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16. Abstract

This project evaluated the procedures proposed by the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) to characterize existing hot-mix asphalt (HMA) layers for rehabilitation purposes. Thirty-three cores were extracted from nine sites in Virginia to measure their dynamic moduli in the lab. Falling-weight deflectometer (FWD) testing was performed at the sites because the backcalculated moduli are needed for the Level 1 procedure. The resilient modulus was also measured in the lab because it is needed for the Level 2 procedure. A visual pavement rating was performed based on pavement condition because it is needed for the Level 3 procedure.

The selected cores were tested for their bulk densities (G_{mb}) using the AASHTO T166 procedure and then for their dynamic modulus in accordance with the AASHTO TP62-03 standard test method. Then the cores were broken down and tested for their maximum theoretical specific gravity (G_{mm}) using the AASHTO T-209 procedure. Finally an ignition test was performed to find the percentage of binder and to reclaim the aggregate for gradation analysis. Volumetric properties were then calculated and used as input for the Witczak dynamic modulus prediction equations to find what the MEPDG calls the undamaged master curve of the HMA layer. The FWD data, resilient modulus data, and pavement rating were used to find the damaged master curve of the HMA layer as suggested for input Levels 1, 2, and 3, respectively.

It was found that the resilient modulus data needed for a Level 2 type of analysis do not represent the entire HMA layer thickness, and therefore it was recommended that this analysis should not be performed by VDOT when implementing the design guide. The use of Level 1 data is recommended because FWD testing appears to be the only procedure investigated that can measure the overall condition of the entire HMA layer.

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Mechanistic-empirical design, dynamic modulus, resilient modulus, falling weight deflectometer, pavement rehabilitation design, damaged master curves

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FINAL CONTRACT REPORT

DETERMINATION OF THE IN-PLACE HOT-MIX ASPHALT LAYER MODULUS FOR REHABILITATION PROJECTS USING A MECHANISTIC-EMPIRICAL PROCEDURE

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UNITS

This report uses US Customary units. To convert from US Customary to SI units, use the following table:

US Customary Units	**Formula**	**Equivalent SI Units**
inch (in)	in x 25.4	millimeter (mm)
kilo pound per square inch (ksi)	ksi x 6.894757	mega Pascal (MPa)
°F	(°F-32) x 5/9	°C
Poise (P)	P x 0.1	Pascal second (Pa.s)

ABSTRACT

This project evaluated the procedures proposed by the Mechanistic-Empirical (M-E) Pavement Design Guide (MEPDG) to characterize existing hot-mix asphalt (HMA) layers for rehabilitation purposes. Thirty-three cores were extracted from nine sites in Virginia to measure their dynamic moduli in the lab. Falling-weight deflectometer (FWD) testing was performed at the sites because the backcalculated moduli are needed for the Level 1 procedure. The resilient modulus was also measured in the lab because it is needed for the Level 2 procedure. A visual pavement rating was performed based on pavement condition because it is needed for the Level 3 procedure.

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It was found that the resilient modulus data needed for a Level 2 type of analysis do not represent the entire HMA layer thickness, and therefore it was recommended that this analysis should not be performed by VDOT when implementing the design guide. The use of Level 1 data is recommended because FWD testing appears to be the only procedure investigated that can measure the overall condition of the entire HMA layer.

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INTRODUCTION

The dynamic modulus is the property used in the proposed Mechanistic-Empirical (M-E) pavement design guide (MEPDG) to characterize hot-mix asphalt (HMA) layers. For designing new pavements, the proposed guide suggests three different input levels for the dynamic modulus. Level 1, considered to be the most accurate level of input, obtains the dynamic modulus through a series of laboratory tests performed at different temperatures and different loading rates to obtain a master curve for the design mix. Level 2, considered to provide an intermediate level of accuracy, estimates the dynamic modulus of HMA from other measured properties of the mix such as effective binder content, binder viscosity, air void content, percentage passing the No. 200 sieve, etc. Level 3, considered to provide the lowest level of accuracy, estimates the dynamic modulus of HMA from known properties of similar mixes without performing any laboratory tests.

Rehabilitation projects use a similar three-level input scheme. Level 1 uses falling-weight deflectometer (FWD) data to backcalculate the combined HMA layer modulus. The as-constructed dynamic modulus is then predicted from the mix volumetric parameters obtained after testing cored samples. A damage factor is then calculated based on the ratio of the backcalculated modulus to the predicted one. The damage factor is then used to develop the dynamic modulus master curve for the field-damaged combined HMA layer. Level 2 uses field cores to measure and calculate the mix volumetric parameters and to measure the resilient modulus in the indirect tensile (IDT) setup. Based on these measurements, the damage factor is obtained, from which the field-damaged dynamic modulus master curve can be developed. Level 3 obtains the damage factor from correlations with the visual pavement rating; the master curve for the field-damaged dynamic modulus is obtained in the same way as in Levels 1 and 2.

In order to evaluate, validate, and implement these processes for rehabilitation design, it is important to apply these techniques on a realistic cross-section of Virginia pavements. In addition, measuring the dynamic moduli of actual composite cores may provide better correlation with the backcalculated moduli, which may suggest an alternative method of obtaining a master curve for the field-damaged HMA layer.

PURPOSE AND SCOPE

The objective of this research was to validate the M-E analysis procedure to characterize HMA layers for rehabilitation purposes. This project takes advantage of extensive field tests and material sampling from nine sites (eight flexible and one composite) from some of Virginia's highest-trafficked pavements. The cores from these pavements were tested in the laboratory to determine their dynamic moduli. Undamaged master curves for the HMA layer were obtained from the volumetric properties and the Witczak prediction equation, while damaged master curves were generated using FWD data, resilient modulus data, and pavement ratings.

METHODS

This project took advantage of some of the FWD data, laboratory resilient modulus data, and pavement distress data collected from the "Field Investigation of High Performance Pavements in Virginia" project (Flintsch et al., 2005). Table 1 presents the sites chosen for this project, and Figure 1 shows their locations. Cores from these sites were prepared for and subjected to dynamic modulus testing. A description of the core preparation, testing, and proposed MEPGD procedure for determining the damaged master curve for HMA layers follows.

Table 1. Selected pavement sites

Site #	County	Route	Direction	Milepost*	Pavement Type	Pavement Age/Surface Age (years)
01	Amherst	29	South	7.80-7.30	Flexible	34 / 11
03	Louisa	64	West	9.91-9.41	Flexible	34 / 9
06	York	64	West	2.62-2.12	Flexible	25 / 7
12	Greensville	95	North	5.50-6.00	Comp. JPCP (rehab)	14 / 6
14	Russell	19	North	8.68-9.18	Flexible	6 / 6
15	Rockbridge	81	South	22.92-22.42	Flexible	37 / 17
16	Frederick	81	North	21.31-21.87	Flexible	39 / 13
17	Washington	81	South	12.50-12.00	Flexible	42 / 11
18	Washington	81	South	1.50-1.00	Flexible	5 / 3

* county milepost

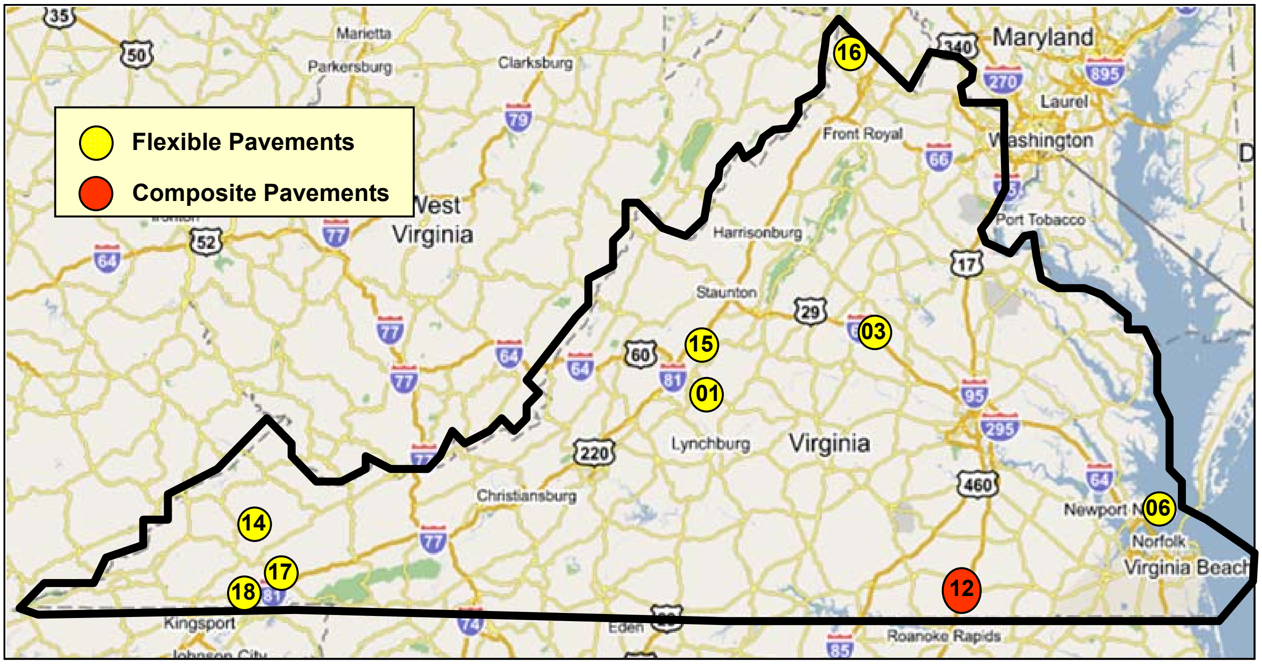


Figure 1. Location of the sites chosen for this project

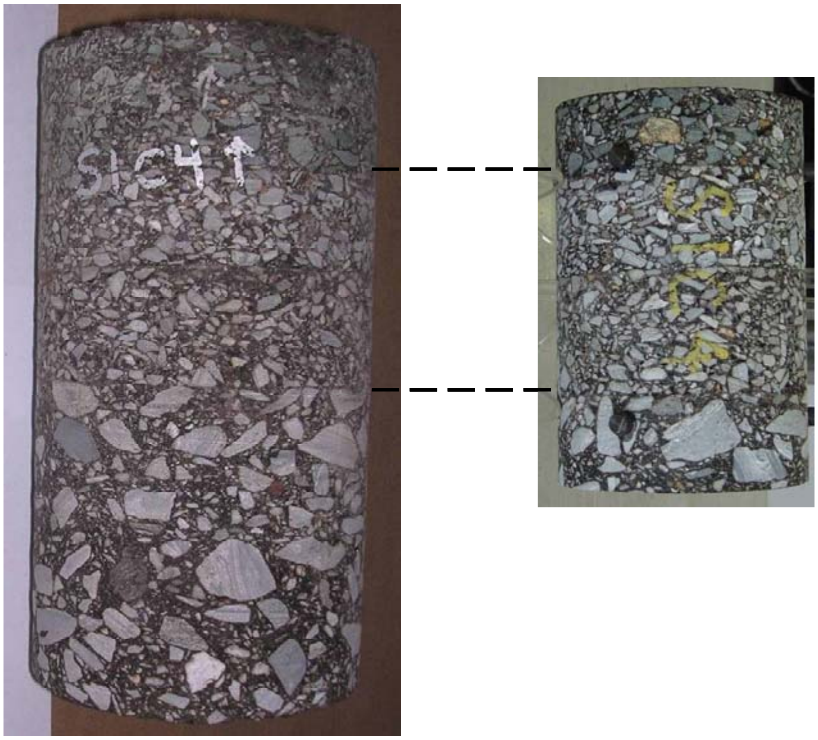
Cores and Specimen Preparation

This study used a total of 33 cores. The number of cores differed from site to site depending on availability and suitability for testing in the dynamic modulus setup. Table 2 shows the tested cores per site. All cores were initially 6 inches in diameter with different thicknesses. They were first cored to 4 inches in diameter and then were cut to a total thickness of 6 inches, as shown in Figure 2. The cutting process was performed by first cutting the upper part of the core in order to have a smooth upper surface, measuring 6 inches down from the resulting core top, and then cutting the bottom part of the core. Figure 3a shows a core from Site 01 (S01C4) prior to preparation while Figure 3b shows the same core after preparation (coring and cutting) ready to be tested in the dynamic modulus setup.

Table 2. Tested cores per site

Site	Cores
01	S01C4, S01C7, S01C8, and S01C10
03	S03C2, S03C4, S03C5, and S03C7
06	S06C1, S06C2, and S06C3
12	S12C2, S12C7, S12C8 and S12C10
14	S14C6, S14C9, and S14C10
15	S15C3, S15C6, S15C7, and S15C10
16	S16C5, S16C8, and S16C9
17	S17C5, and S17C8
18	S18C3 (2 specimens), S18C5 (2 specimens), and S18C9 (2 specimens)

Figure 2. Coring and cutting of dynamic modulus specimens



(a) (b)

Figure 3. Core S01C4 (a) prior to preparation and (b) after preparation

Dynamic Modulus Test (Uniaxial Setup)

Determination of the dynamic moduli of all the cores in this study followed the procedure as described in AASHTO TP62-03. The test is performed by applying sinusoidal vertical load and measuring the corresponding vertical deformation. The dynamic modulus is calculated using Equation 1. The in-phase and out-of-phase components are obtained using Equations 2 and 3, respectively.

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0} \tag{1}$$

$$E' = |E^*| \cos(\delta) \tag{2}$$

$$E'' = |E^*| \sin(\delta) \tag{3}$$

where

σ_0 = applied stress amplitude,

ε_0 = measured strain amplitude, and

δ = phase angle, computed as follows:

$$\delta = \frac{\Delta t}{T} 360° \tag{4}$$

where

Δt = time lag between the applied stress and the corresponding strain, and

T = Period of the applied sinusoidal load

Five test temperatures, 10 °F, 40 °F, 70 °F, 100 °F, and 130 °F, and six frequencies, 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz, and 25 Hz, were used for all the cores, except for the cores from sites 01 and 17, where a temperature of 29.6 °F was mistakenly used instead of 40 °F.

Determination of HMA-Layer Modulus for Rehabilitation Projects

The proposed MEPDG suggests three different input levels for determining the existing (or field-damaged) HMA dynamic modulus for rehabilitation projects.

Input Level 1: For Level 1 design, the MEPDG proposes the following procedure to determine the existing HMA dynamic modulus:

1. Perform an FWD survey on the pavement that needs rehabilitation and backcalculate the average modulus for the HMA layer, E_f at the field temperature T_f.
2. Extract core samples from the field and establish HMA volumetric parameters.
3. Develop an undamaged-HMA dynamic modulus master curve using the Witczak prediction equation, seen in Equation 5:

$$\log E^{*} = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^{2} - 0.058097V_{a} - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_{a}}\right) + \frac{3.871977 - 0.0021\rho_{4} + 0.003958\rho_{38} - 0.000017(\rho_{38})^{2} + 0.005470\rho_{34}}{1+e^{-0.603313-0.313351\log(f)-0.393532\log(\eta)}} \quad (5)$$

where
E^* = dynamic modulus, psi,
ρ_{200} = % passing the #200 sieve,
ρ_4 = cumulative % retained on the #4 sieve,
ρ_{34} = cumulative % retained on the #3/4 sieve,
ρ_{38} = cumulative % retained on the #3/8 sieve,
f = frequency in Hz,
V_{beff} = effective bitumen content, % by volume,
V_a = air void content, and
η = bitumen viscosity, 10^6 Poise.

The bitumen viscosity varies with temperature according to Equation 6:

$$\log(\log(\eta)) = A + VTS \log(T_R) \quad (6)$$

where
η = binder viscosity expressed in cP,
T_R = temperature in degrees Rankine, and
A and VTS = regression parameters. Since the binder was not retrieved for this study, the research used default values as suggested by the proposed MEPDG for a PG64-22 binder: 10.98 for A and -3.68 for VTS. This default binder was selected because most of the materials tested were constructed using an AC-20 asphalt, and the specimens tested included only the undamaged part of the cores.

Once the dynamic modulus is predicted at different temperatures and frequencies, the undamaged master curve at the reference temperature (70 °F for this study) is obtained by fitting a sigmoidal function, given in Equation 7, to the predicted data.

$$\log\left|E^{*}\right| = \delta + \frac{\alpha}{1+e^{\beta-\gamma\log f_r}} \quad (7)$$

where
δ, α, β, and γ = sigmoidal function coefficients (fit parameters) and
f_r = reduced frequency, which is given by the following equation:

$$\log f_r = \log f + \log a_T \quad (8)$$

where
a_T = shift factor at temperature T and is obtained by this equation:

$$\log a_T = 1.25588(\log(\eta) - \log(\eta_r)) \quad (9)$$

where
η = viscosity at temperature T and η_r is the viscosity at the reference temperature.

4. Estimate damage, d_j, expressed as follows:

$$d_j = 1 - \frac{E_f}{E^*} \tag{10}$$

where
E^* = predicted dynamic modulus at a temperature T_f at a frequency equivalent to the load pulse applied by the FWD equipment.

5. Compute α' as shown by Equation 11:

$$\alpha' = (1 - d_j) * \alpha \tag{11}$$

6. Determine the field-damaged HMA master curve by using α' instead of α in Equation 7.

Input Level 2: For Level 2, the same procedure as described above for Level 1 is used except that a FWD survey is not performed. Instead some of the cores collected from the field are tested in the laboratory for their resilient modulus value, M_r. The damage is then computed as shown by Equation 10 with M_r instead of E_f. The factor α' is then computed as shown by Equation 11, and the field-damaged HMA master curve is generated.

Input Level 3: For Level 3, no FWD or laboratory testing are required. Instead the undamaged-HMA master curve is generated from estimated typical mix parameters while the damage is estimated from the pavement condition as shown by Table 3. The factor α' is then computed as shown by Equation 11, and the field-damaged HMA master curve is generated. It should be noted that this study used the undamaged master curve as obtained from the volumetric properties of the cores even for Level 3 input—a modified Level 3 approach.

Table 3. Estimated damage as a function of pavement rating

Category	Damage
Excellent	0.00 – 0.20
Good	0.20 – 0.40
Fair	0.40 – 0.80
Poor	0.80 – 1.20
Very Poor	> 1.2

RESULTS AND DISCUSSION

FWD Testing

The *in situ* elastic moduli for HMA layers were backcalculated from the deflections measured for a 9,000-lb load using ELMOD software in the previous project. Table 4 shows the average values for the sites considered in this study and the temperatures recorded by the FWD at the time of measurement. More details about the FWD analysis are presented in the final report of the "Field Investigation of High Performance Pavements in Virginia" project (Flintsch et al., 2005). Since the FWD loading induces a pulse with duration of 0.03 s (Loulizi et al., 2002), an equivalent frequency of 5.3 Hz ($1/0.03/2\pi$) for the dynamic modulus is used for estimating the damage as shown by Equation 10.

Table 4. Backcalculated field moduli for all the sites

Site	Temp. (°F)	Backcalculated Moduli, ksi
Site 01	74	462
Site 03	63	540
Site 06	73	231
Site 12	69	594
Site 14	90	522
Site 15	74	266
Site 16	65	582
Site 17	69	403
Site 18	78	567

Resilient Modulus Test

The average resilient moduli at 77 °F for the tested HMA layers are presented in Table 5. The tests were performed in accordance with ASTM D4123 (ASTM, 1999). Tests were run for 100 cycles, of which the last five were used to calculate the resilient modulus. The applied load was chosen to induce deformations that are well above the sensitivity of the strain gauges while minimizing damage to the specimens (Flintsch et al., 2005). Table 5 reports the average resilient modulus for the surface mix (SM) and base mix (BM). The combined resilient modulus value, which was used for the later Level 2 analysis, was obtained using the method of equivalent thickness (Ullidtz, 1998). The combined resilient modulus was obtained using the following equation:

$$M_{rc} = \left(\frac{h_1\sqrt[3]{M_{rWS}} + h_2\sqrt[3]{M_{rBM}}}{h_1 + h_2}\right)^3 \tag{12}$$

where
M_{rc} = combined resilient modulus,
M_{rWS} = resilient modulus for the (wearing) surface mix,
M_{rBM} = resilient modulus for the base mix,
h_1 = thickness of the wearing surface, and
h_2 = thickness of the base mix.

Since the resilient modulus test was run with pulse duration of 0.1 s, an equivalent frequency of 1.59 Hz (1/0.1/2π) for the dynamic modulus was used for estimating the damage as shown by Equation 10.

Table 5. Resilient modulus results at 77 °F (ksi)

Site #	Wearing Surface	Base Mix	Combined
01	746	433	569
03	893	704	790
06	541	428	460
12	755	963	923
14	637	593	601
15	920	484	523
16	610	993	948
17	643	656	654
18	600	721	702

Measured Dynamic Modulus

Table 6 shows the results of the measured dynamic modulus and the phase angle at all tested temperatures and frequencies for the cores of site 14. The results for the other sites may be found at http://www.virginiadot.org/vtrc/main/online_reports/pdf/append/07-cr1.htm. As expected, the dynamic modulus values decreased with an increase in temperature and/or decrease in frequency. The phase angle increased with a decrease in frequency up to a temperature of 70 °F. At higher temperatures the behavior of the phase angle is more complex mainly due to the role that aggregate interlock plays at these temperatures.

Table 6. Measured dynamic modulus (ksi) and phase angle (°) for site 14 cores

Core	Frequency (Hz)	Temp. (˚F)									
		10		40		70		100		130	
		|E*|	δ	|E*|	δ	|E*|	δ	|E*|	δ	|E*|	δ
S14C6	25	2,567	4.0	1,954	9.5	1,395	19.5	404	35.1	107	31.0
	10	2,522	4.2	1,779	10.6	1,147	21.6	284	35.2	78	26.7
	5	2,361	4.1	1,671	11.5	967	24.2	212	35.0	64	23.9
	1	2,252	5.8	1,426	14.5	607	29.5	114	32.1	45	18.0
	0.5	2,181	5.7	1,302	17.2	462	34.1	89	30.9	40	16.5
	0.1	1,995	8.2	1,063	21.7	267	36.1	59	24.6	35	14.8
S14C9	25	3,065	3.4	2,953	6.4	1,480	16.4	494	32.3	143	31.2
	10	2,850	3.6	2,694	6.9	1,186	20.0	362	33.0	97	26.6
	5	2,749	4.3	2,491	9.6	1,012	21.4	276	32.8	78	23.6
	1	2,584	4.8	2,031	11.3	661	26.4	152	29.8	55	17.7
	0.5	2,403	6.3	1,832	15.2	526	30.7	119	28.6	50	16.2
	0.1	2,198	6.5	1,405	18.3	318	31.9	81	22.4	43	14.3
S14C10	25	3,611	3.3	1,988	8.6	1,377	20.0	384	35.9	104	31.4
	10	3,741	3.8	1,795	10.9	1,092	22.2	268	35.6	78	26.1
	5	3,612	4.6	1,637	11.6	904	25.3	202	34.8	66	22.9
	1	3,366	7.3	1,367	15.2	558	30.7	112	30.5	49	17.5
	0.5	3,188	7.6	1,226	17.4	421	35.6	91	29.3	46	17.2
	0.1	2,770	7.9	949	22.9	234	37.0	65	23.8	42	16.2

Using the statistical package SAS, a master curve at a reference temperature of 70 °F was generated for each tested core. SAS minimizes the error to find the parameters of the sigmoidal function (Equation 7) as well as the shift factors at each temperature. Figure 4, for example, shows the obtained master curve and the shifted data for core S14C9. For this particular core the values of the parameters were 4.41233, 2.11222, -0.68886, and 0.67177 for δ, α, β, and γ, respectively. All the parameter values obtained for the other cores are shown in Table 7.

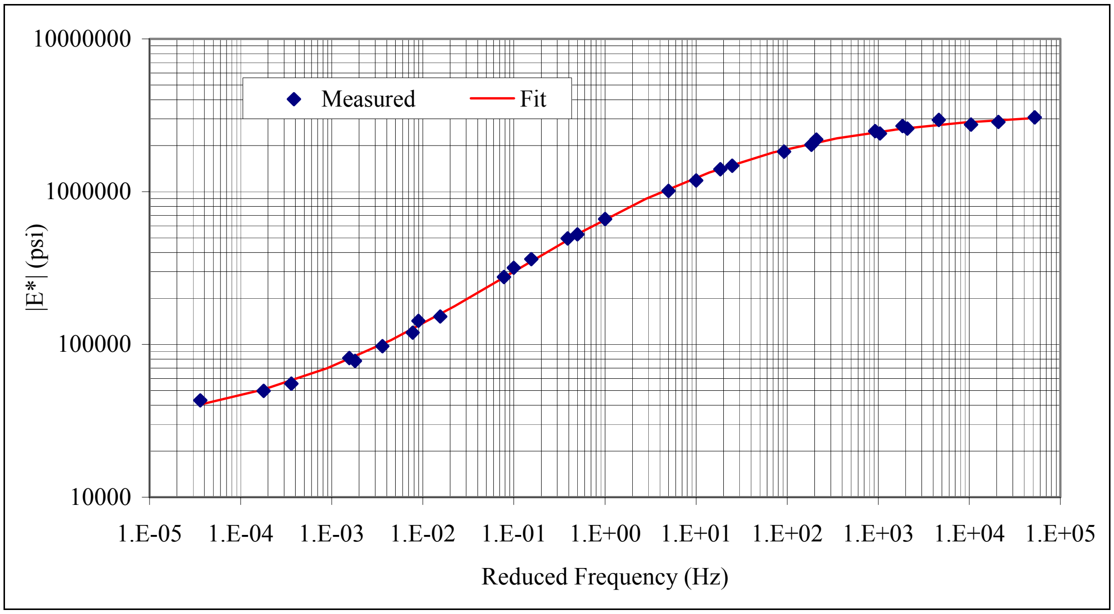


Figure 4. Shifted measured dynamic modulus data and sigmoidal fit for core S14C9

Table 7. Parameters of the sigmoidal function for the measured master curves for all tested cores (Eq. 7)

Core	δ	α	β	γ
Site 01				
S01C4	4.04826	2.35325	-0.6277	0.48737
S01C7	4.33752	2.05483	-0.7605	0.55171
S01C8	3.97876	2.47175	-0.9071	0.41766
S01C10	4.15832	2.22402	-0.9902	0.48149
Site 03				
S03C2	4.48618	1.94165	-0.47470	0.5244
S03C4	4.48138	1.89149	-0.42163	0.60192
S03C5	4.46321	1.95906	-0.65702	0.53498
S03C7	4.08588	2.43094	-0.5065	0.44931
Site 06				
S06C1	4.17763	2.27964	-0.2081	0.64869
S06C2	3.86545	2.6469	-0.5914	0.63091
S06C3	3.94668	2.52943	-0.4960	0.58727
Site 12				
S12C2	4.13743	2.2373	-0.9250	0.58478
S12C7	4.41204	1.97291	-0.8053	0.59124
S12C8	4.10884	2.36392	-0.6469	0.59122
S12C10	4.22877	2.29389	-0.6730	0.60288
Site 14				
S14C6	4.38589	2.00003	-0.8422	0.77344
S14C9	4.41233	2.11222	-0.68886	0.67177
S14C10	4.40894	2.13657	-0.49345	0.64527
Site 15				
S15C3	4.35903	2.06344	-0.7119	0.45652
S15C6	4.31350	2.26324	-0.5889	0.62665
S15C7	4.74050	1.61990	-1.01128	0.78573
S15C10	4.61951	1.79012	-0.32849	0.75344
Site 16				
S16C5	4.26112	2.16823	-0.49335	0.56085
S16C8	4.32482	2.24714	-0.63180	0.59722
S16C9	4.26068	2.15123	-0.71343	0.55781
Site 17				
S17C5	4.37883	2.00194	-0.4097	0.53836
S17C8	4.15515	2.26185	-0.5812	0.42987
Site 18				
S18C3 T	4.26352	2.37443	-0.82922	0.56774
S18C3 B	4.36586	1.97825	-0.90344	0.67010
S18C5 T	4.43231	2.02184	-0.8367	0.74612
S18C5 B	4.30709	2.28245	-0.77448	0.56772
S18C9 T	4.47734	2.00502	-0.75050	0.65278
S18C9 B	4.35173	2.33325	-0.48259	0.58313

Predicted Undamaged Dynamic Modulus Master Curves

The volumetric properties of the different cores were used to predict the dynamic modulus using the Witczak prediction equation (Equation 6) at the temperatures and frequencies used in the laboratory testing. For example, Table 8 presents the volumetric properties for the cores of site 14 combining all HMA layers present in the core. All volumetric properties for the other cores may be found at http://www.virginiadot.org/vtrc/main/online_reports/pdf/ append/07-cr1.htm. Table 9 shows the predicted values of the dynamic modulus for the cores of Site 14. The values for the other cores may be found at http://www.virginiadot.org/ vtrc/main/online_reports/pdf/append/07-cr1.htm.

Table 8. Volumetric properties for Site 14 cores

Core	ρ_{200}	ρ_4	ρ_{34}	ρ_{38}	V_a	V_{beff}
S14C6	8.0	50.7	5.7	27.7	3.5	11.2
S14C9	8.8	54.7	12.2	35.6	3.2	9.4
S14C10	8.3	53.9	4.4	30.5	2.7	11.0

Table 9. Predicted dynamic modulus, |E*|, values (ksi) for site 14 cores

Core	Frequency (Hz)	Temperature (°F)				
		10	40	70	100	130
S14C6	25	3,791	2,792	1,144	387	135
	10	3,554	2,530	955	303	103
	5	3,368	2,332	826	250	83
	1	2,919	1,885	573	157	51
	0.5	2,722	1,701	484	128	41
	0.1	2,263	1,303	318	78	26
S14C9	25	4,400	3,227	1,307	437	150
	10	4,121	2,921	1,089	340	114
	5	3,903	2,690	940	280	92
	1	3,377	2,168	649	175	56
	0.5	3,145	1,953	547	142	45
	0.1	2,609	1,491	357	87	28
S14C10	25	3,792	2,793	1,146	389	136
	10	3,555	2,531	957	304	103
	5	3,369	2,334	828	251	84
	1	2,921	1,887	575	158	51
	0.5	2,723	1,703	485	128	42
	0.1	2,265	1,305	319	79	26

Figure 5 shows the predicted master curve at the reference temperature of 70 °F for core S14C9 after shifting the data presented in Table 9 using the shift factors obtained from Equation 9. A sigmoidal equation was then used to fit to the shifted data as shown in Figure 5 for core S14C9. The parameters for the sigmoidal equation for all the cores for the predicted undamaged master curves are presented in Table 10. It should be noted that the parameters β and γ are the same for all cores because no asphalt extraction was conducted, and the same binder properties were assumed in all cases.

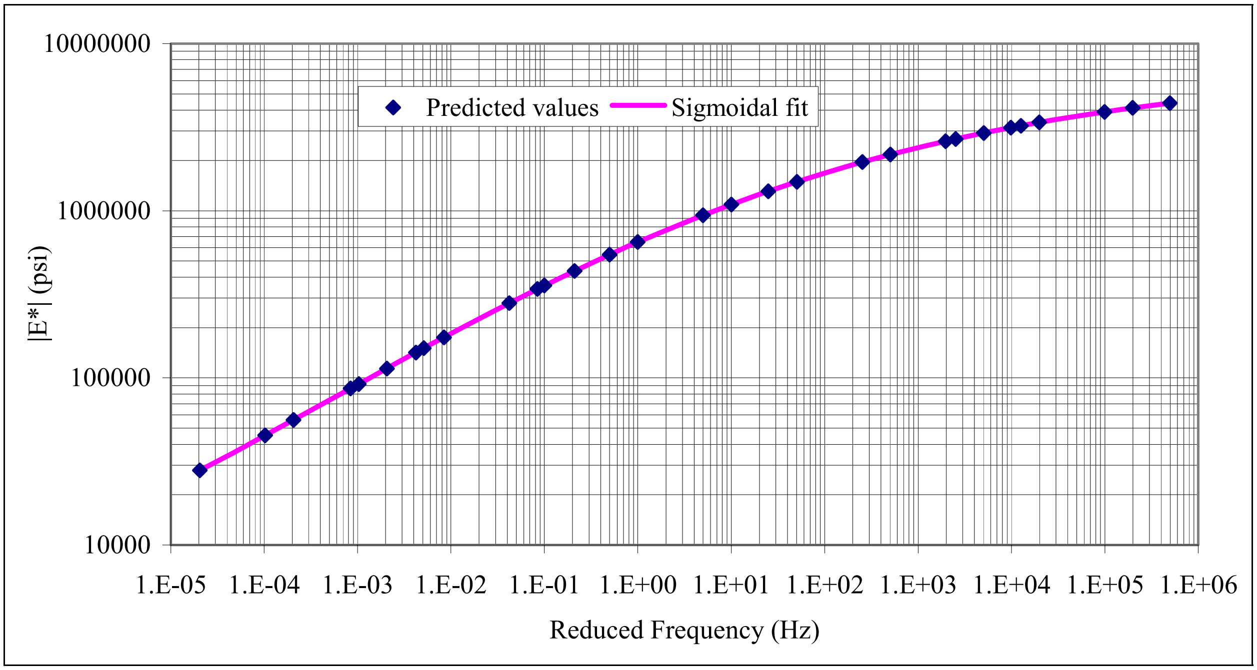


Figure 5. Shifted predicted dynamic modulus data and sigmoidal fit for core S14C9

Table 10. Parameters of the sigmoidal function for the predicted undamaged master curves for all the cores

Core	δ	α	β	γ
Site 01				
S01C4	2.8680620	3.8604290	-0.9996920	0.3136125
S01C7	2.8938074	3.8567869	-0.9996920	0.3136125
S01C8	2.8925282	3.8882415	-0.9996920	0.3136125
S01C10	2.8695930	3.8648969	-0.9996920	0.3136125
Site 03				
S03C2	2.7698649	3.9096899	-0.9996920	0.3136125
S03C4	2.7743114	3.9444226	-0.9996920	0.3136125
S03C5	2.7866495	3.9511645	-0.9996920	0.3136125
S03C7	2.7732063	3.9434689	-0.9996920	0.3136125
Site 06				
S06C1	2.8965789	3.9962180	-0.9996920	0.3136125
S06C2	2.8977343	3.9877258	-0.9996920	0.3136125
S06C3	2.9057845	3.9413528	-0.9996920	0.3136125
Site 12				
S12C2	2.9416532	4.0440458	-0.9996920	0.3136125
S12C7	2.9445695	3.8878343	-0.9996920	0.3136125
S12C8	2.9493143	3.868774	-0.9996920	0.3136125
S12C10	2.9491881	3.8804278	-0.9996920	0.3136125
Site 14				
S14C6	2.9139499	3.890965	-0.9996920	0.3136125
S14C9	2.9312561	3.941250	-0.9996920	0.3136125
S14C10	2.9191976	3.885438	-0.9996920	0.3136125
Site 15				
S15C3	2.9272278	3.9316074	-0.9996920	0.3136125
S15C6	2.9226416	3.9350808	-0.9996920	0.3136125
S15C7	2.9212861	3.9714131	-0.9996920	0.3136125
S15C10	2.9140410	3.9103768	-.9996920	0.3136125
Site 16				
S16C5	2.9508915	3.8874714	-0.9996920	0.3136125
S16C8	2.9258427	3.8966051	-0.9996920	0.3136125
S16C9	2.9417190	3.8757946	-0.9996920	0.3136125
Site 17				
S17C5	2.7410606	3.9131955	-0.9996920	0.3136125
S17C8	2.7914884	3.8827159	-0.9996920	0.3136125
Site 18				
S18C3 T	2.8846760	3.9116398	-0.9996920	0.3136125
S18C3 B	2.9182241	3.9389919	-0.9996920	0.3136125
S18C5 T	2.8944497	3.9546098	-0.9996920	0.3136125
S18C5 B	2.8660647	3.9736669	-0.9996920	0.3136125
S18C9 T	2.9290216	3.9862798	-0.9996920	0.3136125
S18C9 B	2.8928212	3.9385795	-0.9996920	0.3136125

Predicted Damaged Dynamic Modulus Master Curves

The damage factor for all the cores for Levels 1 and 2 was determined by Equation 10 using the FWD backcalculated moduli (Table 4) and the laboratory resilient modulus values (Table 5), respectively. For Level 3, a damage factor was assigned to the different sites based on their ratings (as shown in Table 3). The rating itself was based on the Combined Condition Index (CCI) calculated based on the distress survey (Flintsch et al., 2005). Once the damage factor was established, the parameter α', used to construct the damaged master curve, was calculated using Equation 11 for the three different levels. Table 11 presents the results of all these calculations for all cores and all levels. It should be noted that the Level 3 data reflects the condition of only the surface layer. Since most of the pavements considered have been already overlaid, the estimate may not reflect the actual condition of the entire HMA layer. On the other hand, the estimates based on the FWD test reflect the average modulus of the HMA layers, and thus they consider the deterioration of the deeper HMA layers.

Table 11 shows that most of the calculated damage factors for Level 2 were negative, except for 8 out of the 33 total cores. This means that the measured laboratory resilient modulus was in most instances larger than the predicted undamaged dynamic modulus at the same temperature and equivalent frequency. This is mainly due to the resilient modulus being performed only on the solid top (wearing surface) or solid bottom (base mix) 2 inches of the core, which is not very representative of the whole HMA layer. On the other hand, the calculated damage factors for Level 1 were positive, ranging from 0.15 to 0.76, except for the cores of Site 14, where the calculated damage factors were negative. The backcalculated modulus represents the whole HMA layer, and therefore in most cases it is smaller than the predicted undamaged dynamic modulus at the same temperature and frequency.

The small negative numbers for Site 14 could be due to several factors. First it should be noted that the pavement in this section was just 6 years old and showed no signs of deterioration. Thus, the damage ratio should be close to zero. In addition, a small increase in the HMA modulus early in the life of the pavement has been observed in other studies and can be explained by the stiffening of the binder due to aging. Furthermore, it could also be explained by the use of only the average FWD backcalculated modulus for the whole site. If the backcalculated modulus close to where the core was taken had been used instead, then positive damage would have been calculated. In fact, the backcalculated modulus on the location closest to where core S14C6 was extracted was 476 ksi. If this number had been used instead of the average value of 522 ksi, then a d_j of 0.01 would have been calculated instead of -0.14.

Figure 6 shows five master curves at the reference temperature of 70 °F for core S01C4: one for the measured data, one for the predicted undamaged HMA based on the volumetric properties and Witczak equation, and three for the damaged HMA based on the three data input levels. The master curves for all other cores may be found at (http://www.virginiadot.org/vtrc/main/online_reports/pdf/append/07-cr1.htm). Figure 6 shows that the damaged master curve for Level 2 is higher than all other curves. This is because the damage factor was calculated to be negative as explained before, and therefore the α' parameter is greater than the α parameter of the undamaged condition, which means that the damaged dynamic modulus would appear to be greater than the undamaged one at all frequencies except when the frequency is extremely small; in those cases, the two curves would converge to the value of the parameter δ.

Table 11. Damage factor and α' parameter for all cores and all levels

	d_j			α'		
Core	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Site 01						
S01C4	0.31	-0.22	0.3	2.6636960	4.7097234	2.7023003
S01C7	0.36	-0.15	0.3	2.4683436	4.4353049	2.6997508
S01C8	0.39	-0.10	0.3	2.3718273	4.2770656	2.7217691
S01C10	0.33	-0.20	0.3	2.5894809	4.6506312	2.7054278
Site 03						
S03C2	0.36	-0.95	0.3	2.5022015	7.6238953	2.7367829
S03C4	0.40	-0.82	0.3	2.3666536	7.1788491	2.7610958
S03C5	0.43	-0.75	0.3	2.2521638	6.9145378	2.7658152
S03C7	0.40	-0.83	0.3	2.3660813	7.2165481	2.7604282
Site 06						
S06C1	0.76	0.26	0.3	0.9590923	2.9572013	2.7973526
S06C2	0.76	0.26	0.3	0.9570542	2.9509171	2.7914081
S06C3	0.74	0.21	0.3	1.0247517	3.1136687	2.7589470
Site 12						
S12C2	0.45	-0.23	0.1	1.8198206	4.9741763	3.6396412
S12C7	0.41	-0.58	0.1	2.2938222	6.1427782	3.4990509
S12C8	0.40	-0.61	0.1	2.3212644	6.2287261	3.4818966
S12C10	0.41	-0.58	0.1	2.2894524	6.1310759	3.4923850
Site 14						
S14C6	-0.14	-0.10	0	4.4357001	4.2800615	3.890965
S14C9	-0.01	0.03	0	3.9806627	3.8230127	3.941250
S14C10	-0.14	-0.10	0	4.4293993	4.2739818	3.885438
Site 15						
S15C3	0.70	0.13	0.1	1.1794822	3.4204984	3.538447
S15C6	0.70	0.13	0.1	1.1805242	3.4235203	3.541573
S15C7	0.72	0.18	0.1	1.1119957	3.2565587	3.574272
S15C10	0.68	0.07	0.1	1.2513206	3.6366504	3.519340
Site 16						
S16C5	0.50	-0.60	0.1	1.9437357	6.2199542	3.498724
S16C8	0.47	-0.67	0.1	2.0262346	6.5073305	3.506944
S16C9	0.47	-0.67	0.1	2.0541711	6.4725770	3.488215
Site 17						
S17C5	0.39	-0.72	0.1	2.3870493	6.7306963	3.521876
S17C8	0.42	-0.61	0.1	2.2519752	6.2511726	3.494444
Site 18						
S18C3 Top	0.15	-0.33	0	3.3248938	5.2024809	3.9116398
S18C3 Bottom	0.25	-0.17	0	2.9542439	4.6086205	3.9389919
S18C5 Top	0.23	-0.21	0	3.0450496	4.7850779	3.9546098
S18C5 Bottom	0.20	-0.25	0	3.1789335	4.9670836	3.9736669
S18C9 Top	0.32	-0.06	0	2.7106703	4.2254566	3.9862798
S18C9 Bottom	0.20	-0.25	0	3.1508636	4.9232244	3.9385795

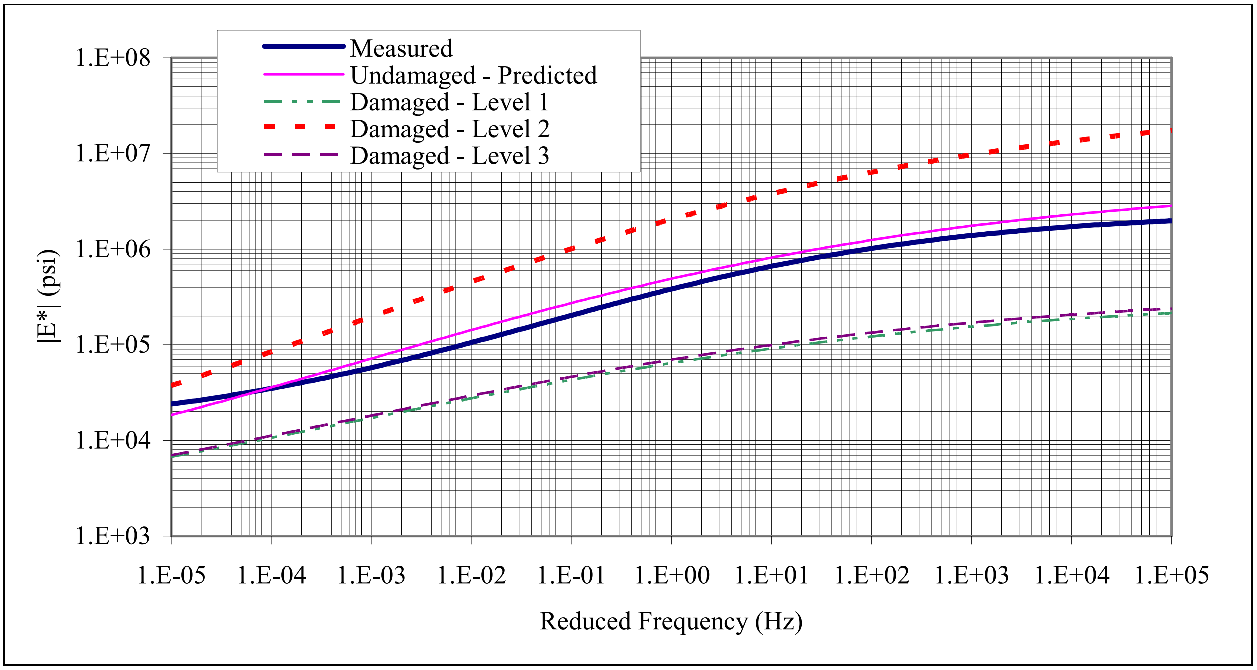


Figure 6. Different types of dynamic modulus master curves for core S01C4

Figure 6 also shows that though the predicted undamaged dynamic modulus values are on the same order of magnitude as the measured ones, noticeable differences exist. As shown in Figure 7, the predicted undamaged dynamic modulus is in the range of 0.77 to 1.44 times the measured dynamic modulus depending on the frequency. The behavior is similar in all other cores except that the frequency dependency is different from one core to another.

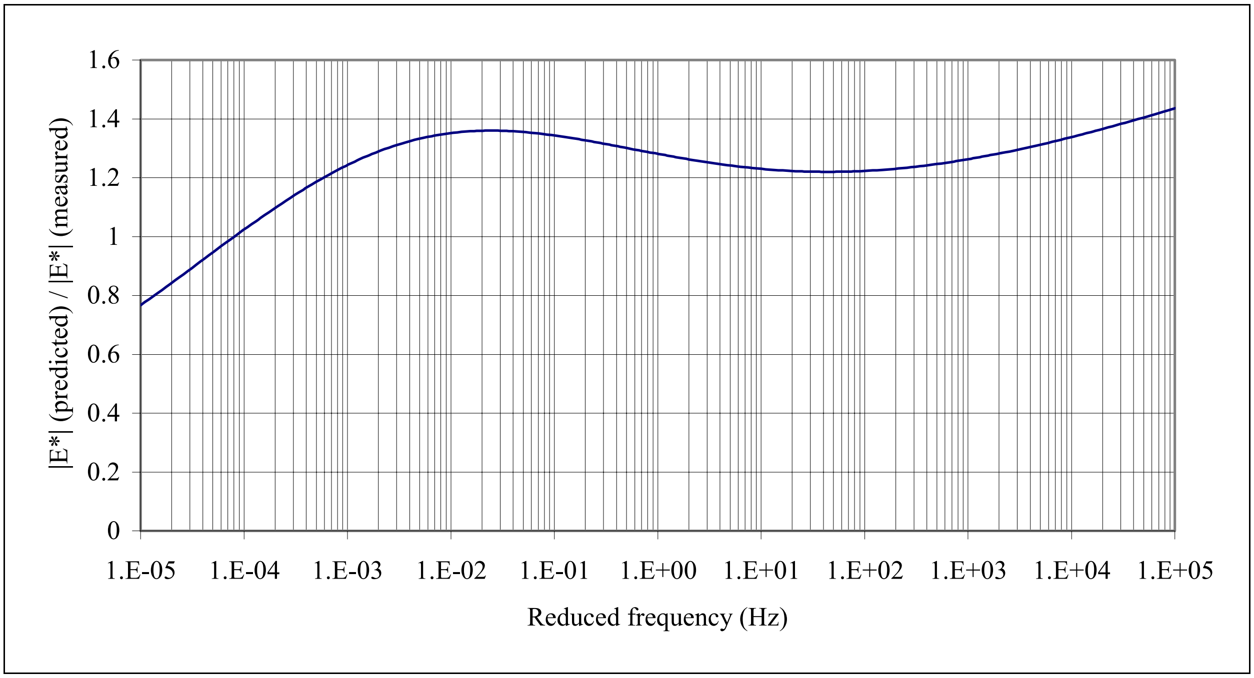


Figure 7. Ratio of the measured dynamic modulus to the predicted one for core S01C4

It should be noted that the measured dynamic modulus and the undamaged predicted one are of the same magnitude probably because the core material that was tested was in very good condition (i.e., intact with all delaminated or stripped layers removed from the original six in the specimen). Likewise, the volumetric properties used in the prediction equation were measured and calculated for the portion of the core that did not include any deteriorated areas if they existed on the original core. Therefore this comparison provides an indication of the ability of the Witczak equation for predicting the dynamic master curve for HMA.

Summary of Findings

In this project, the damaged dynamic master curves for 33 cores from nine different sites were determined using the proposed M-E design procedure with the three different input levels. In addition, the dynamic modulus was measured in the lab at five different temperatures and six different frequencies, from which measurements the dynamic modulus master curves were determined for the same 33 cores. The following are the main findings from the study:

- Volumetric properties from the same site were different from core to core, which resulted in different measured dynamic modulus especially at low temperature (10 °F) or high temperature (130 °F) (see Table 6). This is consistent with the spatial variability observed in the FWD measurements.
- The sigmoidal function provides a very good fit to the dynamic modulus master curve. However, one should be careful with the values of the regression parameters. For example, the δ parameter is the minimum value for the sigmoidal function and provides an idea of the HMA behavior at extremely low frequencies (equivalent to high temperatures). The sum $(\delta + \alpha)$ is the maximum value of the sigmoidal function and provides an idea of the HMA behavior at extremely high frequencies (equivalent to low temperatures).

  However, in some cases, an HMA with a smaller δ does not necessarily mean that it has a lower dynamic modulus at the measured high temperature. For example, the δ values for cores S01C4 and S06C1 were 4.04826 and 4.17763, respectively. However, the measured dynamic modulus at 100 °F and a frequency of 0.5 Hz for Core S01C4 was 120 ksi, while it was only 58 ksi for core S06C1. Core S06C1 could not be tested at the higher temperature of 130 °F because it was broken when tested at 100 °F with a frequency of 0.1 Hz. The sigmoidal parameters are obtained through regression analysis and as such they were only valid for the range of reduced frequencies covered by the testing program. Thus, one should be careful when extrapolating outside of the measuring interval as shown in Figure 8 for cores S01C4 and S06C1.

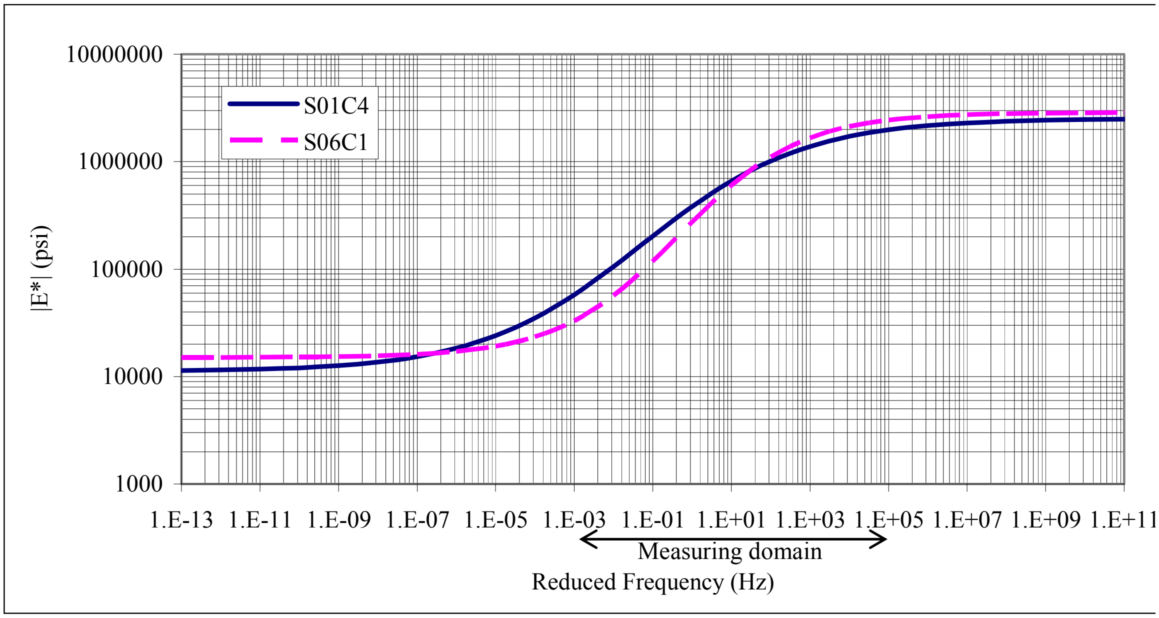


Figure 8. Comparing the δ parameter for cores S01C4 and S06C1

- The laboratory resilient modulus test does not give a good indication of the combined behavior of thick HMA layers. In this study, the values provided by the resilient modulus test were in most cases higher than the predicted or tested dynamic modulus at the same temperature and equivalent frequency.
- Using the average values for the backcalculated FWD may not provide the best estimates for the damage factor as discussed above for site 14. A better way to calculate the damage is to use the backcalculated moduli on the location where the core was taken. Once the damage is calculated at different locations, an average value of this damage could be used for the site.
- The Witczak prediction equation gives reasonable values for the dynamic modulus, which are of the same order of magnitude as the measured values. Except for sites 06 and 12, the predicted-to-measured dynamic modulus ratio was in the range of 0.3 to 1.8. However, for some of the sites the difference was quite significant. The predicted-to-measured modulus ratio was in some cases as high as 3.3 for site 06 and as high as 2.3 for site 12. The effect of this difference on the design of the new overlay needs to be studied as recommended later.
- The use of Level 3 data on previously overlaid pavements may be misleading because the surface condition does not necessarily reflect the overall condition of the entire HMA layer.

CONCLUSIONS

Based on the above-mentioned findings from this study, the following conclusions are drawn:

- Level 2, as currently used in the proposed M-E Guide, provides unreasonable values for the damaged dynamic modulus master curve.
- Level 1 data are necessary to obtain reliable estimates of the properties of the existing HMA layers. FWD testing appears to be the only reliable procedure to measure the overall condition of the entire HMA layer.

RECOMMENDATIONS

The findings and conclusions from this study lead to several recommendations pertaining to characterizing HMA for M-E pavement analysis and design. These recommendations are as follows (note that in each recommendation, “VDOT” refers specifically to VDOT’s Pavement Design and Evaluation experts, central and field offices):

- VDOT should not use Level 2 type of input for rehabilitation when the proposed MEPDG guide is implemented. The results of this investigation suggest that using this level of input may lead to un-conservative overlay designs.
- When VDOT considers the use of Level 1 input, the FWD test should be performed on top of the location from which the core is extracted with the temperature measurement recorded on that particular location. This would allow for a more accurate determination of the damage factor.
- VDOT should develop a policy to determine the level of effort required for different pavement rehabilitation projects. As best as possible, the policy should discriminate based on relative project importance and it should include characteristics such as scale, facility priority/traffic volumes, accessibility, feasible rehabilitation options, and financial constraints. Level 1 input should be used on all projects if and when the required resources are available. Level 3 input may overestimate the modulus of the existing layers, especially for pavement that has been already overlaid.

Other related potential research topics that should be considered include the following:

- Evaluate the Witczak prediction equation with new HMA mixes used in the Commonwealth with characterization of the binder to obtain the A and VTS parameters instead of assuming their values as done in this project.
- Perform a sensitivity analysis on the effect of taking different dynamic modulus master curves of the existing composite HMA layer on the design of the overlay.

BENEFITS AND COSTS ASSESSMENT

Pavement rehabilitation is a major activity performed by highway agencies given the continuing deterioration of existing pavements. Materials characterization of the existing HMA layer is vital for a good design of the HMA overlay. Accurate characterization of the existing HMA layer would lead to realistic overlay thickness designs that will provide an appropriate level of service to the users over the expected service life. The reduction in the number of prematurely failing pavements will aid in reducing the frequency and costs associated with maintenance.

This report recommends eliminating a material characterization method that would not provide useful results and may lead to un-conservative overlay designs (since the damage to the existing pavement would be underestimated). Currently designers may use these Level 2 data in possibly one-third of rehabilitation design cases, which shows that the impact of this method on the overall performance of Virginia's pavement could be very significant.

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