Assessment of the Current Frequency Calculation Methods Used in the Determination of the Dynamic Modulus Value in Pavement Design and Analysis

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Abstract

The dynamic modulus |E*| is used in the Mechanistic-Empirical Pavement Design Guide (MEPDG) to express the viscoelasticity of asphalt material at a range of temperatures and loading frequencies. As a result, the current MEPDG method assumes that frequency is calculated as the opposite of vehicular loading pulse time. In addition, the loading pulse time can be calculated using the Odemark thickness equivalency method according to the MEPDG. On the other hand, the loading frequency as per Qatar Highway Design Manual (QHDM 2021) is estimated based on the average vehicle speed using Losa and Di Natale formula. However, studies found major inadequacies in the adopted method of MEPDG, which might affect the accuracy of the loading frequency and |E*| accordingly which leads to an impact on the pavement design and performance analysis. Hence, it was recommended that alternative frequency determination approaches like the Fast Fourier Transform (FFT) be used rather than traditional time-domain techniques. Therefore, this paper compares the results of the MEPDG and QHDM loading frequency procedure with the dominant frequencies (DF) obtained using the FFT. On the other hand, the loading time pulses are estimated using the Odemark approach and, compared to the ones simulated using 3D Move Analysis software that accurately considers the tire contact pressure, viscoelastic properties, & vehicle speed. It was found that the used frequency determination approach in the pavement design in Qatar, overestimates the frequency values by about 30% to 88%. Furthermore, the findings showed that the MEPDG method for determining loading time and frequency is not conservative.

Keywords: Asphalt; Dynamic Modulus; Loading Pulse; Fast Fourier Transform; Loading frequency

1 Introduction

The, fact that, Hot Mix Asphalt (HMA) is currently defined as viscoelastic material is one of the most significant benefits of the important improvements made by the MEPDG (Al-Qadi et al., 2008). As a result, the |E*| is used to express the viscoelastic behavior of the HMA, considering both the effects of temperature and the rate of loading, as shown in the belowsigmoidal equation (Pellinen et al., 2003).

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

where |E*| is the dynamic modulus (MPa); α is the vertical distance in logarithmic coordinates between the |E*| master curve's lower and upper asymptotes.; δ is the |E*| master curve's lower asymptote in logarithmic coordinates; β, γ are the master curve's shape parameters; γ impacts the rate of change between the upper and lower asymptotes; β impacts the turning point's horizontal location, and f_r is a reduced frequency in Hz.The reduced frequency f_r is the frequency equivalent to the testing temperature in relation to the reference temperature. Furthermore, after determining the shift factor, Equation (2) can be used to determine the reduced frequency (Zhang et al., 2020).

$$f_r = f \times \alpha(T) \qquad (2)$$

where f represents the loading frequency, T represents the temperature, and α(T) represents the temperature shift factoras explained below (Laukkanen et al., 2018):

$$\log(\alpha(T)) = a_1(T^2 - T^2_{ref}) + a_2(T - T_{ref}) \qquad (3)$$

a_1, a_2 are fitting constants affected by material characteristics (Laukkanen et al., 2018).

During the mix design process, the |E*| of the HMA is captured in the frequency domain by using the Asphalt Mixture Performance Tester (AMPT) machine under a wide range of temperatures and frequencies applied to the samples, and it is used to establish the |E*| master curve. However, vehicular loading is applied on-site in the time domain (Harran, 2011). Therefore, several researchers have tested various time-to-frequency conversion methods to accurately measure the associated frequency from vehicle stress or strain pulse length. For example, MEPDG takes the method of calculating frequency to be the inverse of the time pulse (f=1/t). Where f is the frequency in Hz and t is the loading time in (s). The relationship between frequency and time in the dynamic modulus tests is currently a source of heated debate among researchers (Sullivan & Denneman, 2015). A recent study has examined the accuracy of the MEPDG's conversion equation(Dongre et al., 2006), and no supporting reference for that approach was found other than MEPDG. The approach (i.e., MEPDG) is fundamentally inaccurate because it cannot accurately simulate the pulse produced by vehicular loading, which has a complex frequency spectrum (Underwood & Kim, 2009).On the other hand, MEPDG uses equation (4) based on Odemark's thickness equivalency approach to calculate the effective length of the loading pulse at any depth within the pavement system (Al-Qadi et al., 2008).

$$t = \frac{L_{eff}}{17.6V_S} \qquad (4)$$

Where t = time of loading (s); L_{eff} = effective length (in); and v_s = vehicle speed (mph).The Odemark method relies on the pavement structure being converted into a single subgrade layer system. Furthermore, the stress distribution for a given subgrade soil is assumed to be at 45°. The effective depth varies in the transformed section and is calculated as follows (Al-Qadi et al., 2008):

$$z_{eff} = \sum_{i=1}^{n-1} h_i \sqrt[3]{\frac{E_i}{E_{SG}}} + h_n \sqrt[3]{\frac{E_n}{E_{SG}}} \qquad (5)$$

Where, Z_{eff} = effective depth, h_n = thickness of the layer of interest (layer n), E_{SG} = elasticity modulus of subgrade, and E_n= elasticity modulus of the layer of interest. However, many researchers found that the MEPDG method for frequency calculations is associated with a significant error, which affects the accuracy of the entire pavement design process (Katicha et al., 2008; Dongre et al., 2006). Therefore, Al-Qadi et al., (2008) compared the results ofusing the Odemark approachto the loading frequencies in the asphalt layer computed using the advanced Finite Element (FE) model. The results showed that the MEPDG method is not conservative and to improve the MEPDG frequency, a correction factor was proposed by (Al-Qadi et al., 2008). Furthermore, Al-Qadi et al., (2008) used the (FFT) analysis to estimate the equivalent loading frequency based on the measured field loading time pulses to evaluate and quantify the MEPDG's time-frequency conversion process. The equivalent frequencies were assumed to be the weight center of the Fourier spectra. It was reported that the MEPDG frequency calculations method is associated with a frequency estimation error ranging from 40% to 140%, depending on the vehicle speed and pavement depth. Thus, (Al-Qadi et al., 2008)concluded that the inaccuracy in the MEPDG is due to using Odemark's hypothesis and the unrealistic time-frequency conversion approach. Another approach based on Losa and Di Natale equation (6) for frequency determination is adopted in pavement design and analysis in Qatar (Losa & Natale, 2012).

$$f_z = 0.043 \frac{V}{2a} e^{-2.65z+\beta(T)} \quad (6)$$

$$\beta(T) = 1.25x10^{-5}T^3 - 1.6x10^{-3}T^2 + 9.2x10^{-2}T \quad (7)$$

Where, f is the frequency in Hz, v= vehicle speed (m/s), a= radius of tire pressure (m), z= distance from the surface to the center of the asphalt layer (m), and T= average pavement temperature (ºC). However, this method is still not verified or compared by any reliable conversion method such as the FFT which wasrecommended by several studies to be used in the prediction of the frequency spectrum of vehicular loading (Al-Qadi et al., 2008). Therefore, this paper assesses the MEPDG loading frequency calculations and Losa & Di Natale approaches by comparing their results to the dominant frequency (DF) obtained by FFT. In addition, it provides a compersion between the current MEPDG loading time estimation method with the loading pulses generated by the 3D Move analysis software. The used softwareconsiders the viscoelastic material characterization for the pavement layers. The Loading time pules were extracted at different speeds and depths.

2 Methodology

2.1 Experimental Program

In this paper, two pavement sections with different asphalt mixtures were selected. Section 1 was produced with Pen 60–70 base bitumen and based on the Qatar Construction Specifications (QCS), which is following the Marshall procedure. While Polymer Modified Bitumen (PMB) with an SBS modifier was included in Section 2. The |E*| Master Curve parameters for the selected asphalt mixtures in this study can be seen below table.

Table 1: Parameters of the |E*| Master Curves (AMPT) at a Reference Temperature Of 21.1°C for the Selected Asphalt Mixtures

Mix	**δ**	**α**	**β**	**γ**	**a_1**	**a_2**
Pen 60–70 Based Mixture	-1.434	5.964	2.229	0.370	0.0010	−0.173
PMBBased Mixture	-1.388	5.912	2.041	0.316	0.0009	−0.170

Besides, to check the temperature influence on the estimation of the loading pulse and frequency, two seasons (spring & summer) were adopted as per Qatar's environmental conditions. During spring (i.e., low temperature)the average air temperatureof 23°C is considered and the average surface temperature of 25°C is assumed, while in summer (i.e., high temperature), the average air temperature is assumed to be 46°C while the average surface temperature was considered as 63°C. In addition, the average pavement temperatures at the center of the asphalt layers in each season were calculated based on BELLS2 model by Lukanen et al. (2000) which was also adopted in the

QHDM 2021 and considered in the analysis to count for the asphalt viscoelasticity properties. The estimated average pavement temperatures are presented in Table 2. Also, the module for each layer is assumed as per the typical results of the Falling Weight Deflectometer (FWD) test in Qatar.

Table 2 : Summary for the Assumed Modulus of Each Layer (Used in the Calculation of the L_{eff})

Season	Average Pavement Temp. °C	Layers	Assumed Module (MPa)	
			Section 1	Section 2
Spring	23.2	AC	8893	6923
		Subbase	1129	1072
		Subgrade	232	173
Summer	55.9	AC	2282	2171
		Subbase	575	562
		Subgrade	179	173

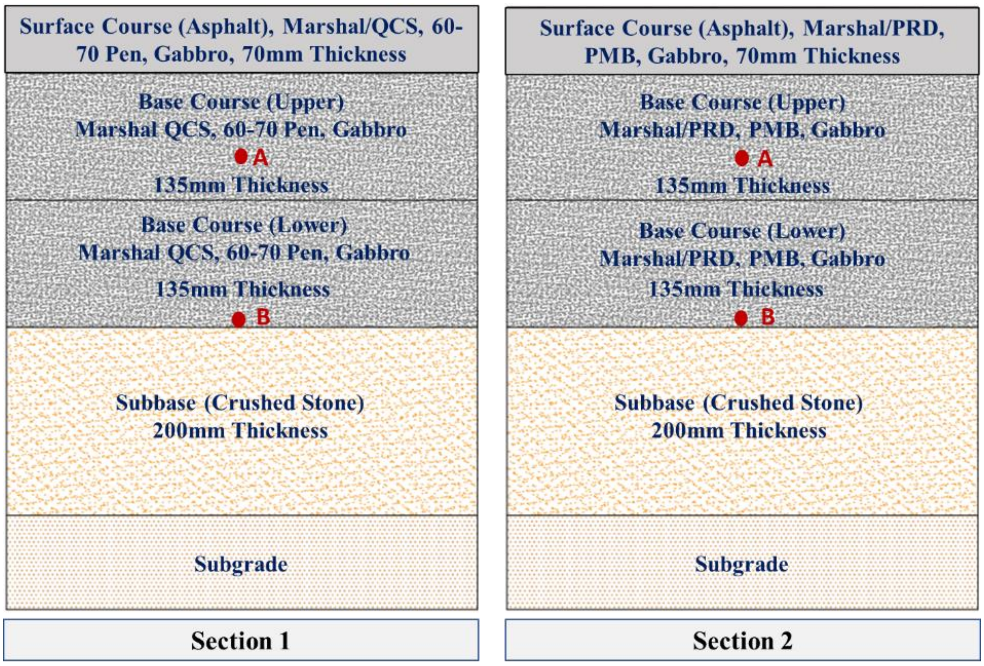

Fig. 1: Layers and Materials' properties of the two selected sections

2.2 Loading Time Pulse Generation

A single tire from a standard single-axle dual tire with a total axle weight of 80 kN was used to generate the vertical stress time pulse (σ_v) using 3D-Move Analysis software. The radius of the tire contact circular area (a_c) was determined by dividing the load on the tire by the inflation pressure (724 kPa). The (a_c) was found to equal 0.093 m. Three target speeds of 24, 40, and 72 km/hr were included in the study and applied in the 3D model at the two sections. Besides, the loading time pulses were captured at two different depths (point A = 170mm) and (point B = 340mm) as shown inFig. 1. On the other hand, the bell-shaped equation (8) is used to represent the generated vertical compressive stress pulse for a moving vehicle.

$$y(t) = e^{-t^2/s^2} \quad (8)$$

Where s= the standard deviation that controls the shape of the curve ($s=n_1v^{-n2}$). The standard deviation (s) is a function of speed for the two variouslocations in the pavement structure, where v is the truck speed in km/hr. Also,n_1&n_2 are the controls factor that varies with the pavement depth (Loulizi et al., 2002).

2.3 Loading Frequency Determination

Four various scenarios were considered to determine the loading frequency from the Loading Time Pulse Duration (t) (see Table 3). The loading frequency determination methods adopted in the MEPDG and QHDM 2021, were compared to the dominant frequencies (DF) values of FFT that are calculated at the weight center of the resulting frequency spectrum to evaluate their accuracy.

Table 3 : Frequency calculation scenarios considered in this study

Scenario #	**Loading Time Duration**	**Loading Frequency Determination Method**
Scenario 1	3D Move Generated Pulse	$f = \frac{1}{t}$
Scenario 2	$t = \frac{L_{eff}}{17.6V_S}$	$f = \frac{1}{t}$
Scenario 3	Losa and Di Natale	$f_z = 0.043\frac{V}{2a}e^{-2.65z+\beta(T)}$
Scenario 4	3D Move Generated Pulse	DF - FFT

3 Results And Discussion

3.1 The Estimated Loading Pulse Time

Fig. **2** displays the vertical stress (σ_v) pulses for a vehicle speed of 40 km/hr, normalized to their peak values at 170mm in Section 1 through the spring and summer seasons. While the generated loading time pulses generated in Section 2 at the same speed in the two seasons were almost the same as the material characteristics have a minor impact on the generated loading pulses. With increasing the depth, the loading pulse width showed longer durations. However, the temperature affected slightly the length of the loading pulses on the two sections. This completely corresponds to the findings of (Loulizi et al., 2002) and (Al-Qadi et al., 2008) in their studies.

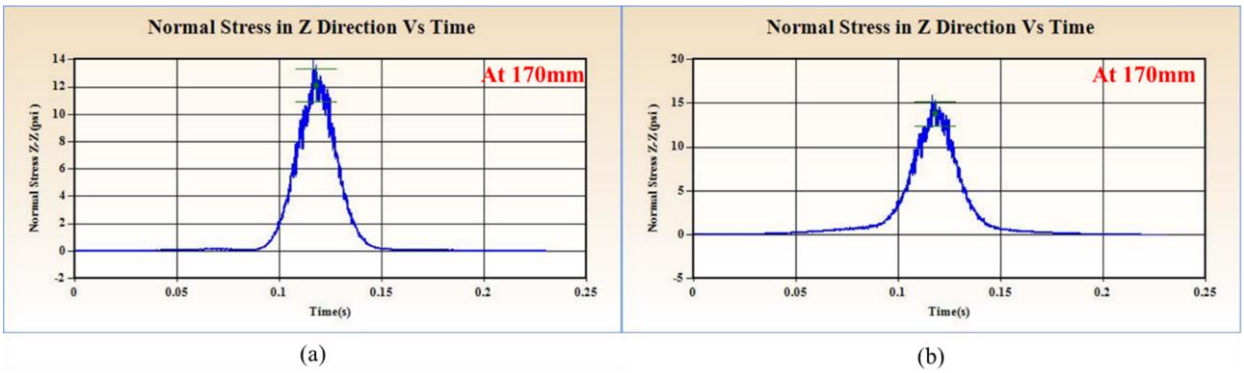

Fig. 2: Loading Time Pulse generated on Section 1 at 40 Km/Hr Speed
At Depth of 170mm (a) spring season (b) summer season

The normalized bell-shaped function has shown an accurate approximation of the produced loading pulse by 3D Move Analysisat different speeds and depths as shown in the below figures.

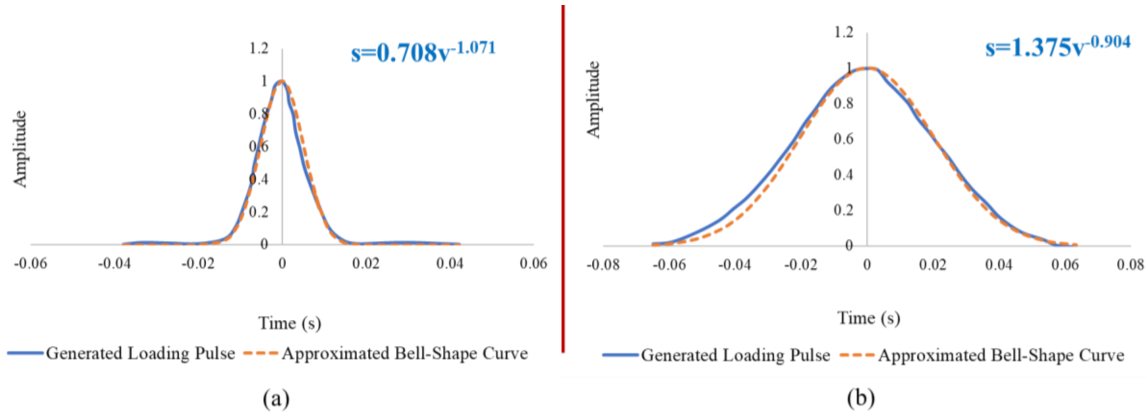

Fig. 3: Normalized Bell-shaped approximations of Loading Pulses for the 72 km/h test applied on section 1 in spring at (a) 170 mm (b) 340 mm

On the other hand, the same criteria and conditions considered in the 3D Move Analysis were used the calculate the vehicular loading time pulse (t) based on equation (4). A summary of the generated loading time pulses using 3D Move Analysis and Odemark approach at different operational conditions in Section 1 & Section 2 are presented in Table 5.

3.2 The Predicted Loading Frequency From Different Scenarios

The built-in FFT routine in Microsoft Excel® was used to perform the frequency analysis of vertical stress pulses in scenario 4 and to find the DF. The FFT analysis was done on a total of 2048 data points obtained at equal intervals. Furthermore, The DF values at the weight center of FFT Fourier spectra were compared against the other frequency calculation approaches. The corresponding normalized FFT wave of the σv pulse was generated at different depths as shown in Fig. **4**.At high depths, the area under the generated frequency spectrums tended to decrease. While,the frequency value significantly was not influenced by the temperature, especially at low speeds.

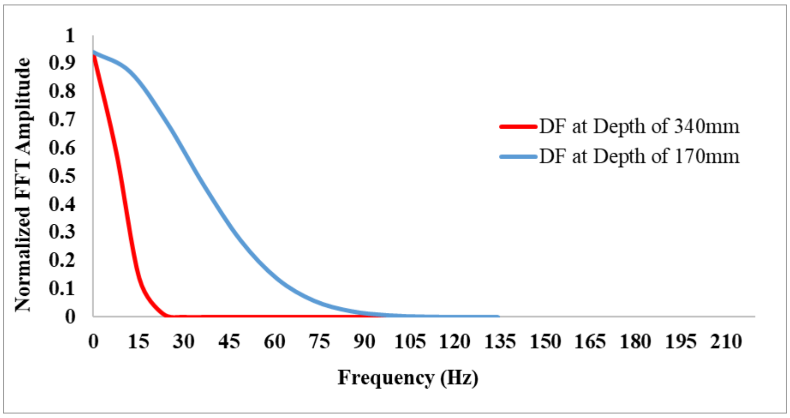

Fig. 4: The Frequency domain of loading pulse on section 1 at 72 km/hr during spring

Nearly similar frequency waves were obtained using FFT at the same conditions in Summer.Table 4 shows a summary of the calculated loading frequency using Losa and Di Natale and FFT methods. Results obtained using FFT agree with the findings of previous studies(Al-Qadi et al., 2008; Shafiee et al., 2015). The difference in frequency value becomes clearer as the speed increases, and it is influenced by the temperature. It's worth noting that in comparison to FFT results, the Losa & Di Natale equation used in the State of Qatar produced high-frequency values, particularly at higher speeds and temperatures.

Also, Table 5 relates the Fourier analysis results to the loading frequency obtained using the MEPDG and the Losa & Di Natale methods. Also, the calculated frequencies using FFT were generally lower than scenario 1 results, particularly at speeds of 40 km/hr and higher.

Table 4 : Summary of the calculated loading frequency using Losa and Di Natale and FFT methods

Sec.#	**Depth mm**	**Speed km/hr**	**Loading Frequency (Hz) using Losa and Di Natale**		**Loading Frequency (Hz) using the DF-FFT**	
			23.2 ºC	55.9 ºC	23.2 ºC	55.9 ºC
1	170	24	5.10	12.50	2.82	2.82
		40	8.49	20.83	4.41	4.34
		72	15.29	37.50	6.59	5.32
	340	24	4.07	9.98	2.25	2.26
		40	6.78	16.63	2.91	2.92
		72	12.20	29.93	3.35	3.66
2	170	24	5.10	12.50	3.57	2.64
		40	8.49	20.83	4.10	3.39
		72	15.29	37.50	6.00	5.01
	340	24	4.07	9.98	2.15	2.08
		40	6.78	16.63	3.05	2.91
		72	12.20	29.93	4.50	4.66

Table 5 : Percentage deviation from the DF -FFT based on the 3D Move Analysis loading pulses (%)

S#	**Depth mm**	**Speed km/hr**	**Loading Pulse Duration (s) - Odemark approach**		**Loading Pulse Duration (s) - 3D Move Analysis**		**Scenario 1**		**Scenario 2**		**Scenario 3**	
			23.2 ºC	55.9 ºC	23.2 ºC	55.9 ºC	23.2 ºC	55.9 ºC	23.2 ºC	55.9 ºC	23.2 ºC	55.9 ºC
1	170	24	0.200	0.147	0.308	0.308	13.1%	16.0%	43.6%	58.5%	44.7%	77.4%
		40	0.120	0.088	0.155	0.155	31.6%	33.2%	47.0%	61.6%	48.1%	79.2%
		72	0.067	0.049	0.080	0.080	47.3%	52.1%	56.0%	73.9%	56.9%	85.8%
	340	24	0.372	0.266	0.382	0.382	14.1%	13.9%	16.3%	39.9%	44.7%	77.4%
		40	0.223	0.160	0.225	0.225	34.6%	33.2%	35.1%	53.4%	57.1%	82.5%
		72	0.124	0.089	0.128	0.128	57.1%	55.1%	58.4%	67.5%	72.5%	87.8%
2	170	24	0.203	0.147	0.246	0.246	12.1%	14.1%	27.6%	61.3%	29.9%	78.9%
		40	0.122	0.088	0.162	0.162	33.6%	32.6%	50.2%	70.1%	51.7%	83.7%
		72	0.068	0.049	0.106	0.106	36.5%	39.4%	59.5%	75.5%	60.7%	86.6%
	340	24	0.377	0.265	0.381	0.381	18.0%	20.4%	19.0%	44.7%	47.2%	79.1%
		40	0.226	0.159	0.224	0.224	31.6%	34.1%	30.9%	53.7%	55.0%	82.5%
		72	0.126	0.088	0.128	0.128	42.4%	42.3%	43.4%	58.8%	63.1%	84.4%

From the previous table, it can be noticed that the loading pulses duration of the Odemark approach is less than the 3D Move Analysis generated loading pulses by (1% to 147%). In addition, using the Odemark approach might overestimate the loading frequency by an error of 0.10% to 59.5%, which will affect the estimation of the asphalt modulus. Moreover, the deviation of scenario 1 from scenario 4 was ranging from 12.11% to 57.09%. This is in agreement with the findings of (Al-Qadi et al., 2008). In addition, the associated error with Scenario 3 (adopted in the state of Qatar) compared to the dominant loading frequencies obtained with FFT was ranging between about 29.88% to 87.77%, which means that it might overestimate the estimation of the loading frequency value and leads to an unreliable estimation of the HMA complex modulus.

4 Conclusion

This study was conducted to evaluate the accuracy of the MEPDG's time-frequency conversion process along with the Losa and Di Natale equation used in the state of Qatar. The 3D Move Analysis software was used to generate the loading pulses for two different sections and at various operational criteria., and the same conditions were used to determine the loading pulse using the Odemark methodapproach. On the other hand, the FFT analysis was performed to find the DF ofthe generated loading pulses using 3D Move Analysis. Four scenarios were developed for frequency determination based on the estimated loading pulse time. Accordingly, the following conclusions were drawn based on the selected sections, material properties, and the other study’s conditions which are in line with pavement design criteria used in the state of Qatar:

1. Using Odemark's approach adopted in MEPDG for frequency calculation produces higher frequencies than those determined by using the 3D move analysis method, particularly at low speeds and high temperatures. This would result in higher complex moduli of the HMA.
2. The simple loading frequency estimation methods used in pavement design and analysis in the state of Qatar, based on this study, can overestimate the loading frequency depending on vehicle speed and measurement depth. The associated error with Losa and Di Natale method compared to the DF-FFT was ranging between 29.88% to 87.77%.
3. In addition, the Deviation of Scenario 1 from DF-FFT was ranging from 12.11% to 57.09%.

It is obvious that DF- FFT produces more accurate moduli and it is recommended to be used in the |E*| determination in the pavement design and analysis in Qatar. While the approach of considering DF at the weight centers of frequency waves needs to be further studied in the future.

References

Al-Qadi et al. (2008). “Accuracy of Current Complex Modulus Selection Procedure from Vehicular Load Pulse: NCHRP Project 1-37a Mechanistic-Empirical Pavement Design Guide.” *Transportation Research Record*, no. 2087: 81–90. https://doi.org/10.3141/2087-09.

Al-Qadi, Imad L., Wei, X. & Elseifi, M. A. (2008). “Frequency Determination from Vehicular Loading Time Pulse to Predict Appropriate Complex Modulus in MEPDG.” *Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions* 77 (January 2008): 739–71.

Dongre, R., Myers, L. & D’angelo, J. (2006). “Conversion of Testing Frequency to Loading Time: Impact on Performance Predictions Obtained from the ME Pavement Design Guide.” *Proceedings of the Transportation Research Board*.

Harran, G. (2011). “Improving the Determination of the Dynamic Modulus of Asphalt Concrete for Mechanistic-Empirical Pavement Design.” *Ph.D. Thesis, University of Manitoba, Winnipeg, Manitoba, Canada*.

Katicha, et al. (2008). “Conversion of Testing Frequency to Loading Time Applied to the Mechanistic-Empirical Pavement Design Guide.” *Transportation Research Record*, no. 2087: 99–108. https://doi.org/10.3141/2087-11.

Laukkanen, et al. (2018). “The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-Forming Liquids.” *Journal of Non-Crystalline Solids 483*(12): 10–17.

https://doi.org/10.1016/j.jnoncrysol.2017.12.029.

Losa, M., & Andrea, N. (2012). "Evaluation of Representative Loading Frequency for Linear Elastic Analysis of Asphalt Pavements." *Transportation Research Record*, no. 2305: 150–61. https://doi.org/10.3141/2305-16.

Loulizi, et al. (2002). "Measurement of Vertical Compressive Stress Pulse in Flexible Pavements: Representation for Dynamic Loading Tests." *Transportation Research Record 1816* (1): 125–36.

Lukanen, et al. (2000). "Temperature Predictions and Adjustment Factors for Asphalt Pavement." Turner-Fairbank Highway Research Center.

Pellinen, T. K., Matthew, W. W., & Bonaquist, R. F. (2003). "Asphalt Mix Master Curve Construction Using Sigmoidal Fitting Function with Non-Linear Least Squares Optimization," 83–101. https://doi.org/10.1061/40709(257)6.

Shafiee, et al. (2015). "Analysis of Loading Frequency in Flexible Pavement Using Fast Fourier Transform." *International Journal of Pavement Research and Technology 8*(6): 403–9. https://doi.org/10.6135/ijprt.org.tw/2015.8(6).403.

Sullivan, B., & Denneman, E. (2015). "Inter-Conversation of Australian Modulus Test Methods Inter-Conversation of Australian Modulus Test Methods." *16th AAPA International Flexible Pavements Conference*.

Underwood, B. S. & Kim, Y. R. (2009). "Determination of the Appropriate Representative Elastic Modulus for Asphalt Concrete." *International Journal of Pavement Engineering 10*(2): 77–86. https://doi.org/10.1080/10298430701827668.

Zhang, et al. (2020). "Predict the Phase Angle Master Curve and Study the Viscoelastic Properties of Warm Mix Crumb Rubber-Modified Asphalt Mixture." *Materials 13*(21): 1–26. https://doi.org/10.3390/ma13215051.

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