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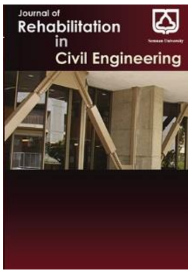

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Mechanistic-Empirical Analysis of Asphalt Dynamic Modulus for Rehabilitation Projects in Iran

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ABSTRACT

In the Mechanistic–Empirical Pavement Design Guide (MEPDG), dynamic modulus of asphalt mixes is used as one of the input parameters in pavement analysis and design. For in-service pavements, MEPDG method uses a combination of some field and laboratory tests for structural evaluation of asphalt layers in rehabilitation projects. In this study, ten new and rehabilitated in-service asphalt pavements with different physical characteristics were selected in provinces of Khuzestan and Kerman in the south of Iran. These provinces are known as hot climate areas and have severe climatic conditions. At each site, Falling Weight Deflectometer (FWD) testing was conducted and core samples were taken. These samples were extracted and mix volumetric properties and binder characteristics were determined. Results of these tests were used as input parameters in Witczak dynamic modulus prediction model for determination of MEPDG undamaged dynamic modulus master curves. Finally, the damaged (in-situ) dynamic modulus master curves were developed upon modifying the undamaged master curves with the damage factors determined from back calculation analysis of FWD data. It was found that with the above mechanistic-empirical procedure, it would be possible to successfully evaluate in-service asphalt layers located in severe climatic areas.

1. Introduction

Dynamic modulus (|E*|) of asphalt materials is one of the most important input parameters in flexible pavement analysis and design. This parameter is a fundamental material property that characterizes the viscoelastic time and temperature dependent behavior of asphalt mixes. The importance of dynamic modulus is in both pavement accurate design and rehabilitation processes.

Asphalt dynamic modulus is measured in laboratory on compacted mix samples according to the standard protocol, AASHTO T342 [1]. In addition, there are several predictive models such as Witczak [2], Modified Witczak [3] and Hirsch [4] that determine |E*| from some properties of the mixture. Laboratory testing for |E*| requires considerable time and is very expensive. In practice, for rehabilitation projects it is not usually possible to have asphalt layers with the thickness required by standard laboratory testing protocols. Utilizing nondestructive testing with these predictive models to derive |E*| master curve of an in-service asphalt pavement, would not only save laboratory time and expenses, but it could also lead to a more accurate prediction of remaining life of the pavement.

The Mechanistic–Empirical Pavement Design Guide (MEPDG) is the state-of-the-practice design procedure that uses dynamic modulus master curve for determining the structural capacity of asphalt layers at three hierarchical levels according to the importance and accuracy of a project. In this guide, for the design of new pavements at input level 1, dynamic modulus testing in laboratory is used in order to determine modulus values at several sets of temperatures and frequencies. Using the time-temperature superposition principle, the dynamic modulus master curve is constructed at a reference temperature (usually 21.1°C). For input levels of 2 and 3, the modulus is predicted from the mix volumetric properties and binder viscosity. The difference between level 2 and level 3 is that level 2 uses mixture volumetric and binder properties measured in the laboratory while level 3 uses typical values from similar mixtures used earlier by the agency [5].

For rehabilitation projects, the MEPDG defines a “damaged” and an “undamaged” modulus and uses a combination of field and laboratory tests for structural evaluation of in-service pavements. At input level 1, Falling Weight Deflectometer (FWD) testing is performed and some core samples are taken from that site for extraction purposes. Witczak model is used to develop an undamaged dynamic modulus master curve utilizing asphalt layer volumetric and binder viscosity properties. A damage factor defined as the ratio of backcalculated FWD modulus to predicted value at the same temperature and frequency, is used to determine the damaged dynamic modulus master curve from the undamaged one. For level 2 analysis, resilient modulus data from core samples is used instead of FWD testing while for level 3, the damage factor is estimated from surface condition rating [5].

MEPDG presents a major change in the philosophy of pavement design and rehabilitation. It computes stresses, strains and deflection whiten a pavement system, and then predicts, through empirical accurate models, various distresses in pavements including rutting, fatigue cracking and roughness during the pavement service life [6]. In addition to the accuracy of MEPDG especially in level 1 analysis, the major benefits of this method for determination of dynamic modulus of in-service asphalt layers, are its simplicity and no need for large amounts of data using a routinely FWD device. Also, static backcalculation using load and deflection peak values would be enough for analysis of proposed method results. These make MEPDG a simple and useful method for implementation in asphalt pavement evaluation.

There are several studies that have used the MEPDG proposed method to design new mixes at these three input levels in several states of USA, Saudi Arabia and Australia [7-12, 6]. While for in-service pavements, there are just numerous researches focused on utilization and evaluation of the MEPDG method in USA and Korea [13, 14]. The research by Loulizi et al. [13] was a valuable study for nine flexible and composite pavements in high performance roads in Virginia. Results showed the ability of MEPDG method in predicting dynamic modulus master curves for in-service pavements while some disadvantages were reported for level 2 analysis. However, it is necessary to accurate evaluation and probably modification of proposed method in different traffic and climatic conditions for completely implementation of MEPDG as a new method in local pavement design and rehabilitation practices. This study would address the applicability of MEPDG proposed method in determining dynamic modulus of asphalt layers as the basic input parameter for adoption of mechanistic-empirical asphalt pavement rehabilitation in Iran.

2. Asphalt Dynamic Modulus in the MEPDG

2.1. |E*| sigmoidal function

Asphalt dynamic modulus master curve can be presented by the sigmoidal function described by Equation (1):

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

where $|E^*|$ = Asphalt dynamic modulus, psi; δ = Regression parameter (10^{δ} = minimum modulus value); α = Specified range from minimum ($10^{\delta+\alpha}$ = maximum modulus value); β and γ = Regression parameters; and, t_r = Reduced time (time of loading at the reference temperature), sec.

The fitting parameters δ and α depend on aggregate gradation, binder content and also air void content. The parameters β and γ depend on the characteristics of the asphalt binder and the magnitude of δ and α. This sigmoidal function describes the time dependency of the modulus at the reference temperature; while the shift factor (Section 2.3) describes the temperature dependency of the modulus [5].

2.2. Undamaged Dynamic Modulus Master Curve

Witczak model is used to predict undamaged dynamic modulus master curve in the MEPDG. This model was developed in 1999 based on 2,750 data points from 205 asphalt mixtures, including modified and unmodified binder grades. It predicts |E*| at different temperatures as a function of aggregate gradation, mix air voids, effective binder content, loading frequency and binder stiffness. The binder stiffness in the model is expressed in terms of the viscosity, which is a function of the temperature. The sigmoidal function can be fitted to this model as expressed in Equation (2) [2]:

$$\log|E^*| = 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977-0.0021\rho_4+0.003958\rho_{38}-0.000017(\rho_{38})^2+0.005470\rho_{34}}{1+e^{(-0.603313-0.313351\log(f)-0.393532\log(\eta))}} \tag{2}$$

where $|E^*|$= Asphalt dynamic modulus, psi; η= Binder viscosity, 10^6 Poise; f = Loading frequency, Hz; ρ_{200} = % passing the #200 sieve, %; ρ_4= Cumulative % retained on the #4 sieve, %; ρ_{34} = Cumulative % retained on the #3/4 sieve, %; ρ_{38} = Cumulative % retained on the #3/8 sieve, %; V_a= Air void content, %; and, V_{beff} = Effective binder content, % by volume.

2.3. Binder Characterization − Shift Factor

Binder viscosity and shift factor can be determined by using Dynamic Shear Rheometer (DSR) test data at various temperatures and minimum of one frequency as following procedure [5]:

- Use Equation (3) for determination of binder viscosity at any G^* and associated δ from DSR:

$$\eta = \frac{G^*}{10}\left(\frac{1}{\sin\delta}\right)^{4.8628} \tag{3}$$

  where η= Asphalt binder viscosity, Pa.s; G^* = Complex shear modulus of binder, Pa; and, δ = Binder phase angle, degree (°).

- Then, it would be possible to define two viscosity parameters, A and VTS [15]:

$$\log\log(\eta) = A + VTS\log(T_R) \tag{4}$$

where η= Asphalt binder viscosity, cP; T_R= Temperature, Rankine; A= Regression intercept; and, VTS= Regression slope of viscosity temperature susceptibility.

- For calculation of shift factor and also reduced time (or frequency) to be used in development of master curve, Equations (5) to (7) were proposed:

$$\log(a_T) = 1.255882(\log(\eta) - \log(\eta_r)) \quad (5)$$
$$\log(t_r) = \log(t) - \log(a_T) \quad (6)$$
$$\log(f_r) = \log(f) + \log(a_T) \quad (7)$$

where a_T= Shift factor as a function of temperature, cP; η = Viscosity at the temperature of interest, cP; η_r = Viscosity at the reference temperature, cP; t = Time of loading, sec; t_r = Reduced time, sec; f = Frequency of loading, Hz; and, f_r = Reduced frequency, Hz.

2.4. Mechanistic-Empirical Methodology for Determination of Asphalt Dynamic Modulus in Rehabilitation Projects

For determining the dynamic modulus of in-service asphalt layers in rehabilitation projects, MEPDG procedure is proposed at three hierarchical levels according to the importance and accuracy of a project. In this study the highest accurate level, i.e. level 1 is used to construct the damaged dynamic modulus master curve in following steps [5]:

- Use FWD backcalculation approach. Measure deflections, backcalculate (combined) asphalt bound layer modulus at points along the project.
- Establish backcalculated E_i at temperature-time conditions for which the FWD data was collected along the project.
- Obtain field cores to establish mix volumetric parameters (air voids, asphalt volume, gradation, and binder viscosity parameters) to determine undamaged master curve.
- Develop undamaged master curve using sigmoidal function (Equation 1).
- Estimate damage, d_j, expressed as follows:

$$d_j = 1 - \frac{E_i}{E^*} \quad (8)$$

where E_i= Backcalculated modulus at a given reference temperature recorded in the field; E^*= Predicted modulus at the same temperature as above from Equation 1.

- Define new range parameter, α' as shown below:

$$\alpha' = (1 - d_j)\alpha \quad (9)$$

- Develop field damaged master curve using α' instead of α in sigmoidal function.

The procedure is shown in Fig.1.

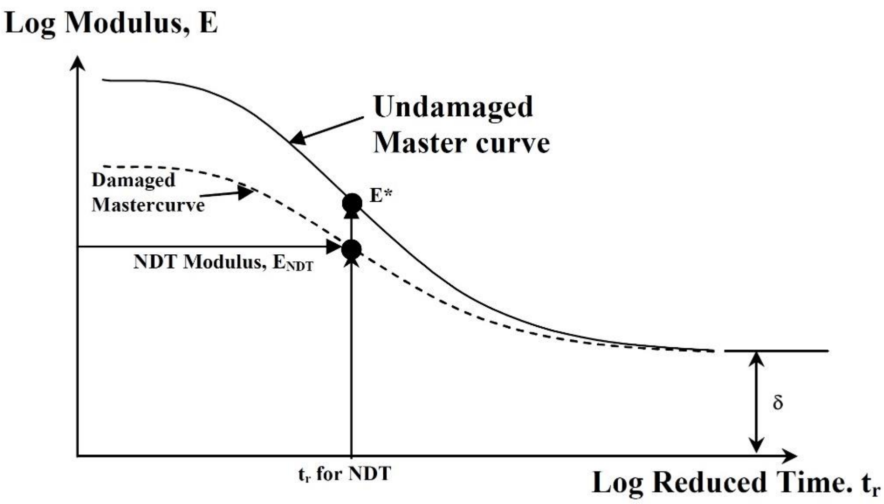

Figure 1. Asphalt layer damage computation, MEPDG Level-1 [5]

3. Experimental Work

Ten flexible pavement sites were selected in two provinces of Khuzestan and Kerman in south of Iran to determine in-situ dynamic modulus of asphalt layers. All these sites experience severe summer temperatures. Table 1 presents geographical and general climatic information of the testing pavement sites while Fig. 2 shows test locations.

Table 1. Geographical and general climatic information for selected locations

Province	Khuzestan	Kerman
City	Ahvaz	Sirjan
Coordinates	31°19′13″N	29°27′07″N
	48°40′09″E	55°40′53″E
Elevation (m)	17	1730
Daily Mean Temp. (°C)	25.4	17.4
Average High Temp. (°C)	33.0	25.3
Humidity (%)	43	35
Precipitation (mm)	160	228

Table 2 reports the general characteristics of the above pavement sites. These sites were selected from different roads in the above two provinces to include pavements that have different thicknesses, various numbers of layers, different ages and different types of base and subbase layers. As it can be seen in this table, there are two types of new and rehabilitated pavements that thicknesses of asphalt layers varies from 75 to 400 mm. The base and subbase layers are either granular or stabilized with emulsion (Site S05). Site S10 was on a bridge deck and had no base and subbase layers. In this site, 400 mm of asphalt layers were laid on the concrete bridge deck. Sites S09 and S10 had some 50-meter distance from each other. Hence, in these sites the asphalt mixes and pavement temperatures were the same, while thicknesses of their asphalt layers were different and one had no unbound layers. The ages of the pavement sites varied from 2 weeks to 25 years.

3.1. FWD Testing

In this work a Dynatest 8000 FWD device was used to apply loading on pavements and measure deflections at various locations. The test was conducted during July and August, 2014 period. In order to accurately determine field modulus values of various layers, four different stress levels were applied. More geophones were located near the center of loading plate in order to measure responses of asphalt layers more accurately. FWD testing and temperature measurements at each test site were conducted at half an hour intervals from 6:00 a.m. to 6:00 p.m. during a full working day. In addition, temperatures were measured at depths of d/2 and d/3 of asphalt layers (d is thickness of asphalt layer).

Figure 2. Location of pavement sites in provinces of Khuzestan (Left) and Kerman (Right)

Table 2. General characteristics of the pavement sites

Location	Site ID	Road Name	Pavement Type	Pavement Age	Total Thickness of Asphalt Layers (mm)	Thickness of Asphalt Sublayers (mm)				Total Thickness of Base and Subbase Layers (mm)	Binder Grade (Pen)	Type of Base & Subbase
						1	2	3	4			
Khuzestan	S01	Ahvaz - Shirin Shahr	New	New (2 weeks)	75	75	--	--	--	300	60/70	Granular
	S02	Ahvaz - Shush	New	4 Years	95	95	--	--	--	345	60/70	Granular
	S03	Ahvaz - Hamidiyeh (1)	New	5 Years	115	115	--	--	--	215	40/50	Granular
	S04	Ahvaz - Hamidiyeh (2)	Rehabilitated	10 Years	190	40	70	80	--	200	60/70	Granular
	S05	Ahvaz - Khorramshahr	Rehabilitated	25 Years	220	60	40	120	--	150	60/70	Stabilized
Kerman	S06	Sirjan - Baft	New	6 Months	120	60	60	--	--	250	60/70	Granular
	S07	Sirjan Expressway	New	1 Year	120	60	60	--	--	320	60/70	Granular
	S08	Sirjan - Shahr-e Babak	New Overlay	1 Year	145	45	50	50	--	305	60/70	Granular
	S09	Sirjan - Bandar Abbas (1)	Rehabilitated	15 Years	300	60	60	80	100	220	60/70	Granular
	S10	Sirjan - Bandar Abbas (2)	Rehabilitated	15 Years	400	60	60	80	200	Bridge Deck	60/70	Concrete

Figure 3. FWD testing and depth temperature measurements of asphalt layers

Air and surface temperatures were automatically recorded by FWD device every half an hour. Although temperature at various depths of asphalt layers can be predicted using some methods such as the temperature graph defined in AASHTO pavement design method [16] and the BELLS Model [17], however, in this work the temperatures were measured directly in pavements applying a drilling hole and using a digital thermometer. Fig. 3 shows a typical FWD testing site and the drilled holes for measuring temperature of asphalt layers. As it can be seen in this figure, FWD loading was conducted in outer wheel path with no cracking (according to the MEPDG instruction) and temperature measurements were taken just near the loading area.

3.2. Laboratory Mixture Volumetric Properties and Binder DSR Testing

Mix volumetric properties and binder viscosity characterization were used to estimate the undamaged dynamic modulus master curve using Witczak model. Core samples taken from the field were extracted and their binder were separated. Since some sample cores were made up of several asphalt layers, they were cut before extraction. Aggregate gradation was done and mix volumetric parameters were determined. In addition, DSR testing was conducted on the extracted binder. For accurate characterization of binder viscosity parameters, DSR testing was done at temperatures from 5 to 60ºC with 1ºC intervals and at a standard frequency of 1.59Hz (10 rad/s).

4. Results and Discussion

4.1. FWD Backcalculated Moduli

Backcalculated moduli of asphalt layers (considered as a single layer) were determined from FWD deflection data using ELMOD backcalculation software [18]. For this purpose, pavement was modeled as a three-layer system. With this context, the total asphalt layers are defined as the first layer having elastic behavior. The base and subbase layers are modeled as second layer (again having elastic behavior) and the subgrade is defined as third layer with infinite thickness and nonlinear elastic behavior. Due to the high temperature of areas, reference temperature was selected on 35ºC for constructing dynamic modulus master curves. The backcalculated moduli of asphalt layers in all tested sites at this temperature are presented in Table 3. In this table, maximum value of modulus belonged to Site S05 (site with stabilized base). The age of pavement in this site was higher than the others. Hence, the effects of aging and asphalt stiffening has been reflected on backcalculation modulus from FWD testing. Minimum value of modulus was attributed to Site S01 with 75 mm thickness of asphalt layer and age of only two weeks. In the other sites, different modulus values were achieved based on pavement deflection and layer thicknesses.

Table 3. FWD backcalculated modulus results

Pavement Site ID	Layer Depth Temperature (°C)	FWD Modulus (MPa)
S01	35	1425
S02	35	6112
S03	35	3948
S04	35	5688
S05	35	12430
S06	35	5150
S07	35	3633
S08	35	3994
S09	35	3134
S10	35	8023

4.2. Undamaged Dynamic Modulus Master Curves

Undamaged (predicted) dynamic modulus master curves were developed using Witczak model based on mix volumetric properties and binder viscosity parameters. Table 4 reports these volumetric properties and binder characterization values for all tested samples. Using the Witczak model along with the volumetric and binder properties from this table, Fig. 4 shows the predicted dynamic modulus master curves at the reference temperature of 35ºC for all pavement sites. As expected, for all frequencies the maximum predicted dynamic modulus values were obtained for Site S05, while minimum values were obtained for Site S01 due to their asphalt characteristics explained earlier.

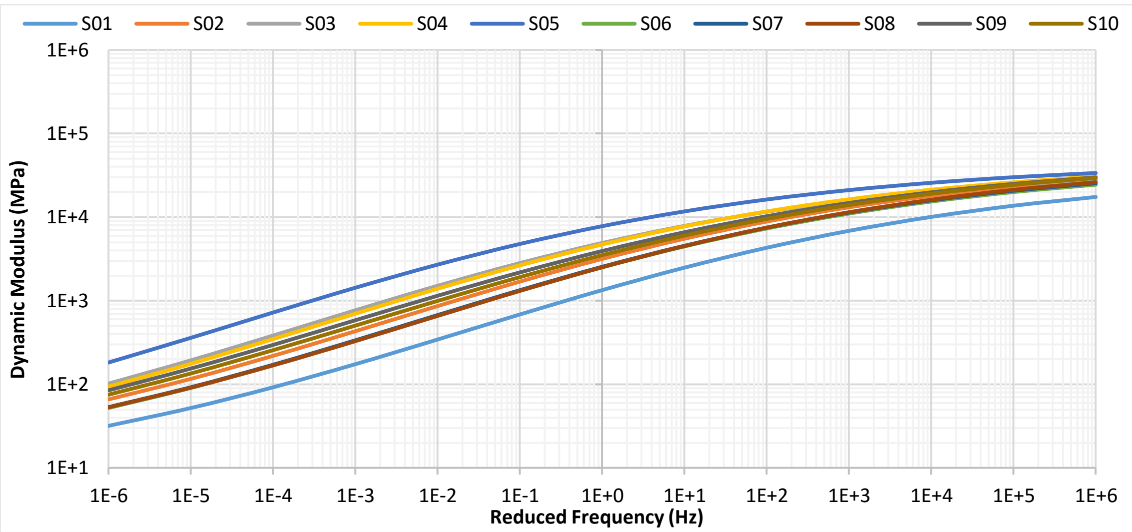

Figure 4. Undamaged (predicted) dynamic modulus master curves for all pavement sites

Table 4. Mix volumetric properties and asphalt binder viscosity parameters for all samples

Sample ID	Mix Volumetric Properties						Binder Viscosity Parameters	
	ρ_{200}	ρ_4	ρ_{38}	ρ_{34}	V_a	V_{beff}	A	VTS
S01L1	5.0	52.0	22.0	0.0	6.2	8.5	7.8108	-2.5217
S02L1	7.9	33.0	11.0	1.0	5.7	7.1	7.0816	-2.2418
S03L1	6.4	49.0	27.0	0.0	6.6	7.0	5.9842	-1.8270
S04L1	4.1	47.9	28.9	3.7	6.3	6.2	5.5108	-1.6526
S04L2	3.7	40.6	18.9	4.8	5.9	6.4	5.6345	-1.6993
S04L3	6.2	60.3	37.8	13.0	5.2	7.7	6.1744	-1.9060
S05L1	8.7	41.0	19.7	0.8	5.7	8.2	6.4522	-1.9826
S05L2	8.7	36.8	15.2	0.0	3.0	8.8	6.0357	-1.8300
S05L3	4.9	55.5	34.3	7.0	3.2	8.2	6.2332	-1.9116
S06L1	12.0	32.0	19.0	5.0	5.5	9.4	7.7897	-2.5004
S06L2	7.2	32.0	11.0	0.0	4.5	11.0	8.7667	-2.8616
S07L1	8.5	32.0	7.0	0.0	6.9	7.6	8.3994	-2.7266
S07L2	7.6	35.1	19.9	6.6	6.3	7.5	7.2200	-2.2918
S08L1	7.7	34.4	5.3	0.0	4.0	7.1	7.7827	-2.5041
S08L2	7.8	46.0	30.0	5.0	7.1	5.3	8.3506	-2.7099
S08L3	8.2	35.0	19.0	2.0	8.2	6.4	8.6255	-2.8089
S09L1	7.0	34.2	15.1	0.0	2.1	9.5	6.2579	-1.9171
S09L2	8.7	37.8	24.3	0.0	2.1	10.6	6.2400	-1.9175
S09L3	4.4	37.0	20.0	1.0	4.2	7.3	8.0928	-2.6159
S09L4	6.2	41.0	31.0	3.0	5.5	6.4	7.3857	-2.3610
S10L1	7.0	34.2	15.1	0.0	2.1	9.5	6.2579	-1.9171
S10L2	8.7	37.8	24.3	0.0	2.1	10.6	6.2400	-1.9175
S10L3	4.4	37.0	20.0	1.0	4.2	7.3	8.0928	-2.6159
S10L4	6.2	41.0	31.0	3.0	5.5	6.4	7.3857	-2.3610

Figure 5. Individual asphalt layers of core samples in Site S05

4.3. Damaged (In-Situ) Dynamic Modulus Master Curves

In order to develop damaged dynamic modulus master curve, damage factor should be computed. For this purpose, FWD modulus at the reference temperature and the corresponding predicted dynamic modulus value at the same temperature and frequency were used. Reference temperature was selected at 35°C and equivalent frequency of FWD was obtained from its loading time histories. An average loading time of 0.030s was considered and FWD frequency was calculated using Equation "$f_{FWD} = 1/2\Delta t$" [21] that resulted 16.67Hz.

Table 5 reports damage factor values for all pavement sites at MEPDG input level 1. In this table, some negative values show that damaged modulus obtained from FWD is greater than undamaged predicted modulus. This may cause from the effects of aging and asphalt stiffening in some mentioned testing sites and shows some need for modification of the procedure for determining the damage used by MEPDG.

After determination of the damage factors, damaged (in-situ) dynamic modulus master curves were developed for all pavement sites. Fig. 6 and Fig. 7 show damaged and undamaged master curves respectively for Site S01 a newly constructed pavement and Site S09 a rehabilitated one. It can be seen for Site S01, damaged dynamic modulus master curve is closer to undamaged one in low frequencies rather than high frequencies. In Site S09, a rehabilitated pavement, the same behavior of dynamic modulus master curves similar to newly constructed Site S01 was observed. These differences are greater in rehabilitated pavements rather than new constructed pavements. However, it can be seen a very good result by using this mechanistic-empirical method for computation of damage and then develop in-situ dynamic modulus master curve for in-service asphalt pavements. Damaged (in-situ) dynamic modulus master curves of asphalt layers for all pavements have been shown in Fig. 8 using this mechanistic-empirical approach.

Table 5. Damage computed for all pavements

Site ID	Damage factor, dj
S01	0.50
S02	0.01
S03	0.54
S04	0.33
S05	0.02
S06	-0.02
S07	0.34
S08	0.21
S09	0.57
S10	-0.20

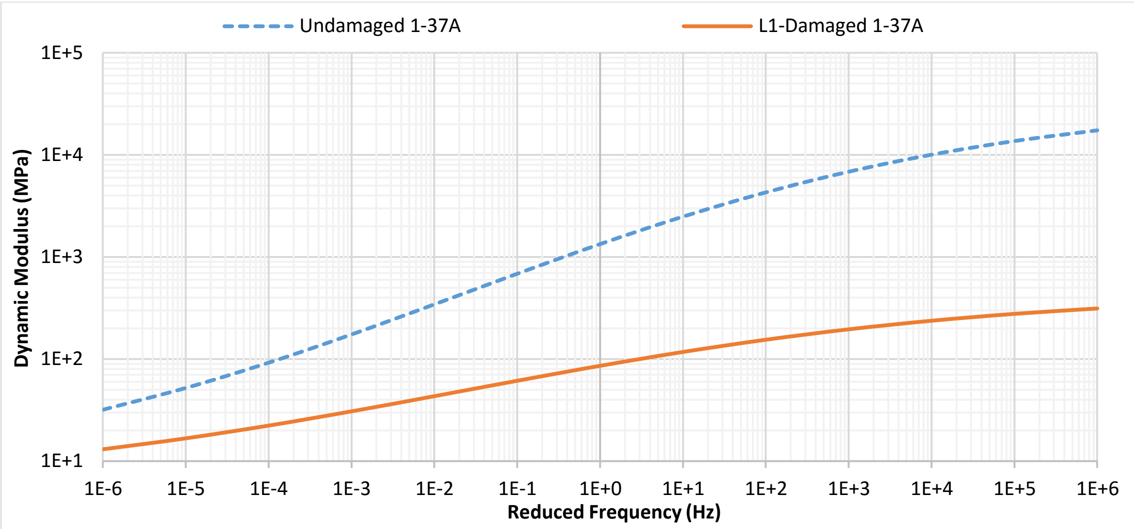

Figure 6. Damaged and undamaged dynamic modulus master curves: Site S01, a new pavement

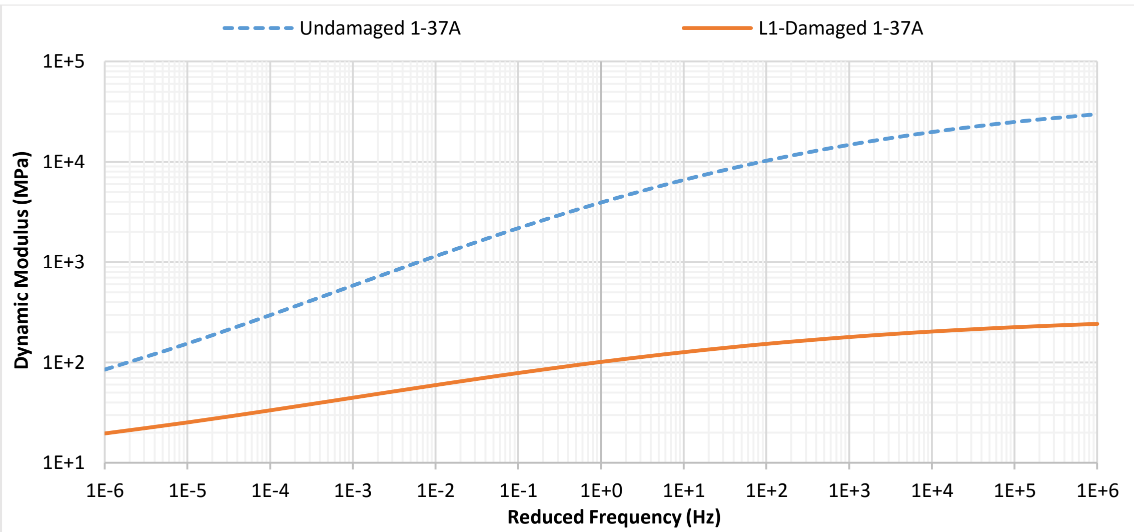

Figure 7. Damaged and undamaged dynamic modulus master curves: Site S09, a rehabilitated pavement

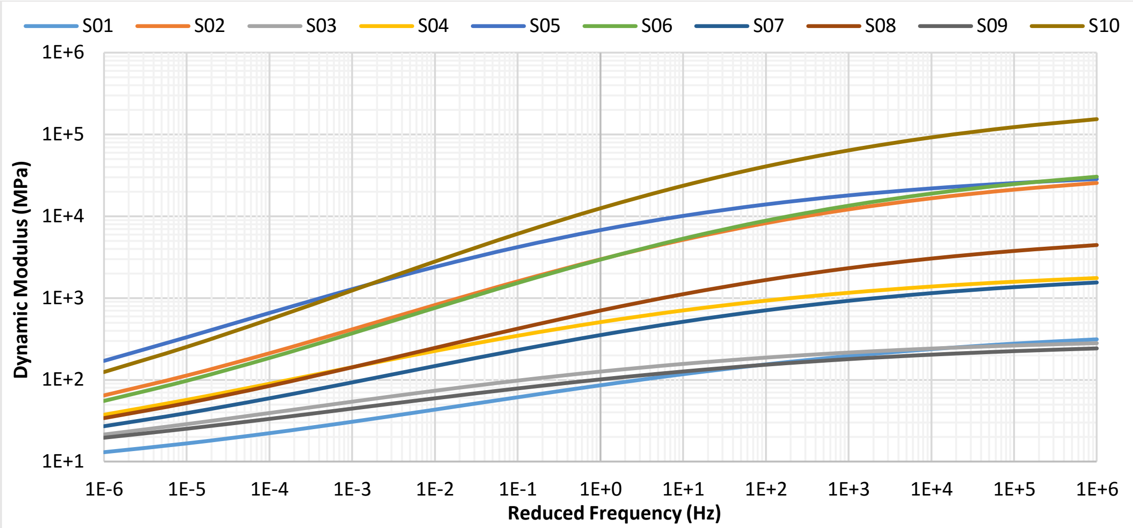

Figure 8. In-situ dynamic modulus master curves for all sites using mechanistic-empirical approach

5. Conclusions

Mechanistic-empirical methodology was adopted to develop dynamic modulus master curves of in-service asphalt layers. Following conclusions were achieved:

- Some verification should be done on MEPDG method in local implementation especially in severe hot climatic conditions like south of Iran.
- Some negative damage factor values showed that damaged modulus values obtained from FWD testing were greater than undamaged predicted values. This shows some need for modification of the procedure for determining the damage used by MEPDG.
- Damaged dynamic modulus master curve is closer to undamaged one in low frequencies rather than high frequencies. These differences are greater in rehabilitated pavements rather than new constructed pavements.
- Mechanistic-empirical approach was successfully applied in both new and rehabilitated in-service pavements by conducting a routinely FWD testing in severe environmental temperatures. This shows ability of implementation of the MEPDG method in structural evaluation for pavement rehabilitation projects in Iran and other countries which have similar severe climatic conditions.

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