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Research Article

An Approach for Adjusting the Laboratory-Determined Dynamic Modulus Master Curve of Asphalt Layers Based on Falling Weight Deflectometer Measurements

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Structural assessment is critical for designing asphalt pavement overlays, estimating the remaining life of pavements, and selecting an appropriate rehabilitation strategy for existing pavements. The falling weight deflectometer (FWD) serves as the primary nondestructive test used for evaluating the in situ properties and structural capacity of asphalt pavements. The current procedure involves analyzing the FWD response and estimating layer moduli by assuming an elastic response. However, the response of asphalt layers is viscoelastic (i.e., temperature- and frequency-dependent). This study proposes an approach that combines FWD data with laboratory measurements of the dynamic moduli of field cores to determine the in situ viscoelastic properties of asphalt layers. This approach is implemented by analyzing FWD data from four pavement sections in Qatar. Furthermore, the paper includes a comparative analysis of the response of pavement sections in which the asphalt layers are modeled using dynamic modulus master curves obtained from laboratory tests and those obtained using the approach presented in this study. It was found that using the laboratory-based master curves overestimated pavement performance (i.e., underestimated pavement distresses). It is recommended to use the dynamic moduli from the method presented in this paper for a more accurate estimation of pavement response and performance.

1. Introduction

Pavement structures wear down over time due to traffic and environmental effects. One of the critical components of an effective pavement management system is an accurate assessment of the structural condition of existing pavements. This assessment is used to estimate the pavement's remaining service life and to select appropriate preventive and rehabilitation strategies [1, 2]. Generally, the most important parameters required to assess pavement conditions are layer moduli, which can be obtained by nondestructive field tests such as the falling weight deflectometer (FWD) or laboratory tests of field cores [3–6]. The FWD device applies a load pulse to the pavement surface and measures the resulting surface deflections. Then, analyzing these surface deflections provides back-calculated layer elastic moduli [7–9]. The nondestructive nature of FWD makes it attractive for assessing pavement structural capacity [9–11]. However, the main challenge in the FWD test is that its pulse load consists of many frequencies, while the analysis method yields only a single value of the asphalt layer elastic modulus. There have been research efforts to interpret FWD data by considering the frequencies of the loading pulse and extracting the frequency-dependent (or time-dependent) response of the asphalt layer.

A common practice in the analysis of FWD data is to consider the load frequency (f) of the pulse to be a constant value that is the inverse of the FWD load pulse duration (t_{FWD}) [12]. Typically, the pulse duration of the FWD load is 30–40 msec, which is considered equivalent to a moving wheel on a pavement surface at a frequency of about 30 Hz [13–15]. On the other hand, Loulizi et al. [16] showed that the FWD load pulse could be simulated by a haversine wave with a time duration of 30 msec, which was considered equivalent to a frequency of 16 Hz ($f = 1/(2 \times 30\,\text{msec})$). Gedafa et al. [17] accounted for the stress sensitivity of pavement materials in analyzing FWD measurements. The FWD load pulse duration ranged between 25 and 30 msec, which was converted to 25 Hz. Gedafa et al. [17] concluded that back-calculated moduli are equivalent to laboratory measurements of the dynamic modulus at 25 Hz. Clyne et al. [18] compared dynamic moduli measured at different frequencies and temperatures with FWD measurements of the different sections. They concluded that the FWD load frequency is equivalent to 17.9 Hz [18]. Bazi and Assi [19] developed a finite element (FE) model and used it to simulate the surface deflections of three flexible pavement structures incorporating two asphalt mixtures. The asphalt concrete layer was modeled as a linear viscoelastic (LVE) material. According to their study, the dominant frequency of the FWD impulse is approximately 17 Hz [19]. Cheng et al. [20] considered the corresponding frequency for the FWD loading pulse to be 33.33 Hz (i.e., 1/30 msec). Emin Kutay et al. [9] developed a procedure based on analyzing the time history of FWD deflections to extract the damaged $|E^*|$ master curve of the asphalt concrete in an existing pavement (i.e., field viscoelastic properties). The study was able to back-calculate the relaxation modulus curve, $E(t)$, up to about $t \sim 10^{-1}$ s, and the dynamic modulus curve, $|E^*|$, starting from $f = 10^{-3}$ Hz [9]. Furthermore, Seo et al. [21] used experimental tests and numerical analyses to propose a framework to estimate the dynamic modulus $|E^*|$ using volumetric parameters and FWD data. Solatifar et al. [4] used FWD test data to develop a method for determining the dynamic modulus master curve of asphalt layers for use in the mechanistic–empirical analysis. They conducted FWD tests on the asphalt pavements with various physical properties and performed dynamic modulus tests on cores recovered from these pavements. Solatifar et al. [4] proposed a method to obtain the in situ dynamic modulus master curves by adjusting the laboratory measurements using the FWD data.

The relationship between the asphalt layer moduli under vehicle loading and FWD loading was examined in a study by Cheng et al. [20]. Based on the measured responses and the FE model, the researchers developed modulus master curves of the asphalt layers in the field pavements. The study also reported that the developed master curves could precisely predict the asphalt layer moduli under vehicular or FWD loading. Additionally, it was noted that regardless of temperature, the ratios of asphalt layer moduli under the vehicular loading to those under FWD loading are typically lower than 1.0 in a wide range of vehicular speeds [21]. In a recent study, Cheng et al. [20] sought to create a comprehensive method for determining the asphalt layer moduli under three laboratory loading modes as well as FWD. With an average deviation of 9.75%, the asphalt moduli obtained from the modulus master curves closely matched the actual asphalt moduli that were back-calculated from the deflection basins [22].

The above review shows that most studies assume the load frequency to be equal to the inverse of the load pulse duration. However, this assumption would lead to inaccurate analysis of pavement responses because the FWD load pulse consists of many frequencies [16, 21, 22–25]. Therefore, several researchers recommended using the fast Fourier transform (FFT) method to analyze the load pulse, whether from FWD or a moving wheel, to obtain the dominant frequency and then using this frequency to determine the dynamic modulus $|E^*|$ from the laboratory measurements [26, 27]. This study aims to develop an approach that combines laboratory and field measurements to adjust the laboratory-determined dynamic modulus master curve of asphalt layers based on FWD measurements and to determine the in situ frequency-dependent properties of the asphalt layers (i.e., FWD-Adjusted $|E^*|$ master curve). In addition, the study seeks to demonstrate the efficacy of this method through the analysis of the performance of different pavement sections.

2. Research Methodology

The study aims to develop a method for determining the in situ frequency-dependent dynamic moduli of the asphalt layers. These moduli can be used to determine the pavement responses under different traffic loads and frequencies. The study objectives were achieved through the following tasks:

(1) Construct a master curve for dynamic moduli of field cores based on the Asphalt Mixture Performance Tester (AMPT) laboratory tests conducted at different frequencies and temperatures.
(2) Determine the dominant frequency of the FWD load pulse using FFT.
(3) Analyze FWD data for different pavement sections in Qatar to determine the moduli at FWD dominant frequency and field temperatures.
(4) Use the dominant frequency of the FWD pulse (from Task 2) and the FWD moduli (Task 3) to shift/correct the dynamic modulus master curve (from Task 1). This task gives the in situ adjusted dynamic modulus curves.
(5) Perform a comparative pavement performance analysis using the 3D-Move Analysis software for multiple pavement structures. Compare the results of laboratory dynamic moduli (Task 1) versus adjusted in situ dynamic moduli (Task 4).

The proposed research methodology begins by developing field cores' frequency-dependent, dynamic modulus curves based on the laboratory measurements at various frequencies and temperatures. In parallel, FWD tests are conducted on selected pavement sections to estimate the asphalt moduli ($E_{m\text{-FWD}}$) at the FWD loading frequency and field temperatures. The FWD loading pulse (t_{FWD}), which has a duration of around 30 msec, is analyzed using FFT to determine the dominant loading frequency. Then, the FWD reduced frequency ($f_{r\text{-FWD}}$) computed based on the dominant frequency of the FWD pulse is employed to determine the dynamic modulus $\left(E_p^*\right)$ from the laboratory measurements conducted on field cores. Subsequently, the adjustment factor

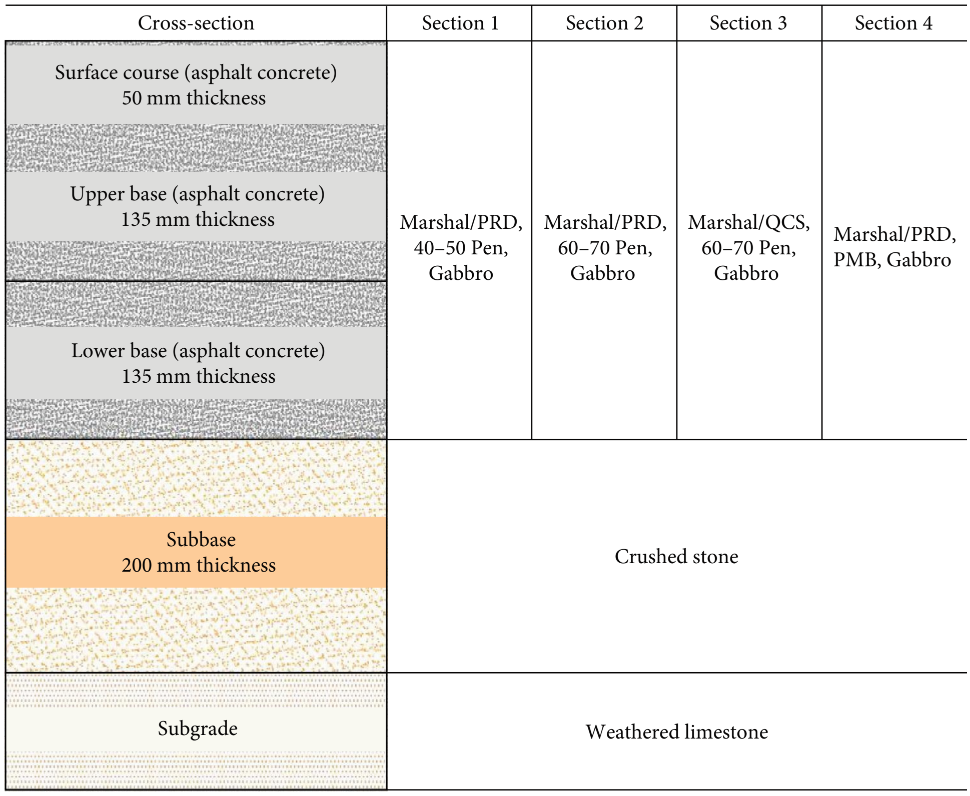

Figure 1: Properties of materials and layers in four trial sections.

Table 1: Binder contents by weight (%) for asphalt surface and base course layers.

Section #	Asphalt mixture description	Binder content by weight (%) in asphalt surface course	Binder content by weight (%) in asphalt base course
1	Marshall/PRD, 40–50 Pen, Gabbro	3.9	3.6
2	Marshall/PRD, 60–70 Pen, Gabbro	3.8	3.4
3	Marshall/QCS, 60–70 Pen, Gabbro	3.8	3.5
4	Marshall/PRD, PG76–22, Gabbro	3.8	3.5

(AF) is estimated as the ratio of the measured FWD asphalt modulus ($E_{m\text{-FWD}}$) to the dynamic modulus $\left(E_p^*\right)$ of field cores at the same frequency. The FWD $|E^*|$ curves are finally obtained by applying the same AF to moduli measured at all other frequencies.

2.1. FWD Measurements of Pavement Trial Sections. As part of the "Road Pavement Technology" project with the Transport Research Laboratory (TRL), Qatar's Public Works Authority (PWA) constructed a trial road in 2010 to investigate the influence of using different materials and asphalt mixture designs on the performance. The road consisted of six different pavement sections, mainly used by truck traffic. Sadek et al. [28] investigated the mechanical properties and performance of these sections after 3 years of service. The study involved back-calculation of layer moduli based on FWD measurements and laboratory measurements of the dynamic moduli on field cores. In this study, the data from four different asphalt pavement sections were selected for further analysis due to the variety of their asphalt mixture properties, as presented in Figure 1.

The asphalt used in the surface and base course of these sections differed in terms of asphalt type, aggregate, and mixture design, as shown in Table 1. Section 3 is the control section that follows the Marshall mix design requirements listed in the Qatar Construction Specifications (QCS). Gabbro aggregate with Pen 40–50 asphalt was used in Section 1, and Gabbro aggregate with Pen 60–70 asphalt was utilized in Sections 2 and 3. A Polymer-modified binder (PMB) with an Styrene-Butadiene-Styrene modifier was used in Section 4. The same granular subbase with limestone aggregate was used for all sections. The California bearing ratio (CBR) values for the subbase and subgrade layers are 60% and 20%, respectively. By utilizing Powell's equation (Equation (1)) [29], the estimated design modulus (E_s) for the subbase is 242 MPa, and the design modulus for the weathered limestone subgrade is 120 MPa [28].

$$E_s(\text{MPa}) = 17.58 \times \text{CBR}^{0.64}. \quad (1)$$

Section 3 was designed following the Marshal mix design criteria as described in QCS, while the mix design in

Table 2: Summary of back-calculated dynamic moduli using the FWD test ($E_{m\text{-FWD}}$) [28].

Season	Average surface temperature (°C)	Layer	Back-calculated (in-service) moduli ($E_{m\text{-FWD}}$) (MPa)			
			Section 1	Section 2	Section 3	Section 4
Winter	25	AC	9,368	11,288	8,893	6,923
		Subbase	979	1,057	1,129	1,072
		Subgrade	228	225	232	173
Summer	63	AC	2,198	2,488	2,282	2,171
		Subbase	702	716	575	562
		Subgrade	209	242	179	173

Table 3: Parameters of the lab-determined $|E^*|$ master curves at a reference temperature of 21.1°C.

Mix	Extracted from section #	δ	α	β	γ	a_1	a_2
Mix A	1	−1.404	6.056	2.011	0.372	0.0010	−0.176
Mix B	2	−1.435	5.968	2.179	0.362	0.0009	−0.170
Mix C	3	−1.434	5.964	2.229	0.370	0.0010	−0.173
Mix D	4	−1.388	5.912	2.041	0.316	0.0009	−0.170

Sections 1, 2, and 4 adopted the percentage refusal density (PRD) requirement in addition to satisfying the Marshal design. In this paper, the mixtures used in these trial sections were named Mix A, Mix B, Mix C, and Mix D, extracted from Sections 1, to 4, respectively. Sadek et al. [28] study gives more information about the mix designs.

The FWD test was carried out in February (Winter season) and August (Summer season) of 2012 to assess the sections at low- and high-service temperatures. The average surface temperatures were approximately 25 and 63°C in February and August, respectively [28].

The measured deflections, temperatures, and thicknesses of layers were used to back-calculate the moduli (stiffnesses) of the different layers—asphalt concrete, granular subbase, and subgrade—using the Deflection Basin Fit tool in the Dynatest Elmod6 software. The back-calculated moduli from the FWD measurements are shown in Table 2. On the other hand, average pavement temperatures at the center of the AC layers are determined using the BELLS2 model by Lukanen et al. [30]. The average air and pavement surface temperatures during the FWD test in each season were considered in the calculations. The pavement temperatures were approximately 23.2 and 55.9°C in February and August, respectively.

2.2. Lab-Determined Dynamic Modulus Master Curves of Field Cores. The dynamic modulus curve is typically developed by fitting the data to a sigmoidal function [31]. This study used the master curve model (Equation (2)) to fit the dynamic modulus data obtained using the AMPT method at different temperatures.

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

where $|E^*|$ is the laboratory dynamic modulus in MPa; δ is the lower asymptote of the $|E^*|$ master curve in logarithmic coordinates; α is the vertical span between the lower and upper asymptotes of the $|E^*|$ master curve in logarithmic coordinates; β and γ are shape coefficients of the master curve; and f_r is reduced frequency, Hz, which is the experimental temperature's equivalent frequency with respect to the reference temperature. Equation (3) can be used to calculate the reduced frequency once the shift factor is determined [31].

$$f_r = f \times \alpha(T), \tag{3}$$

where f is the frequency of loading at the desired temperature, T is the actual temperature, and $\alpha(T)$ is the shift factor as a function of temperature. The shift factor utilized in this study is the logarithm of the shift factor computed by using a second-order polynomial [9, 32], as follows:

$$\log(\alpha(T)) = a_1\left(T^2 - T_{ref}^2\right) + a_2(T - T_{ref}), \tag{4}$$

a_1 and a_2 are fitting constants that depend on the material properties, and T_{ref} is the reference temperature [33].

Field cores from four sections were tested to determine their dynamic modulus and phase angle at several temperatures and frequencies. Two core replicates were extracted from each section and trimmed to a standard size of 100 mm in diameter and 150 mm in height. The cores were tested using the AMPT test at repeated load with zero confinement, which was applied at 4.4, 21.1, 37.8, and 54°C with loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz (AASHTO designation: TP 79-11 (AASHTO 2011)). In this study, 21.1°C was considered as the reference temperature. Table 3 shows the shift parameters of the $|E^*|$ master curves (AMPT) at a reference temperature of 21.1°C. Figure 2 presents the laboratory master curves for the mixtures used in the four trial sections (see Figure 1).

2.3. Analysis of FWD Pulse and Dominant Frequency. In 2002, Loulizi et al. [34] applied FWD loads to the Virginia

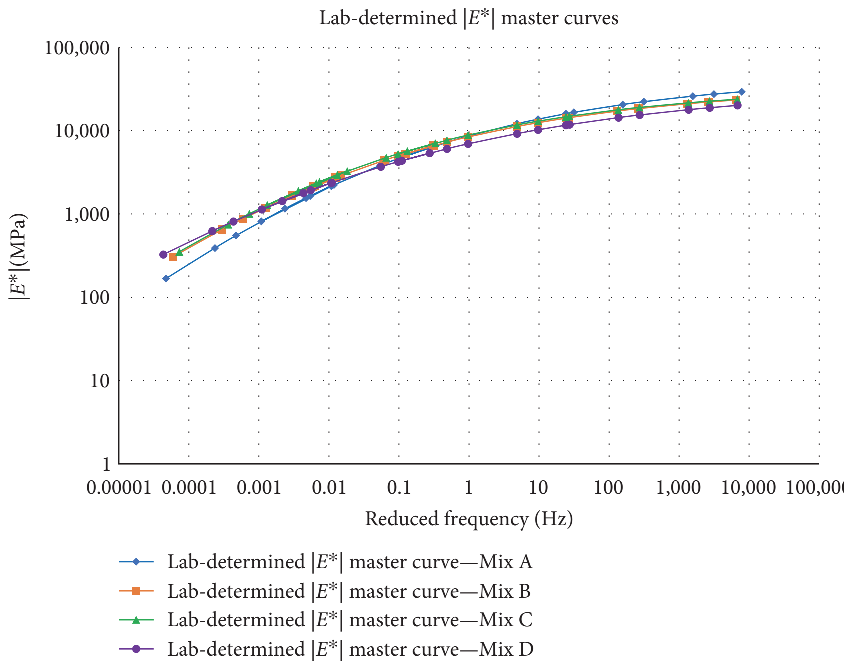

Figure 2: Lab-determined dynamic modulus $|E^*|$ master curves (AMPT) at a reference temperature of 21.1°C.

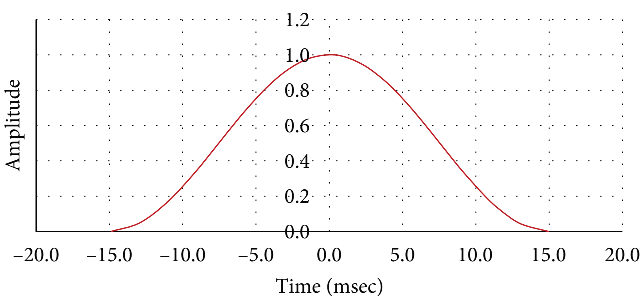

Figure 3: Haversine function that represents the FWD loading pulse (30 msec).

Smart Road and measured stress pulses at different depths under the pavement surface. The results showed that the stress pulses under the FWD loading stayed the same across the pavement depth. A haversine representation with a duration of 30–35 msec reasonably approximates the FWD pulse, as shown in Figure 3 [9, 34].

The frequencies of the FWD loading pulse were obtained using FFT, a built-in Fourier analysis routine in Microsoft Excel®. This routine limits the number of data points in the time domain to a power of two, such as 1,024 or 2,048. As a result, the FFT analysis in this paper considered 2,048 data points obtained at equal intervals.

2.4. Development of FWD-Adjusted Dynamic Modulus Master Curve. As discussed earlier, the objective is to determine the FWD-Adjusted dynamic modulus of the asphalt layer by combining FWD measurements with the laboratory dynamic modulus data. The process is described in the following steps, as shown in Figure 4.

(1) Develop the lab-determined dynamic modulus $|E^*|$ master curve using the model shown in Equation (2), which is used to fit AMPT measurements of field cores at different frequencies and temperatures.

(2) Determine the reduced frequency of FWD loading ($f_{r\text{-FWD}}$) using Equation (3) and utilizing the dominant frequency of the FWD loading pulse.

(3) Calculate the predicted dynamic modulus (E_p^*) at the corresponding reduced frequency of the FWD test ($f_{r\text{-FWD}}$).

(4) Determine the AF, which is the ratio of the measured FWD asphalt modulus ($E_{m\text{-FWD}}$) to the value of the predicted master curve dynamic modulus at the same frequency (E_p^*).

$$\text{Adjustment factor, AF} = \left(\frac{E_{m-\text{FWD}}}{E_p^*}\right). \tag{5}$$

(5) Shift the AMPT dynamic modulus $|E^*|$ master curve using theAF at all frequencies to extract the FWD-Adjusted $|E^*|$ master curve.

Equation (6), which was proposed by Solatifar et al. [4], is used to fit the sigmoidal function to determine the final FWD-Adjusted $|E^*|$ master curve:

$$\log\left(\left|E^*_{\text{FWD-adjusted}}\right|\right) = \delta + \frac{\alpha}{1 + e^{-\beta-\gamma(\log fr)}} + \log\left(\frac{E_{m-\text{FWD}}}{E_p^*}\right), \tag{6}$$

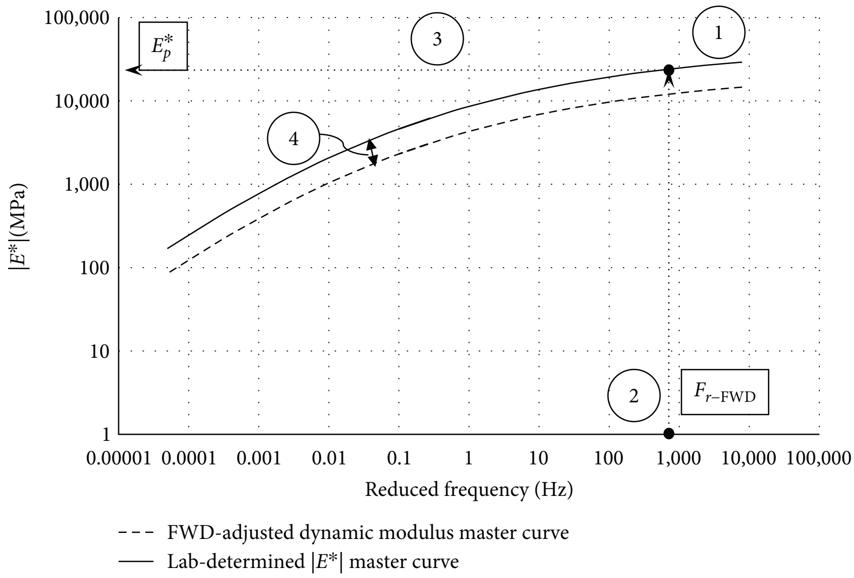

Figure 4: A proposed method for the development of an FWD-Adjusted $|E^*|$ master curve [4].

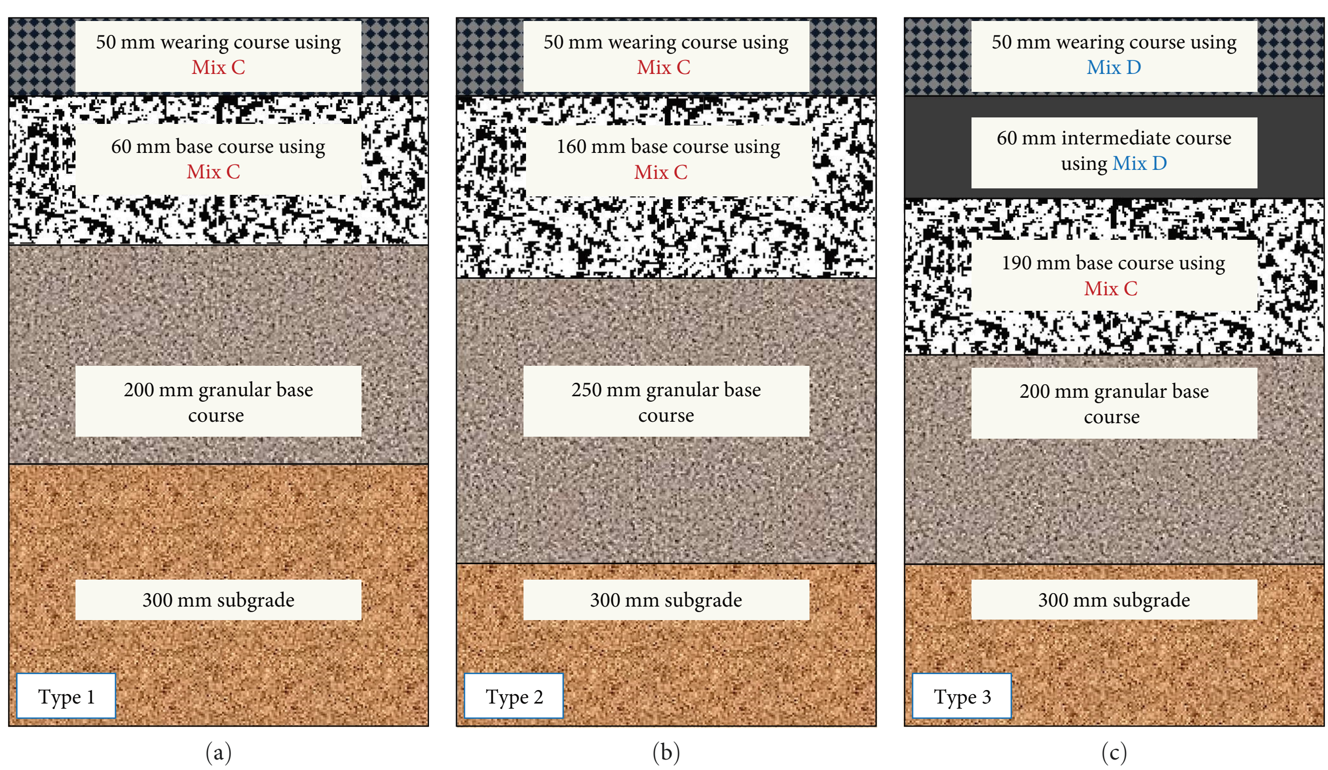

Figure 5: Selected asphalt section types for the pavement performance assessment, (a) Type 1, (b) Type 2, and (c) Type 3.

where $E^*_{\text{FWD-adjusted}}$ is the FWD-Adjusted (i.e., in situ) dynamic modulus of the asphalt layer in MPa; $E_{m-\text{FWD}}$: FWD back-calculated moduli, MPa; E^*_p: predicted dynamic modulus at the corresponding reduced frequency of FWD loading, MPa; and δ, α, β, γ, and f_r are as previously defined in Equations (2) and (3).

2.5. Analysis of Pavement Performance. In this section, two sets of material properties were used to conduct a comparative analysis of the pavement response and performance: (1) the AMPT (before adjustment) laboratory $|E^*|$ master curves for two asphalt mixtures (Mix C, which is used in Section 3 in Figure 1, and Mix D, which is used in Section 4 in Figure 1; and (2) the FWD-Adjusted $|E^*|$ master curves for the same mixtures. Both were used to assess three different pavement sections used in Qatar for different design loads (Figure 5).

The 3D-Move pavement analysis program was used to evaluate the performance of the pavement structures. This

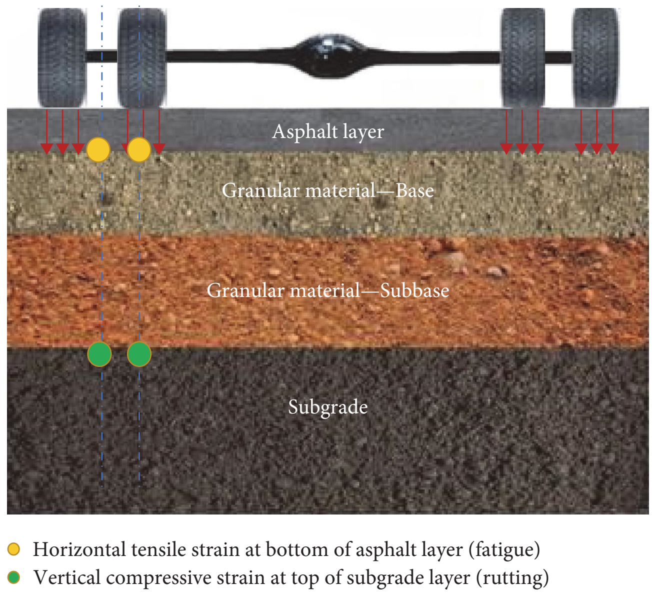

Figure 6: The critical locations for pavement responses.

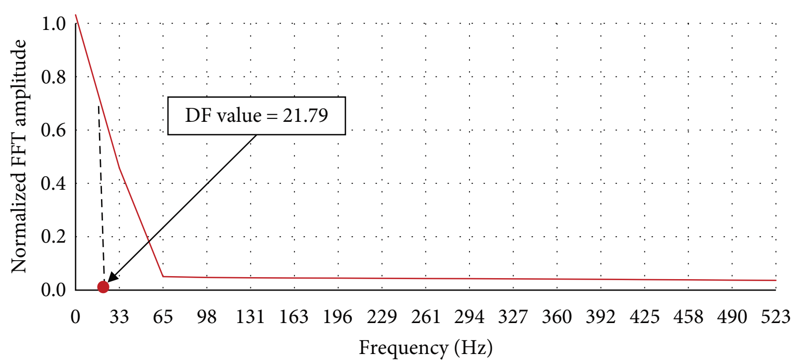

Figure 7: FWD frequency spectrum using FFT of the Haversine function.

software uses a Fourier transform-based continuum-based finite layer method that can handle complex surface loadings and account for significant pavement response factors such as vehicle speed and viscoelastic material characterization for the pavement layers. In addition, it considers the damping coefficient and the dynamic modulus as a function of frequency at the representative AC temperature as key input parameters for the simulation purposes [35].

A standard single-axle dual tire with a total axle weight of 80 kN was used to predict pavement distress at critical (horizontal and vertical) locations, as shown in Figure 6. Each tire was loaded with a force of 20 kN. The radius (r_c) of the tire contact circular area was determined by dividing the tire load by the inflation pressure (650 kPa). The r_c was found to equal 92 mm.

The performance assessment included two target speeds of 50 and 100 km/hr and was applied in the 3D model in the three sections. Besides, the performance evaluation was conducted in two seasons (Winter and Summer), and the average pavement temperatures encountered during the FWD test were considered in the models to count for the viscoelastic properties. The 3D-Move Analysis Software version 2.1 utilizes performance models developed in the NCHRP 1-37A project [35]. These models are for AC top–down cracking, AC bottom-up cracking, AC rutting, base rutting, subbase rutting, and subgrade rutting.

3. Results and Discussion

3.1. The FWD Frequency Spectrum Using FFT Analysis. The FFT is used to analyze the FWD loading pulse as shown in Figure 3 to determine the frequency spectrum. The resulting frequency spectrum of the FWD loading pulse is shown in Figure 7.

As recommended by Al-Qadi et al. [26] and Li et al. [36], the equivalent frequency (i.e., dominant frequency, DF) is the weight center of the Fourier spectra. The resulting shape of the frequency wave approximates the shape of a triangle, and the weight center at the first third of the triangle's base, as shown in Figure 7, is considered the projection of the DF. Therefore, the resulting FFT dominant frequency value is about 21.79 Hz. This value is in line with the estimated values

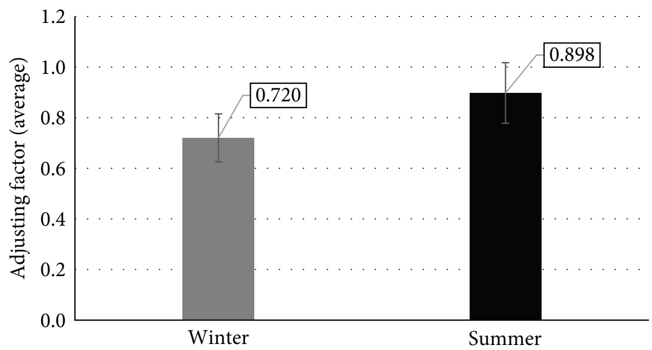

FIGURE 8: The adjustment factors used to determine the FWD-Adjusted dynamic modulus of asphalt layers $\left|E^*_{\text{FWD-adjusted}}\right|$ (error bars represent the standard deviation).

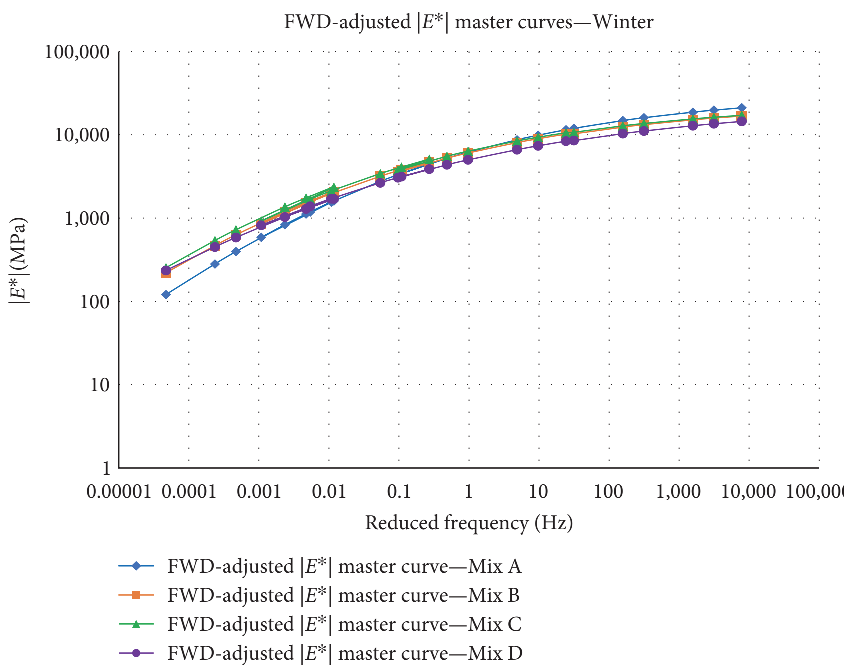

FIGURE 9: The FWD-Adjusted $|E^*|$ master curve—winter.

in the previous studies [17–19]. The measured FWD DF is used to determine the reduced frequency ($f_{r\text{-FWD}}$) based on the frequency–temperature shift factor at the temperature of interest using Equation (3) (i.e., $f_r = f \times \alpha(T)$), where $\alpha(T)$ is the frequency–temperature shift factor as shown in Equation (4) [9, 32].

3.2. Adjustment Factors. The AF_{Winter} and AF_{Summer}, which are the ratios of the measured FWD asphalt modulus ($E_{m\text{-FWD}}$) to the value of the predicted master curve dynamic modulus E_p^* at the same frequency, are applied for two ranges of temperatures as shown in Figure 8. For example, AF_{Winter} can be used to determine the FWD-Adjusted dynamic modulus of asphalt layers $\left|E^*_{\text{FWD-adjusted}}\right|$ for low and moderate pavement temperatures, which can be encountered in Spring and Winter while AF_{Summer} is used to determine the FWD-Adjusted dynamic modulus of asphalt layers $\left|E^*_{\text{FWD-adjusted}}\right|$ for high-pavement temperatures (i.e., Summer). In addition, the average value for the two developed AF (i.e., 0.81) can also be considered if one decides to use one factor for all seasons.

The ratios of the measured FWD-asphalt modulus ($E_{m\text{-FWD}}$) to the value of the predicted master curve dynamic modulus E_p^* at the same frequency are generally lower than 1.0 at different temperatures. For the sections evaluated in this study, the difference between the FWD and lab moduli is higher (lower AF) in the Winter than in the Summer.

3.3. FWD-Adjusted Master Curve. Figure 9 shows the FWD-Adjusted $|E^*|$ master curves during Winter using the AF_{Winter}. In addition, FWD-Adjusted $|E^*|$ master curves for the Summer season after applying the AF_{Summer} are illustrated in Figure 10.

It can be seen in Figures 9 and 10 that the FWD-Adjusted $|E^*|$ values for Mix D, which included modified PG 76-22

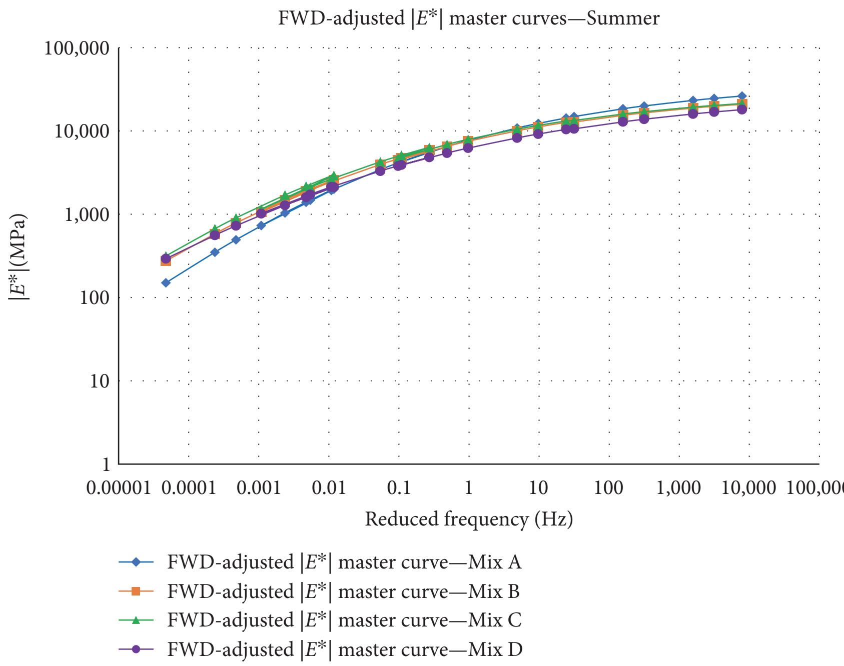

Figure 10: The FWD-Adjusted $|E^*|$ master curve—summer.

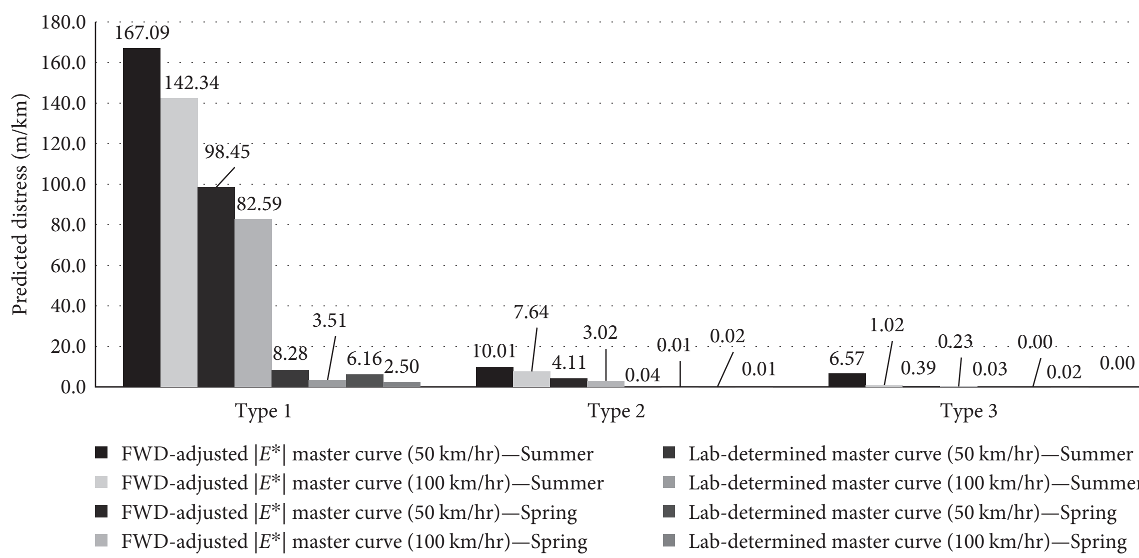

Figure 11: AC topdown cracking at two different speeds.

asphalt in Section 4, exhibited the least change with frequency.

3.4. Comparative Analysis of Pavement Performance. Three pavement sections (Type 1, Type 2, and Type 3) were evaluated using the FWD-Adjusted and laboratory-determined $|E^*|$ values for two different mixes (Mix C and Mix D). As mentioned earlier, the pavement performance analysis was conducted at two different speeds (50 and 100 km/hr) and average surface temperatures (25 and 63°C). The Type 1 section was evaluated under a traffic load of 5 million ESALs, the Type 2 section was subjected to a traffic load of 15 million ESALs, and the Type 3 section was subjected to 20 million ESALs. The AC top–down cracking, AC bottom-up cracking, AC rutting, base rutting, subbase rutting, and subgrade rutting were all determined using 3D-move software. Figures 11–14 show the results extracted from the 3D-move analysis.

The predicted AC top–down cracking of the three analyzed sections in Winter and Summer is presented in Figure 11. The sections that use the FWD-Adjusted $|E^*|$ master curves experienced more AC top–down cracking (m/km). In addition, the sections exposed to high temperatures (i.e.,

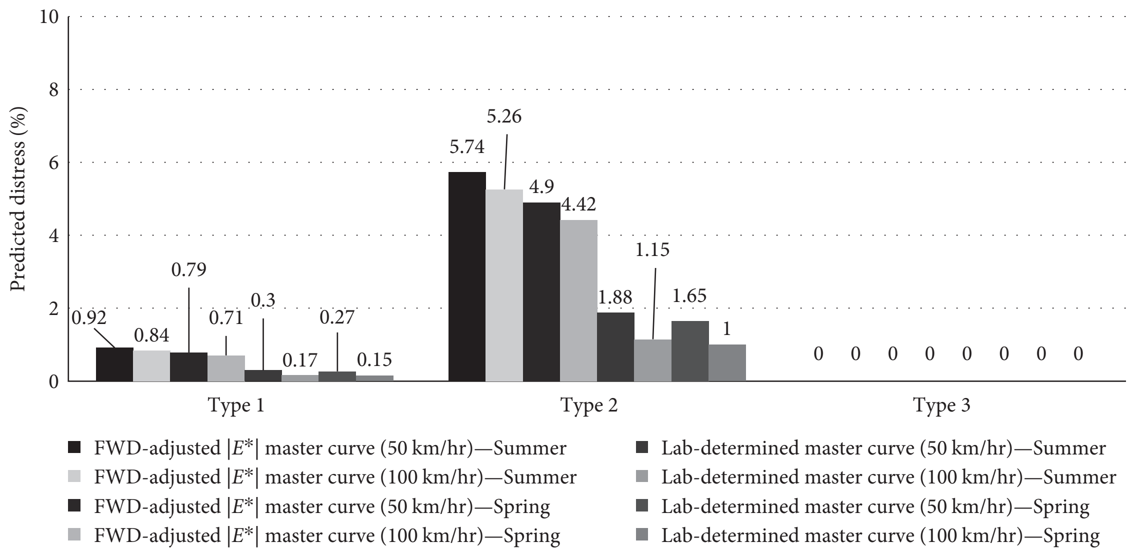

Figure 12: AC bottom-up cracking at two different speeds.

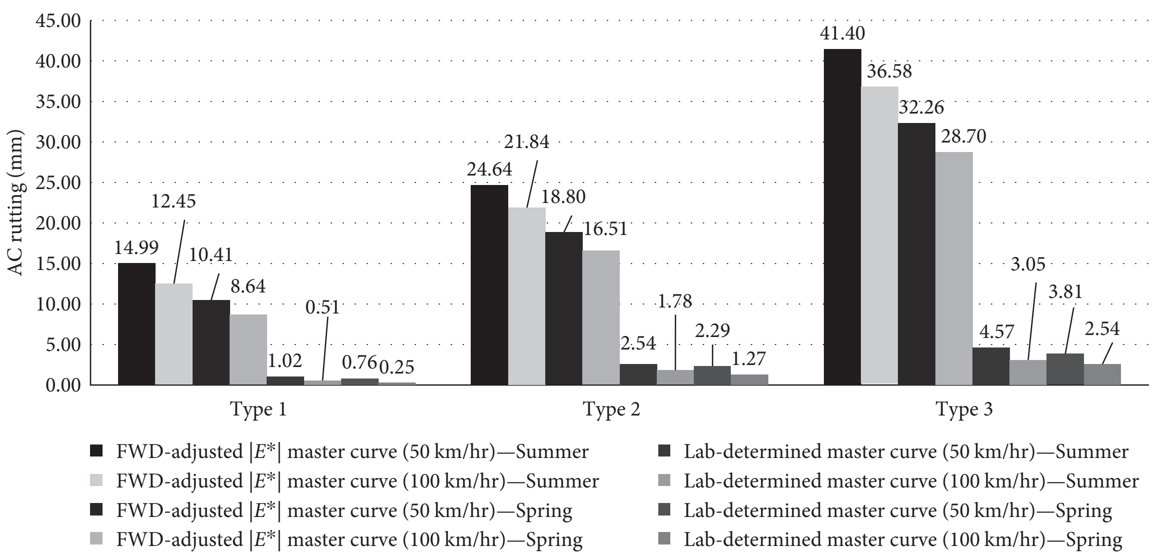

Figure 13: AC rutting in wearing course at two different speeds.

Summer) exhibited significantly higher AC top–down cracking than those at lower temperatures. The results are consistent with a previous study by Čygas et al. [37].

The AC bottom-up cracking results are presented in Figure 12. Similar to the AC top–down cracking, more cracking occurred in the Summer than in the Winter. However, it should be noted that these results do not consider the effect of moisture or freeze–thaw conditions in unbound and subgrade layers on the performance. These conditions would exacerbate cracking in the Winter season.

The predicted results of the AC rutting of the wearing course layer are presented in Figure 13, while the rutting of all AC layers is given in Figure 14 below. As expected, the AC rutting value (mm) increased significantly with increased temperature. However, a noticeable drop was reported in the AC rutting value (mm) at high speeds. In addition, the AC rutting has dramatically increased due to the use of the FWD-Adjusted $|E^*|$ master curve.

In general, the predicted levels for the considered distress types in this paper have increased by about 41%–140% at low and intermediate temperatures after using the FWD-Adjusted $|E^*|$ master curves, while the gap has declined in Summer to reach 10%–5%. In other words, using the laboratory $|E^*|$ master curve causes underprediction of pavement distresses.

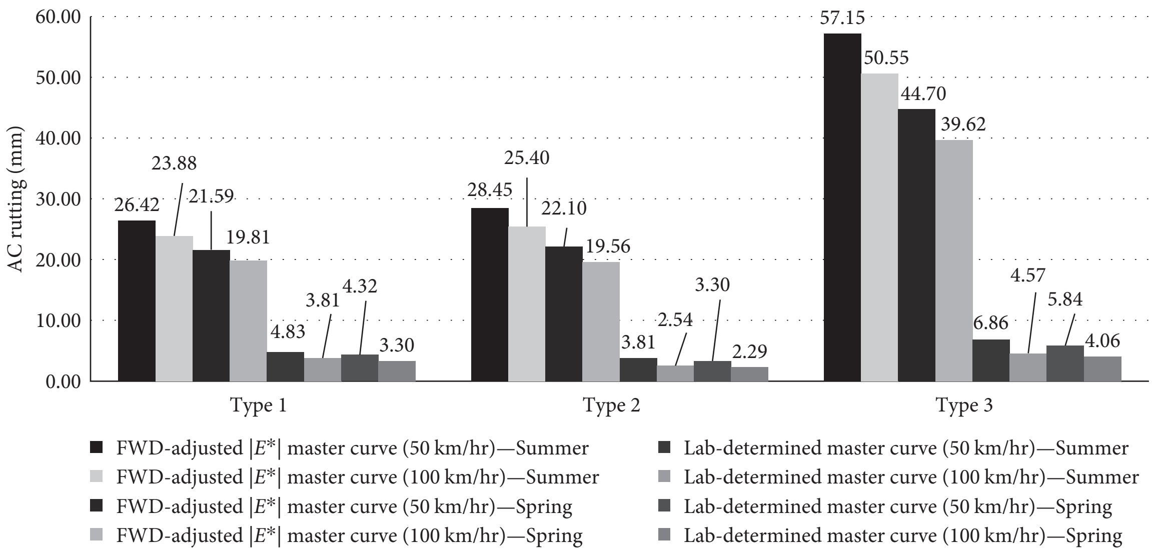

Figure 14: AC rutting in all AC layers at two different speeds.

4. Conclusions

A simple and practical methodology is proposed to determine the FWD-Adjusted dynamic modulus $|E^*|$ master curve in this study. The methodology consists of several steps. First, the dynamic modulus $|E^*|$ master curve is developed based on the laboratory measurements conducted on field cores at various frequencies and temperatures. The second step is to determine the reduced dominant frequency of FWD loading ($f_{r\text{-FWD}}$). This is followed by calculating the predicted dynamic modulus $|E_p^*|$ at the corresponding reduced frequency of the FWD test ($f_{r\text{-FWD}}$). The AF is determined as the ratio of the measured FWD asphalt modulus ($E_{m\text{-FWD}}$) to the value of the predicted master curve dynamic modulus at the same frequency $|E_p^*|$. Finally, the dynamic modulus $|E^*|$ master curve is shifted using the AF at all frequencies to determine the FWD-Adjusted $|E^*|$ master curve.

The 3D-move analysis program was employed to assess the performance of three pavement sections that utilized either the laboratory dynamic modulus $|E^*|$ master curve or the FWD-Adjusted dynamic modulus master curve. The findings from this study indicate that employing the laboratory dynamic modulus $|E^*|$ master curve in these pavement sections resulted in an overestimation of the asphalt layer modulus, which led to an overestimation of performance (less rutting, top–down cracking, and bottom-up cracking in the pavement sections).

Data Availability

The data used to support the findings of this study are included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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