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# Analytical Review of the HMA Temperature Correction Factors from Laboratory and Falling Weight Deflectometer Tests

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**Abstract:** The investigation of temperature dependency of asphalt mixtures and pavements has several applications in pavement engineering. To estimate the modulus of asphalt pavement layers from field deflection tests such as Falling Weight Deflectometer (FWD), it is necessary to adjust the deflections or backcalculated moduli to a reference temperature. The main objective of this study was to compare the temperature dependencies of Hot Mix Asphalt (HMA) from laboratory tests such as dynamic modulus and resilient modulus tests with the empirical models suggested for the correction of asphalt pavement modulus from FWD testing. A database including dynamic modulus of 42 asphalt mixtures as well as resilient modulus of 37 asphalt mixtures from several North American studies were analyzed to investigate the variation of their laboratory moduli with testing temperatures. An exponential model was proposed for the temperature dependency of the dynamic and resilient moduli of asphalt mixtures. Additionally, thirteen temperature correction factor models for FWD testing were reviewed. While existing pavement practices do not consider mixture dependency for temperature correction factors, this study concluded that mixture dependency of temperature correction factor is important and should be considered.

***Key words****: Dynamic modulus; FWD; HMA; Resilient modulus; Temperature correction factor.*

## Introduction

The new AASHTO Mechanistic–Empirical Pavement Design Guide (MEPDG), based on the National Cooperative Highway Research Program (NCHRP) 1-37A study, uses the dynamic modulus of asphalt mixture, $|E^*|$, as the asphalt material input in its pavement analysis [1]. Although the concept of a dynamic modulus protocol was originally developed by Coffman and Pagen in the 1960s, as has been mentioned by Dougan *et al*. [2], this test was not implemented for pavement design and analysis until recently. Dynamic modulus testing characterizes asphalt mixture as a linear visco-elastic material over a wide range of temperatures and loading frequencies. In the MEPDG, dynamic modulus testing results are used to generate a master curve for each mixture by the time-temperature superposition methodology [1]. As the dynamic modulus is a fundamental asphalt mixture property, in addition to its main application in the MEPDG it can be used to investigate the temperature and loading frequency dependencies of Hot Mix Asphalt (HMA).

The resilient modulus test is another HMA characteristic that was used in many asphalt pavement guides such as AASHTO 86 and AASHTO 93. Generally, resilient modulus can be measured in different ways such as triaxial compression, diametral tension, uniaxial compression, or flexure loading conditions; however, most HMA resilient modulus specifications including ASTM D 7369-09 recommend indirect tension loading for this test [3]. It is believed that the resilient modulus is not a comprehensive characteristic of HMA testing relative to dynamic modulus, as resilient modulus only characterizes HMA at one loading condition while the dynamic modulus test provides modulus of material at various loading frequencies [4].

Characterization of HMA at different temperatures is required in many pavement engineering studies including analysis of field testing results and in asphalt pavement deflection testing for rehabilitation projects. By developing temperature correction factors for laboratory tests such as dynamic modulus and resilient modulus, one can estimate HMA moduli at temperatures other than testing temperature. In evaluating the structural capacity of pavement for rehabilitation projects, deflection tests such as Falling Weight Deflectometer (FWD) are used. Pavement deflections under specific loading pulse are measured at various pavement temperatures. Backcalculation methodologies or computer programs are used to estimate the pavement structure and/or pavement layers' moduli based on different algorithms and assumptions. As the pavement deflections are measured at different pavement temperatures, they have to be converted to a reference deflection by applying a temperature correction factor. In another approach, moduli of asphalt layers, estimated based on testing pavement temperatures, are converted to moduli at a reference temperature by applying temperature correction factors.

Several research studies have investigated the influence of pavement temperatures on backcalculated asphalt pavement moduli and have proposed models for the adjustment of asphalt moduli to a reference temperature [5-15]. These temperature correction models were developed through specific experimental design, size of data, age and thicknesses of pavements and different asphalt pavement types. One issue in the application of these models is that they are used routinely for asphalt pavements that are different than asphalt pavements that were calibrated. The extension of the application of these models beyond their calibration ranges has the potential to cause inaccurate estimations of pavement moduli and inaccurate pavement design.

Another application of temperature correction factors is in pavement instrumentation projects when pavement responses such

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as deflection, stresses and strains are measured at different environmental temperatures. In many cases, they need to be converted to a reference temperature in order to compare pavement responses by applying correction factors.

As highway agencies are moving forward to implement the MEPDG, and testing equipment for the dynamic modulus is becoming increasingly accessible, it is important to expand the use of dynamic modulus testing results to other applications. Additionally, many highway agencies have used the resilient modulus test for characterization of their pavements and consequently have valuable experience and testing results for their mixtures.

## Scope and Objectives

The main objectives of this study were to analytically examine the temperature dependency of asphalt mixtures from both dynamic modulus and resilient modulus laboratory testing results as well as to compare laboratory temperature correction factors and FWD temperature correction models. Laboratory testing results, including dynamic modulus for 42 asphalt mixtures and resilient modulus for 37 mixes, from published North American studies, along with 13 temperature correction models for FWD were reviewed and analyzed in this study.

## HMA Modulus Data

Results of dynamic modulus testing from 42 North American HMA mixtures, representing different climatic and materials conditions, were collected from research publications [16-22]. Table 1 provides information regarding these mixtures, including their gradation and asphalt binder contents and types. As Table 1 indicates, asphalt mixtures considered in this study included a broad range of aggregate gradations, asphalt binder contents and types, and air voids. The upper and lower limits for gradations of all asphalt mixtures considered in this paper are shown in Fig. 1. Two asphalt mixtures with polymer modified asphalt binders were also included. All of the mixtures were tested at frequencies of 0.1, 0.5, 1, 5, 10 and 25 Hz, as specified by AASHTO TP 62 [23]. Most of the studies considered in this paper likewise tested their samples at temperatures specified by AASHTO TP 62 (-10 to 54.4 °C), while a few studies tested their samples in the same temperature range but at temperatures other than those specified by AASHTO TP 62.

Another set of data including results of resilient modulus from 37 North American asphalt mixtures were collected from various studies [4, 24-28]. Table 2 represents information regarding resilient modulus data from six North American studies. Mixture types, method of specimen compaction, testing configuration, type of binder, asphalt content, and aggregate gradation information are included in Table 2. Unlike dynamic modulus testing results, resilient modulus was conducted on limited loading frequencies, as indicated in Table 2. Resilient modulus could be performed on lab specimens or field cores [3]. From the study conducted in Minnesota (in Table 2), test results on laboratory specimens as well as field cores which were taken after construction were utilized in this study. The Virginia study (in Table 2) also included field cores along with laboratory specimens. Two testing configurations were used by the studies: Indirect Tension (IT) and Uniaxial Compression (UC). The IT specimens had a diameter of 100 mm, except for mixtures SM-9.5A (150) and BM-25.0 from the Virginia study, and all of the mixtures in the North Carolina study were 150 mm in diameter. For the Indirect Tension test, the specimens had a ratio of thickness to diameter from 0.25 to 0.60. ASTM D 7369-09 has recommended specimens of 100 mm or 150 mm in diameter with a ratio of thickness to diameter of 0.375 or 0.416, respectively. Therefore, not all specimens had the sizes suggested by ASTM D 7369-09. Out of 37 mixes, aggregate gradation information was only available for 18, for which the upper and lower gradation limits are shown in Fig. 1. As can be seen from Fig. 1, the upper and lower limits of aggregate gradations for dynamic and resilient modulus tests are close together.

## Changes in HMA Modulus with Temperature

Fig. 2 and 3 show typical relationships of dynamic modulus and resilient modulus, respectively, with regard to various testing temperatures and different loading frequencies for mixture HL3 from the Ontario study (Table 1) and mixture Trap1 from the Texas study (Table 2), respectively. As Fig. 2 and 3 show, for each loading frequency, HMA modulus decreases exponentially with increasing temperature. Using the least squared regression method as an exponential relationship, Eq. (1) was found to fit the mixture HL3 data with a minimum correlation coefficient ($R^2$) of 0.98. Exponential trends similar to Eq. (1) were observed for the mixture Trap1 data shown in Fig. 3 with a minimum correlation coefficient ($R^2$) of 0.99. Table 3 represents parameters "$a$", "$b$" and $R^2$ for these two mixtures.

$$\left|E^*\right| = a.e^{bT} \quad \text{for} \quad f = f_o \tag{1}$$

Where:

$\left|E^*\right|$ = dynamic modulus at $f = f_o$ (MPa)

$f$ = loading frequency of testing (Hz)

$f_o$ = specific loading frequency (Hz)

$T$ = testing temperature (°C)

$a$, $b$ = regression coefficients

Similar trends were observed for all other dynamic modulus and resilient modulus results for mixtures listed in Tables 1 and 2. Table 4 provides the maximum and minimum dynamic modulus and resilient modulus, regression coefficient and correlation coefficient values for all mixtures based on Eq. (1), for tested loading frequencies. It should be noted that, in Table 4, frequencies which were close together, such as (1.0 and 1.6) and (5.0 and 5.3), were considered in the same category. High correlation coefficient values for all mixtures, at all tested loading frequencies, indicated that the exponential model of Eq. (1) explains the temperature dependency of HMA from both moduli laboratory tests (dynamic modulus, resilient Modulus).

Regression coefficients "$a$" and "$b$" are functions of material properties. As Tables 1 and 2 include a broad range of mixture types, it is expected that the range of "$a$" and "$b$" values in Table 4 provide

**Table 1.** Information Regarding Dynamic Modulus Tests on Asphalt Mixtures Used in This Study.

| Location of Study (Reference) | Mixture Type | Air Voids % | Binder Type | Asphalt Content % | $R_{3/4}$ % | $R_{3/8}$ % | $R_4$ % | $R_{200}$ % |
|---|---|---|---|---|---|---|---|---|
| Idaho [16] | 1-1 | 3.8 | PG 70-28 | 4.9 | 14 | 36 | 49 | 96 |
| | 1-2 | 4 | PG 70-34 | 4.9 | 14 | 36 | 49 | 96 |
| | 2-1 | 3.9 | PG 64-34 | 4.4 | 0 | 35 | 63 | 95.3 |
| | 2-2 | 4.5 | PG 70-28 | 4.9 | 0 | 35 | 63 | 95.3 |
| | CA | 4.1 | PG 70-28 | 4.9 | 29 | 72 | 76 | 96 |
| Ontario [17] | HL3 | 6.2 | PG 58-28 | 5.3 | 0 | 14 | 40 | 96.3 |
| | SMA L | 6.4 | PG 70-28 PM[a] | 5.7 | 0 | 28.4 | 74.6 | 90.9 |
| | SMA G | 5.8 | PG 70-28 PM[a] | 5.7 | 0 | 34.3 | 75 | 92 |
| | SP 19D | 6.5 | PG 64-24 | 4.4 | 2.8 | 31.8 | 39.8 | 95.8 |
| | SP 19E | 5.7 | PG 70-28 | 4.6 | 3 | 36.8 | 62 | 96.2 |
| Arizona [18] | MR16-1 | 8.2 | AC-20 | 5.1 | 0 | 6.7 | 32.7 | 95.4 |
| | MR17-1 | 7.7 | AC-20 | 5.5 | 0 | 6.7 | 32.2 | 95.8 |
| | MR18-1 | 5.6 | AC-20 | 5.8 | 0 | 7.2 | 32.2 | 95.6 |
| | MR20-1 | 6.3 | 120-150 Pen | 6.1 | 0 | 6.2 | 31.7 | 95.2 |
| | MR22-1 | 6.5 | 120-150 Pen | 5.4 | 0 | 6 | 31.5 | 95.7 |
| Arkansas [19] | MCA 1 | 4.8 | PG 70-22 | NA | 0 | 20 | 49 | 95.8 |
| | MCA 2 | 7.3 | PG 70-22 | NA | 0 | 20 | 49 | 95.8 |
| | GMQ 1 | 3.8 | PG 76-22 | NA | 29 | 41 | 54 | 96.2 |
| | GMQ 2 | 6.9 | PG 76-22 | NA | 29 | 41 | 54 | 96.2 |
| | JET 1 | 4.5 | PG 70-22 | NA | 10 | 46 | 63 | 96.8 |
| | JET 2 | 7.4 | PG 70-22 | NA | 10 | 46 | 63 | 96.8 |
| | ARK 1 | 4.3 | PG 70-22 | NA | 0 | 15 | 45 | 94.3 |
| | ARK 2 | 6.8 | PG 70-22 | NA | 0 | 15 | 45 | 94.3 |
| | ARK 3 | 3.8 | PG 76-22 | NA | 0 | 14 | 45 | 94.3 |
| | ARK 4 | 7.3 | PG 76-22 | NA | 0 | 14 | 45 | 94.3 |
| Oklahoma [20] | S3 Norman | 4.8 | PG 64-22 | 4.6 | 15 | 26 | 48 | 97.3 |
| | S3 Clinton | 4.7 | PG 70-28 | 4.1 | 0 | 31 | 53 | 96 |
| | S4 Arkhola | 3.7 | PG 76-28 | 5.4 | 0 | 14 | 45 | 95.9 |
| | S4 Cummins Enid-2 | 4.8 | PG 76-28 | 4.8 | 0 | 11 | 46 | 95.8 |
| | S4 TSI | 4.3 | PG 64-22 | 5 | 0 | 14 | 36 | 94 |
| Alberta [21] | H1-1 | 6.8 | PG 58-34 | NA | 0 | 20 | 40 | 94.2 |
| | S3-1 | 6.8 | 120-150A | NA | 8 | 38 | 52 | 93 |
| | H1-2 | 6.3 | PG 58-34 | NA | 0 | 20 | 29 | 93 |
| | L1-1 | 6.6 | 200-300A | NA | 0 | 13 | 40 | 93.3 |
| | M1-1 | 6.5 | 200-300A | NA | 0 | 14 | 41 | 93.5 |
| Texas[b] [22] | 1/2" HDSMA (Layer 1) | NA | PG 70-28 | 6.8 | 6.7 | 34.5 | 73 | 91.6 |
| | 3/4" SFHMAC (Layer 2) | NA | PG 76-22 | 4.2 | 24 | NA | 50 | 96.9 |
| | TxDOT Type C (Layer 2) | NA | PG 70-22 | 4.4 | 0 | 22.9 | 50 | 96.1 |
| | 1" SFHMAC (Layer 3) | NA | PG 70-22 | 4 | 32 | NA | 66 | 96.8 |
| | TxDOT Type B (Layer 3) | NA | PG 64-22 | 4.5 | 25 | NA | 55 | 96.8 |
| | 3/4" SFHMAC (Layer 4) | NA | PG 64-22 | 4.2 | 24 | NA | 55 | 95 |
| | TxDOT Type C (Layer 4) | NA | PG 64-22 | 5.3 | 0 | NA | 47 | 95 |

[a] Polymer Modified (cellulose fibre 0.3%)

$R_{3/4}$, $R_{1/2}$, $R_{3/8}$, $R_4$, and $R_{200}$ = cumulative aggregate retained on sieves No. 3/4, No. 1/2, No. 3/8, No. 4, and No. 200, respectively

NA = Not Available

[b] For Texas mixtures, results for No. 3/4 were not available, so percentages retained on sieve No. 1/2 are represented here.

a good representation of possible values for HMA moduli from different North American highway agencies. Due to the nature of exponential models, regression coefficient values "*a*" varied significantly; however, the regression coefficient "*b*" did not change extensively with changes in loading frequencies. Maximum and minimum of regression coefficient "*b*" values for all testing temperatures and loading frequencies changed from -0.037 to -0.099 for dynamic modulus and from -0.016 to -0.105 for resilient modulus. Moreover, ranges of "*b*" value for all of the frequencies for both tests are reasonably close together.

**Table 2.** Information Regarding Resilient Modulus Tests on Asphalt Mixtures Used in This Study.

| Location of Study (Reference) | $f$ (Hz) | $T$ (°C) | Mix Type | Compaction Method | Test[a] | Air Voids % | Binder Type | Asphalt Content % | $R_{3/4}$ % | $R_{3/8}$ % | $R_4$ % | $R_{200}$ % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Texas [4] | 25, 10, 5, 1, 0.5, 0.1 | -2 to 37 | 1/2A | NA | UC | 6.2 | PG 70-22 | 6 | 0 | 15 | 48 | 90 |
| | | | 1A | NA | UC | 4.9 | PG 76-22 | 4.9 | 10 | 50 | 73 | 92 |
| | | | FC1 | Field | UC | 5.8 | PG 64-22 | 4.5 | 5 | 32 | 55 | 95 |
| | | | Trap1 | Field | UC | 4.2 | PG 76-22 | 5.6 | 0 | 32 | 58 | 92 |
| Virginia [24] | 5.3 | -15 to 40 | SM-9.5A(100) | Gyratory | IT | 3.6 | NA | NA | 0 | 8 | 43 | 92 |
| | | | SM-9.5A(150) | Gyratory | IT | 3.6 | NA | NA | 0 | 8 | 43 | 92 |
| | | | BM-25.0 | Gyratory | IT | 6.2 | NA | NA | 15 | 30 | 48 | 95 |
| North Carolina [25] | 10 | 5 to 40 | S12.5C | Gyratory | IT | 3.5 to 4.5 | PG 64-22 | NA | NA | NA | NA | NA |
| | | | S12.5FE | Gyratory | IT | 3.5 to 4.5 | PG 64-22 | NA | NA | NA | NA | NA |
| | | | B25.0C | Gyratory | IT | 3.5 to 4.5 | PG 64-22 | NA | NA | NA | NA | NA |
| | | | S12.5CM | Gyratory | IT | 3.5 to 4.5 | PG 64-22 | NA | NA | NA | NA | NA |
| Virginia [26] | 1.6 and 5.3 | 5 to 40 | SM-12.5D (A-D/L) | Gyratory | IT | NA | PG 70-22 | 5.6 | 0 | 10.1 | 49.9 | 94 |
| | | | SM-9.5D (B-D/L) | Gyratory | IT | NA | PG 70-22 | 5.6 | 0 | 13.9 | 66.3 | 94.5 |
| | | | SM-9.5E (C-D/L) | Gyratory | IT | NA | PG 76-22 | 5.8 | 0 | 10.1 | 55.1 | 93.4 |
| | | | SM-9.5A (D-D/L) | Gyratory | IT | NA | PG 64-22 | 5.6 | 0 | 7.7 | 41.7 | 93.7 |
| | | | SM-9.5A (I-D/L) | Gyratory | IT | NA | PG 64-22 | 4.8 | 0 | 11.4 | 43.3 | 92.4 |
| | | | SMA-12.5 (L-D/L) | Gyratory | IT | NA | PG 76-22 | 7.2[b] | 0 | 27.9 | 72.2 | 88.3 |
| | | | SM-12.5D (A-F/F) | Field | IT | NA | PG 70-22 | NA | 0 | 1.5 | 15.8 | 94.4 |
| | | | SM-9.5D (B-F/F) | Field | IT | NA | PG 70-22 | NA | NA | 9.7 | 48.1 | 92.2 |
| | | | SM-9.5E (C-F/F) | Field | IT | NA | PG 76-22 | NA | NA | 5 | 38.3 | 91.8 |
| | | | SM-9.5A (D-F/F) | Field | IT | NA | PG 64-22 | NA | NA | 7.6 | 45.1 | 90.8 |
| | | | SM-9.5D (H-F/F) | Field | IT | NA | PG 70-22 | NA | NA | 5.7 | 36.2 | 92.4 |
| | | | SM-9.5A (I-F/F) | Field | IT | NA | PG 64-22 | NA | 0 | 5 | 48.2 | 92.7 |
| Minnesota [27] | 1, 0.5, 0.1 | -18 to 40 | Cell 16 | Gyratory | IT | NA | AC-20 | NA | NA | NA | NA | NA |
| | | | Cell 19 | Marshall 35 | IT | NA | AC-20 | NA | NA | NA | NA | NA |
| | | | Cell 26 | Marshall 50 | IT | NA | 120-150 Pen | NA | NA | NA | NA | NA |
| | | | Cell 30 | Marshall 75 | IT | NA | 120-150 Pen | NA | NA | NA | NA | NA |
| | | | Cell 16 (Core) | Field | IT | NA | AC-20 | NA | NA | NA | NA | NA |
| | | | Cell 19 (Core) | Field | IT | NA | AC-20 | NA | NA | NA | NA | NA |
| | | | Cell 26 (Core) | Field | IT | NA | 120-150 Pen | NA | NA | NA | NA | NA |
| | | | Cell 30 (Core) | Field | IT | NA | 120-150 Pen | NA | NA | NA | NA | NA |
| Oklahoma [28] | 1.6 | 0 to 40 | Sample 1 | Gyratory | UC | 7.6 | PG 64-22 | 5.1 | NA | NA | NA | NA |
| | | | Sample 2 | Gyratory | UC | 4.7 | PG 70-28 | 5.4 | NA | NA | NA | NA |
| | | | Sample 3 | Gyratory | UC | 5.5 | PG 70-28 | 4.9 | NA | NA | NA | NA |
| | | | Sample 4 | Gyratory | UC | 7.4 | PG 70-28 | 4.9 | NA | NA | NA | NA |
| | | | Sample 5 | Gyratory | UC | 6.5 | PG 64-22 | 4.6 | NA | NA | NA | NA |
| | | | Sample 6 | Gyratory | UC | 3.4 | PG 64-22 | 4.6 | NA | NA | NA | NA |
| | | | Sample 7 | Gyratory | UC | 3.1 | PG 64-22 | 5.6 | NA | NA | NA | NA |
| | | | Sample 8 | Gyratory | UC | 10.1 | PG 64-22 | 5.6 | NA | NA | NA | NA |
| | | | Sample 9 | Gyratory | UC | 12.1 | PG 70-28 | 5.9 | NA | NA | NA | NA |
| | | | Sample 10 | Gyratory | UC | 8.6 | PG 70-28 | 5.9 | NA | NA | NA | NA |

[a] Testing Configuration
IT: Indirect Tension
UC: Uniaxial Compression
[b] plus 0.3% Cellulose fiber; NA: Not Available

## Temperature Correction Factors from Laboratory Modulus Tests

Based on Eq. (1), a temperature correction factor was defined as the ratio of the modulus at a reference temperature to any testing temperature at a specific frequency. This exponential model can be simplified as shown in Eq. (2).

$$CF_{|E^*|} = \frac{|E^*|_{(T_0)}}{|E^*|_{(T_1)}} = \frac{ae^{bT_0}}{ae^{bT_1}} = e^{b(T_0 - T_1)} \quad \text{for} \quad f = f_o \tag{2}$$

where:

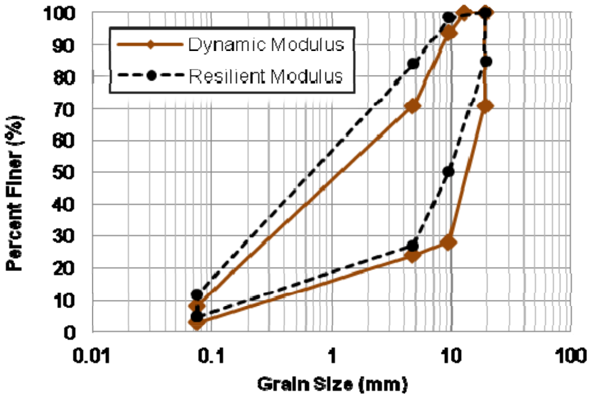


**Fig. 1.** Upper and Lower Limits of Aggregates Gradations for Mixtures Considered in This Study.

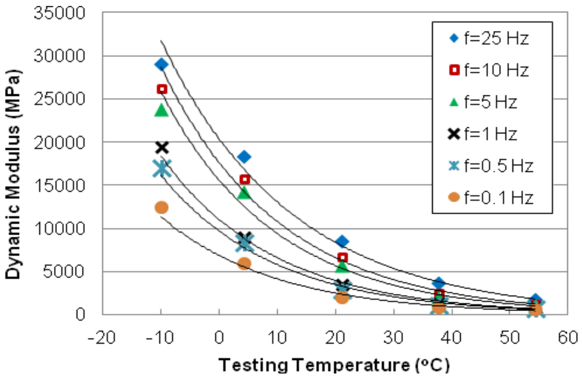


**Fig. 2. Dynamic Modulus vs. Temperature at Various Loading Frequencies for Mixture HL3 from the Ontario Study (17).**

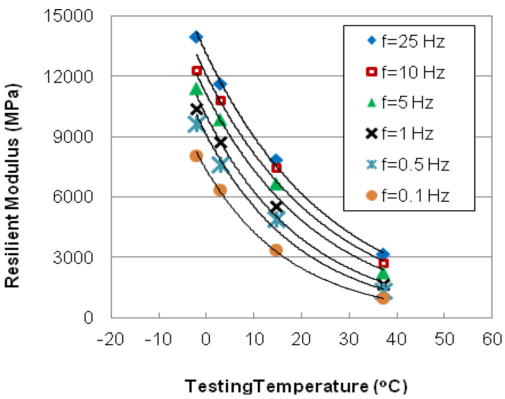


**Fig. 3.** Resilient Modulus Versus Temperature at Various Loading Frequencies for Mixture Trap1 from the Texas Study (4).

$CF_{|E^*|}$ = laboratory modulus temperature correction factor
$T_0$ = reference temperature (°C)
$T_1$ = testing temperature (°C)
*a* and *b* = regression coefficients
$f$ = loading frequency of testing (Hz)
$f_o$ = specific loading frequency (Hz)

Based on Eq. (2), the temperature correction factor is a function of regression coefficient "*b*", which is a function of asphalt mixture type and testing temperatures. The maximum and minimum of "*b*" for each loading frequency for both laboratory tests were used for the purpose of comparison between temperature correction factors. Fig. 4, as an example, shows temperature correction factors for dynamic modulus and resilient modulus at frequencies of 1 and 1.6 Hz. Temperature correction factors for dynamic modulus are shown with solid lines, while dashed lines are used for resilient modulus models.

One of the objectives of this study was to compare laboratory temperature correction factors with FWD models, the latter of which are presented in the next section. Several FWD models were reviewed, most of which were calibrated at a temperature range of 20 to 25 °C. Therefore, a reference temperature of 21.1 °C (70 °F) was selected to compare laboratory and field tests.

As Fig. 4 indicates, temperature correction factors are less than one for temperatures below the reference temperature and are more than one for temperatures above the reference temperature for all dynamic modulus and resilient modulus testing. The ranges of temperature correction factors are very narrow for temperatures below the reference temperature but wider for temperatures above the reference temperature. For all other frequencies in Table 3, similar trends were observed for laboratory moduli temperature correction factors. Based on the available data for this study, the upper and lower limits of temperature correction factors of resilient modulus tests were reasonably consistent with dynamic modulus temperature correction factor values (Table 4). It can be concluded that the aforementioned exponential model represents the temperature dependency of HMA modulus from both tests very well. The variation in temperature correction factors for the two tests can be attributed to different experimental results (not on the same materials for both tests) and data sizes in each study. Moreover, in Table 4, close (not the same) frequencies were considered at the same categories (5, 5.3 Hz and 1, 1.6 Hz).

## Temperature Correction Models from FWD Testing

**Table 3.** Regression Coefficients *a*, *b*, and Correlation Coefficient, $R^2$, for Dynamic Modulus of HL3 Mixture from Ontario and Resilient Modulus of Trap1(Core) Mixture from Texas.

| Loading | Coefficients for Dynamic Modulus on Mixture HL3 | | | Coefficients for Resilient Modulus on Mixture Trap1(Core) | | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | *a* | *b* | $R^2$ | *a* | *b* | $R^2$ |
| 25 | 20,381 | -0.044 | 0.996 | 13,130 | -0.038 | 0.998 |
| 10 | 17,615 | -0.049 | 0.995 | 12,071 | -0.039 | 0.989 |
| 5 | 15,594 | -0.050 | 0.993 | 11,118 | -0.042 | 0.991 |
| 1 | 11,025 | -0.051 | 0.991 | 10,035 | -0.047 | 0.992 |
| 0.5 | 9,688 | -0.051 | 0.985 | 9,102 | -0.050 | 0.992 |
| 0.1 | 6,852 | -0.050 | 0.982 | 7,358 | -0.055 | 1.000 |

**Table 4.** Maximum and Minimum of Regression Coefficient and Correlation Coefficient Values for Dynamic and Resilient Modulus Testing Results at Different Frequencies and Temperatures for Mixtures Considered in This Study.

| *f* (Hz) | Test | No. of Studies | No. of Mixes | Modulus (MPa) | | Model Coefficients | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *a* | | *b* | | $R^2$ | |
| | | | | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. |
| 25 | DM | 7 | 42 | 180 | 38,907 | 9,200 | 57,813 | -0.076 | -0.037 | 0.908 | 0.999 |
| | $M_r$ | 1 | 4 | 811 | 25,442 | 13,130 | 27,980 | -0.086 | -0.038 | 0.966 | 0.998 |
| 10 | DM | 7 | 42 | 135 | 33,718 | 7,779 | 40,607 | -0.083 | -0.040 | 0.916 | 0.999 |
| | $M_r$ | 2 | 8 | 612 | 24,724 | 12,071 | 35,828 | -0.091 | -0.039 | 0.975 | 1.000 |
| 5[a] | DM | 7 | 42 | 103 | 33,395 | 6,906 | 31,956 | -0.088 | -0.042 | 0.930 | 1.000 |
| | $M_r$ | 3 | 14 | 444 | 23,456 | 11,118 | 24,926 | -0.097 | -0.027 | 0.918 | 1.000 |
| 1[b] | DM | 7 | 42 | 77 | 30,943 | 5,198 | 24,222 | -0.093 | -0.044 | 0.918 | 1.000 |
| | $M_r$ | 4 | 33 | 306 | 39,507 | 3,249 | 46,949 | -0.101 | -0.016 | 0.836 | 1.000 |
| 0.5 | DM | 7 | 40 | 66 | 29,799 | 3,596 | 20,929 | -0.093 | -0.043 | 0.909 | 0.998 |
| | $M_r$ | 2 | 8 | 164 | 18,584 | 3,509 | 18,579 | -0.103 | -0.029 | 0.816 | 1.000 |
| 0.1 | DM | 7 | 42 | 33 | 27,082 | 3,039 | 17,537 | -0.099 | -0.039 | 0.922 | 0.994 |
| | $M_r$ | 2 | 8 | 161 | 15,046 | 3,103 | 14,113 | -0.105 | -0.041 | 0.900 | 1.000 |

[a] *f* = 5, 5.3 Hz for resilient modulus tests
[b] *f* = 1, 1.6 Hz for resilient modulus tests
DM: Dynamic Modulus
$M_r$: Resilient Modulus

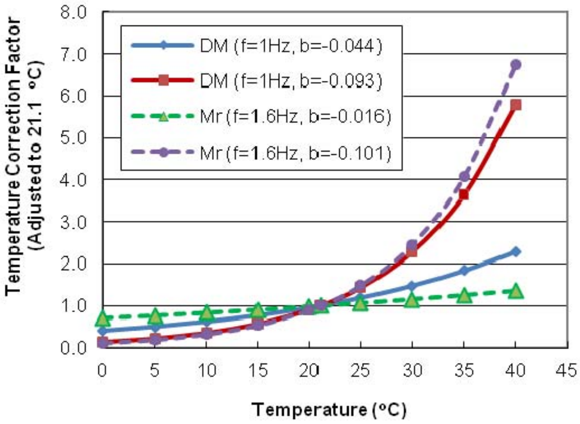


**Fig. 4.** Upper and Lower Limits of Correction Factors for Dynamic Modulus (DM) and Resilient Modulus (Mr) versus Temperature at Loading Frequencies of 1 and 1.6 Hz.

For FWD testing, the temperature correction factor was defined as the ratio of the modulus of asphalt pavement at the reference temperature to the modulus of asphalt pavement at the testing temperature, as shown in Eq. (3).

$$CF_{FWD} = \frac{E_r}{E_m} \tag{3}$$

Where:
$CF_{FWD}$= temperature correction factor for asphalt modulus
$E_r$ = asphalt pavement modulus at reference temperature
$E_m$ = asphalt pavement modulus at testing temperature

In this study, eleven correction factor models were reviewed from the literature [5-15]. A summary of these models and their parameters is presented in Table 5. Two other temperature correction factors, including a correction factor which is used in EVERCALC [29] and MICHBACK [30] backcalculation programs and a correction factor from the AASHTO 93 model [31], were included. The temperature correction model in the EVERCALC/MICHBACK programs is based on the Asphalt Institute pavement temperature model [32]. The AASHTO correction factor model has been reported as a graph in the standard, not as an equation. Therefore, it was not included in Table 5.

## Comparison between Laboratory and Field Temperature Correction Models

To compare laboratory and field temperature correction models, the closest mutual loading frequency between FWD and dynamic and resilient modulus was selected. The literature indicated that the loading frequency of FWD is in the range of approximately 30 to 40 Hz [33, 34] which corresponds to a passing wheel with a speed of approximately 70 km/h [35]. Therefore, to compare the correction factors from the laboratory modulus tests and FWD models, the closest mutual loading frequency of 25 Hz was selected.

To evaluate temperature correction models from the laboratory or field, they must be at the same reference temperature. Most FWD models have been calibrated at a temperature range of 20 to 25 °C. Therefore, a reference temperature of 21.1 °C (70°F) was selected for laboratory and FWD models.

The maximum and minimum of regression coefficient "*b*", from the dynamic modulus for all mixtures at a frequency of 25 Hz, were found as -0.037 and -0.076, respectively. For resilient modulus, the corresponding values were -0.038 and -0.086, respectively. By selecting a maximum and minimum for regression coefficient "*b*", the regression coefficients for other mixtures were between these values. The maximum and minimum values for regression coefficient "*b*" were used to compare temperature correction models from the laboratory tests with FWD models.

Fig. 5 presents temperature correction factors from FWD models

**Table 5.** Summary of FWD Temperature Correction Models for Asphalt Pavement Modulus.

| No. | Author or Computer Program (Reference) | Temperature Correction Model | Explanation of Parameters | Additional Information |
|---|---|---|---|---|
| 1 | Stubstad *et al.* [5] | $\frac{E_{ref}}{E_{AC}} = \frac{1}{1-2.2\log\left(\frac{T_{AC}}{T_{ref}}\right)}$ | $E_{ref}$ and $E_{AC}$ = Reference and Backcalculated Asphalt Moduli<br>$T_{ref}$ = Reference Temperature (°C)<br>$T_{AC}$ = Temperature at 1/3 of Pavement Thickness (°C) | Proposed for BELLS Temperature Prediction Model |
| 2 | Baltzer and Jansen [6] | $\frac{E_{ref}}{E_{AC}} = 10^{-0.018(20-T_{AC})}$ | $T_{AC}$ , $E_{ref}$ , $E_{AC}$ = as defined in No. 1<br>Reference Temperature = 20°C | Proposed for BELLS Temperature Prediction Model |
| 3 | Lukanen *et al.* [7] | $ATAF = 10^{slope.(T_r - T_m)}$ | $ATAF$ = Asphalt Temperature Adjustment Factor<br>*Slope* *Slope* of the Log Modulus Versus Temperature Curve, recommended as -0.0195 for the Wheelpath<br>$T_r$ = Reference Temperature (°C)<br>$T_m$ = Pavement Temperature at Mid-depth (°C) | Proposed for BELLS2 Model |
| 4 | Kim *et al.* [8] | $\frac{E_{68}}{E_T} = 10^{-0.0153(68-T)}$ | $E_{68}$ = Asphalt Modulus at Temperature 68 F° (20°C)<br>$E_T$ = Backcalculated Asphalt Modulus at Temperature $T$<br>$T$ = Temperature at Mid-depth of Asphalt Pavement (° F)<br>Reference Temperature = 68° F (20 °C) | Based on Data from Four Pavements in North Carolina |
| 5 | Johnson and Baus [9] | $\frac{E_{std}}{E_{field}} = 10^{-0.0002175(70^{1.886} - T^{1.886})}$ | $E_{std}$ = AC Modulus at Standard (Reference) Temperature<br>$E_{field}$ = AC Modulus Field Temperature<br>$T$ = Measured Temperature (° F)<br>Reference Temperature = 70° F (21.1°C) | Based on Approximation from the Asphalt Institute |
| 6 | Ullidtz and Peattie [10] | $\frac{S_T}{S_{15}} = 1 - 1.384\ \log(\frac{T}{15})$ | $S_T$ , $S_{15}$ = Asphalt Moduli at Temperatures of $T$ (°C) and 15°C<br>Reference Temperature = 15°C | Based on Deflection Data from the AASHO Road Test and SHELL Procedure<br>For $T > 1$°C |
| 7 | Ullidtz [11] | $\frac{E_{To}}{E_T} = \frac{1}{3.177 - 1.673\ \log\ T}$ | $E_{To}$ , $E_{T1}$ = Asphalt Moduli at Temperatures of $T_0$ and $T$ (°C) | Based on Backcalculated Moduli from the AASHO Road Test Deflection data |
| 8 | Antunes [12] | $\frac{E_{T1}}{E_{T2}} = \frac{1.635 - 0.0317\ T_1}{1.635 - 0.0317\ T_2}$ | $E_{T1}$ , $E_{T2}$ = Asphalt Moduli at Temperatures of $T_1$ and $T_2$ (°C) | |
| 9 | Chen *et al.* [13] | $\frac{E_{Tw}}{E_{Tc}} = \frac{(1.8T_c + 32)^{2.4462}}{(1.8T_w + 32)^{2.4462}}$ | $E_{Tw}$, $E_{Tc}$ = Asphalt Moduli at Temperatures of $T_w$ and $T_c$ (°C) (Mid-depth Temperature) | Based on Data from Mobile Load Simulator (MLS) Research Project |
| 10 | Chang *et al.* [14] | $\frac{E_r}{E_0} = 10^{-0.02822(25-T_c)}$ | $E_r$ = Adjusted Modulus to 25°C<br>$E_0$ = Measured Modulus at Temperature<br>$T_C$ = Mid-depth Asphalt Pavement Temperature (°C)<br>Reference Temperature = 25°C | Based on Data from 1176 FWD Tests on Two Specific Sections in Taiwan |

**Table 5.** (Continued)

| No. | Author or Computer Program (Reference) | Temperature Correction Model | Explanation of Parameters | Additional Information |
|---|---|---|---|---|
| 11 | Appea [15] | $\frac{E_{25}}{E_T} = e^{-0.031\ (25-T)}$ | $E_{25}$, $E_T$ = Moduli at Temperatures of 25 and $T$ (°C)<br>$T$ = Measured Temperature at the Bottom of Asphalt Pavement<br>Reference Temperature = 25°C | Based on Data from Virginia Smart Road Test Sections |
| 12 | EVERCALC [29], MICHPAVE [30] | $TAF = 10^{-0.000147362.(77^2 - T_p^2)}$ | $TAF$ = temperature adjustment factor<br>$T_p$ = Asphalt Pavement Temperature (° F)<br>Reference Temperature = 77° F (25° C) | Based on the Relationship between Modulus and Temperature for WSDOT Class B HMA |

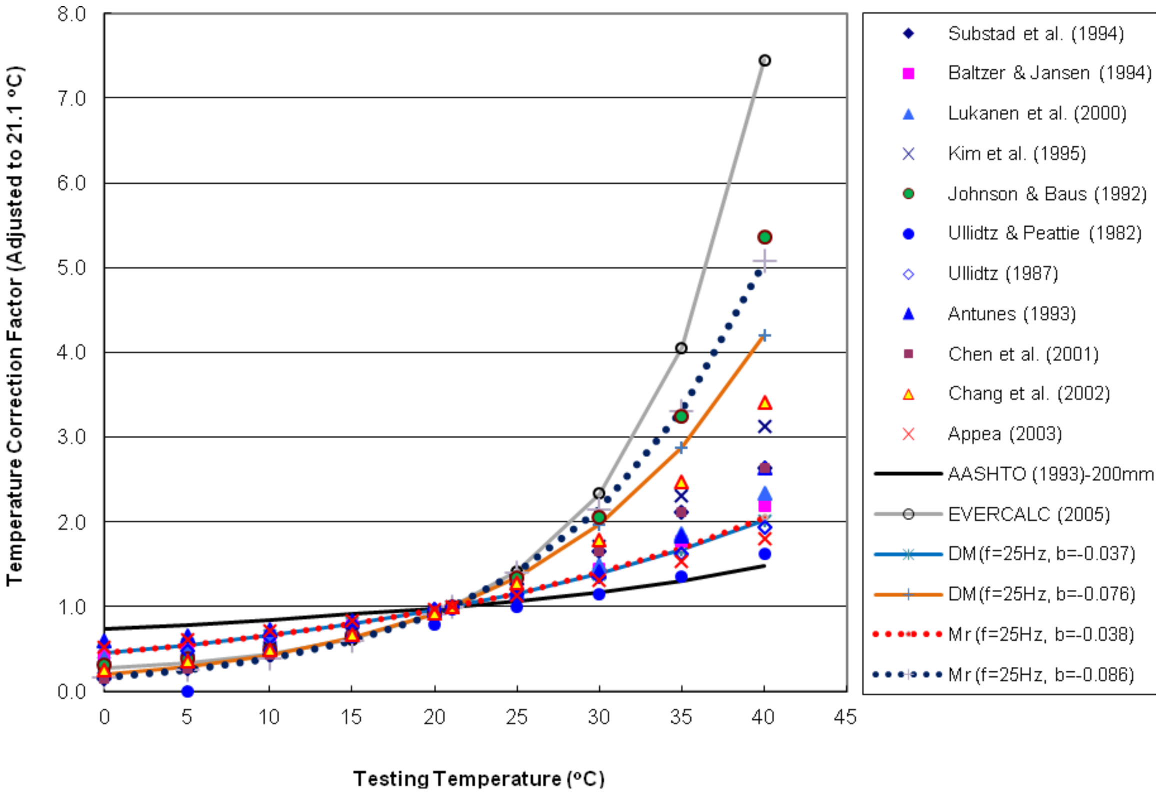


**Fig. 5.** Temperature Correction Factors from Dynamic Modulus, Resilient Modulus and FWD at a Frequency of 25 Hz.

in Table 5 in point format. It also includes two solid lines representing the temperature correction factors from two exponential models with minimum and maximum "*b*" values at 25 Hz for dynamic modulus as well as two dotted lines with minimum and maximum "*b*" values at 25 Hz from resilient modulus testing results. In addition, the AASHTO 93 temperature correction factor for 200 mm asphalt pavement layer thickness is shown as a solid dark line. Finally, the temperature correction factor from EVERCALC/MICHBACK backcalculation programs is shown as a solid grey line.

Based on Fig. 5, there are some variations between FWD temperature correction factors. The variation is less for temperatures below the reference temperature and more for temperatures above the reference temperature. The variation between FWD models can be attributed to the different experimental designs and data sizes in each study. Other parameters that cause variations in temperature correction factors from FWD models are: variations of pavement thicknesses in the field, age of pavement at the time of testing, type of pavement structure and materials, definition of pavement depth for pavement temperature in models (some mid or one-third of pavement depth), and inconsistencies in the selection of reference temperatures in models. There is not a direct relationship to pavement asphalt type in any of the existing FWD correction factor models; however, Eq. (2), based on laboratory tests, shows that each asphalt mixture has a unique temperature correction factor. This is an important observation, as existing practice in using temperature correction factors does not consider the influence of asphalt mixture type. This shortcoming can be overcome if a temperature correction model such as Eq. (2) is used.

From Fig. 5, it can be concluded that the AASHTO model over-estimates the asphalt pavement modulus for temperatures below the reference (21.1 °C) and under-estimates the asphalt pavement modulus for temperatures above the reference temperature. This means that the moduli of pavement layers and/or overlay designs, for temperatures below the reference temperature, might be inaccurate.

The temperature correction factors based on the EVERCALC/MICHBACK model are very close to the temperature correction factors of dynamic and resilient modulus tests with a minimum "*b*" value for temperatures below the reference temperature; however, for temperatures above the reference temperature, the model gives higher correction factors than all other FWD models and dynamic and resilient modulus tests values. This means that these backcalculation programs apply a higher temperature correction factor for temperatures above the reference temperature, which results in estimating a higher asphalt modulus and probably under-estimating overlay design.

One important consequence of inaccurately estimating modulus of asphalt pavement due to various temperature correction factors is that not only the modulus of the asphalt pavement layer is inaccurately estimated, but it will also impact the estimation of modulus of subgrade and other layers. This means that the total pavement modulus as well as the required overlay could be either over- or under-estimated. One solution to this problem is to use an FWD temperature correction factor specifically related to the same pavement material from the laboratory modulus testing results.

## Summary and Conclusions

Temperature dependencies of hot mix asphalt mixtures were analyzed using a database that included results of dynamic modulus testing of 42 different mixtures as well as results of resilient modulus testing of 37 different mixtures, all from North America. Thirteen temperature correction models for FWD were also considered in this study. Temperature correction factors from FWD models and HMA dynamic and resilient modulus were compared. For the range of mixture types and FWD models considered in this study, the following observations and conclusions can be drawn:

1. Results from laboratory dynamic and resilient modulus testing for asphalt mixtures can be used to estimate temperature correction factors for the same mix in the field. It is expected that this method provides a more accurate estimation of asphalt pavement modulus and overlay design.
2. Exponential relationships with high correlation coefficients were found between both dynamic and resilient modulus and testing temperatures at all loading frequencies. Regression coefficients in the proposed model are functions of material properties.
3. A correction factor model was developed based on the temperature dependency of dynamic and resilient modulus testing results. The proposed temperature correction factor is a function of regression coefficient "*b*" in the exponential fit, which is a function of asphalt mixture type and testing temperatures. Maximum and minimum of coefficient "*b*" for both laboratory tests were consistent for all frequencies.
4. Some variations between FWD correction factor models in estimating temperature correction factors were observed. The variation was more significant at higher pavement temperatures, which could be attributed to the viscoelastic behaviour of asphalt mixture at higher testing temperatures.
5. The AASHTO temperature correction model under-estimates the backcalculated asphalt pavement layers at a temperatures above the reference temperature (21.1 °C) and over-estimates the pavement modulus for temperatures below the reference temperature.
6. The temperature correction model in EVERCALC/MICHBACK backcalculation computer programs over-estimates the asphalt layer modulus for temperatures above the reference temperature (21.1 °C). This might result in an inaccurate estimation of other pavement layers and of overlay design.

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