temperatures, for instance), or to failures in sample preparation (e.g., improper gluing of LVDT gauge points to the specimen), it is possible that not every single |E*| data point required by DarwinME to properly run a structural design with Input Level 1 be available after a dynamic modulus test.

When this happens, after the summary data from the AMPT is imported and processed, and the master curve parameters for the mix tested have been generated (as described in an earlier section in this document), the HMA AT software can be then used to calculate the dynamic modulus values at the temperatures and frequencies needed by the DarwinME software, facilitating the use of the actual dynamic modulus test data available. Although it is recognized that these calculations could be done outside the HMA AT software if the master curve parameters are known, having this feature readily available within the application proves to be very convenient.

Generally speaking, although dynamic modulus testing is done somewhat regularly these days and practitioners have gained experience on its execution, it is not rare to find that once the results have been used for the specific purpose for which they were generated (for instance, dispute resolution and QC/QA procedures), the data will, at best, remain hidden in a computer or somewhere in an office desk to never be used again. The HMA AT software application could be a useful resource to process available |E*| test data and to generate a wealth of information about the characteristics of the asphalt mixtures used regularly in local projects, which can become a very valuable resource to make educated guesses about typical modulus values of local asphalt mixtures.

In addition, if dynamic modulus testing is also performed regularly on cores taken from existing roads, it may be possible to have an insight into the evolution of modulus with time for a given mix if enough data becomes available, enhancing the applicability of the |E*| database generated with the HMA AT. Finally, it is envisioned that the use of such a tool can be helpful for educational purposes in undergraduate and graduate courses related to HMA.

Summary and Conclusions

While technologies available today allow the precise determination of material fundamental properties to be used in mechanistic pavement designs, these technologies are often confined to the realm of research and theoretical analysis at universities and research centers. A reason commonly cited to explain this situation is the lack of trained personnel in the road agencies (and in the practicing engineering community at large) to properly interpret the results obtained from these tests, often perceived as "too complex", "research grade", or "not practical". In addition, the information generated from a dynamic modulus test run with the AMPT can be overwhelming for the less experienced users, in particular if a significant number of tests is being continuously run.

To facilitate bridging the gap between proper material characterization and practicality in pavement engineering, a specifically designed computer application, called the Hot Mix Asphalt Analysis Tool (HMA AT) was developed.

The HMA AT software package, as described in this document, facilitates the practical use of actual dynamic modulus tests performed with the commercially available Asphalt Mixture Performance Tester (AMPT). The application allows the user to select one or multiple output files from the AMPT system to be imported, and then combines them into a single table with all E* test data. The information can then be evaluated for inconsistencies or non-compliance in specified data quality indicators, altered by selecting data points to be excluded from evaluation if they do not meet the specification requirements, and used to generate the master curve parameters of the |E*| sigmoidal function incorporated into AASHTO's DarwinME Pavement Design Guide, which can then be used to calculate the dynamic modulus of the mix at virtually any temperature and loading frequency.

Although the examples included in this document involve a limited number of mixes, they provide a glimpse of practical applications in which data generated with the AMPT can be used, and will hopefully contribute to generate ideas about how interested users could make the most out of the data generated with their AMPT systems. Only applications involving data quality control and pavement design were described, but the possibilities for generating knowledge from consistently using the AMPT to measure the dynamic modulus of HMA at a local level are endless. If |E*| data is continuously and consistently filed, processed, and used by an agency or producer, enough information to better understand the performance of asphalt mixtures used locally could be assembled.

It is important to realize that even though accurate estimates of |E*| can be generated with the master curve parameters of a particular mix after being tested at a wide range of temperatures and frequencies, executing a proper pavement design also requires knowledge of other fundamental properties of asphalt mixtures and other materials used in road construction.

The current global trend towards adopting new technologies and utilizing more fundamental principles in pavement engineering is encouraging. Fundamental characterization of road materials becomes even more relevant when new and innovative materials and processes are introduced, especially considering the fact that the behaviour of these new materials is likely different from that of road materials traditionally used.

If it is expected that the benefits from the use of these new technologies materialize in practice, their generalized implementation and adoption is necessary, and all contributions directed towards achieving this goal, such as the one presented in this paper, will hopefully prove beneficial in the long run.

Acknowledgments

The contents of this paper reflect the view of the authors, who are responsible for the facts and accuracy of the data presented herein.

The contents in this document do not necessarily reflect any official views or policies of any public or private entity, and do not constitute a standard, specification or regulation. The support from both IPC Global and the University of Hawaii is greatly appreciated.

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