Journal of Innovative Transportation, 2(1), 2102

Research Article

JOURNAL OF INNOVATIVE TRANSPORTATION

e-ISSN: 2717-8889

Comparison of dynamic elastisty modulus with different prediction approaches for Karaman – Konya highway pavement

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Highlights

- Mechanistic empirical design
- Pavement design
- Dynamic Elasticity Modules

Abstract

In pavement design and analysis processes among mechanistic-empirical pavement design method, defining the Dynamic Elasticity Modulus(E*) of asphalt layers are very important. In analysis processes, predicting the deteriorations and E* requires some special devices and a lot of time. To simplify this process different prediction models and different approaches have been developed to predict E*. These prediction approaches prepared with huge amount of input data gathered both from construction site and laboratory tests to predict the binder and the volumetric properties of the HMA. In this paper four prediction equations have been applied to predict E* and compared the results with each other. The infrastructure model has chosen as an existing highway section with known HMA material properties. The analyses have done for five different temperatures (10°F, 40°F, 70°F, 100°F and 130°F) by using two different frequency values (4Hz and 10 Hz). The aim of this research study is doing a comparative assessment of four widely used E* prediction models. Results have shown a large bias between compared E*prediction results due to temperature, frequency, and material properties. Higher Frequency and newest models have shown higher E* values.

Information

Received:
29.12.2020

Received in revised:
01.07.2021

Accepted:
01.07.2021

Keywords: *Pavement, dynamic elasticity modules, mechanistic empirical design.*

1. Introduction

The cost of highway infrastructure requires huge funding and maintenance. Also, there are so many predictions and uncertainties including design assumptions, laboratory tests, construction choices, maintenance strategies and result analyses during the lifecycle of an asphalt pavement infrastructure. This pressure leads governments to invent a systematic use of funding to most needed sector in infrastructure system at their regions [1,2].

Empirical methods such as AASHTO pavement design guides (AASHTO 1972, 1986, 1993) were valid in specific environment impact with limited material and loading conditions. But the AASHTO Joint Task Force on Pavements (JTFP) developed a pavement design procedure without these limitations [3-7].

There were alternative methods such as the finite element (FE) method for pavement design and analyses. The FE has been developed very quickly in past decades. Beside its widely usage, there are still some limitations in the FE methods. Complicated FE softwares, the need for time for training processes and simplifications of modeling demands exhausting efforts for pavement infrastructures modelling. Also, these softwares needs developments in computational speed both without increasing the resource requirement and without changing the computational accuracy [8,9].

But, at the workshop held in Irvine, California, in March 1996, JTFP announced the results of a long-term project. By this project mechanistic principles developed for the NCHRP Project 1-37A mechanistic-empirical design guide for design of new and rehabilitated pavement structures [6,7,10]. In NCHRP 1-37A, 2200 LTPP test section have

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https://doi.org/10.53635/jit.849544

observed in USA and completed the long-term tests in 2004 [10,11]. A mechanistic-empirical principle-based pavement design tool called 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG) have developed [12-14].

Also, a design software was obtained from this project which can analyze the pavement infrastructure to predict the pavement layer performances according to different sets of parameters (traffic, structure, and environment). [10,14,15]. Many design inputs are considering according to this complex pavement design procedures [16].

The MEPDG had three input levels and the dynamic modulus is a basic design input parameter for asphalt mixtures in pavement layers, which has the highest precision level, can be obtained through laboratory tests. The field performance of asphalt mixture is associated with the dynamic modulus test. This test complements the mix design properties in mechanistic-empirical pavement design (MEPD) [17]. However, numerous studies were established to develop default dynamic modulus values for various regions.

The hierarchical approach used in the AASHTO M-E design guide describes three levels for the determination of E* asphalt mixture values [10]:
– Level 1 requires direct measurement by laboratory or field testing of the dynamic modulus of asphalt mixtures.
– Level 2 suggests using the Witczak model with laboratory calculated binder stiffness or viscosity to estimate E* values.
– Level 3 also suggests that the Witczak model be used to predict E* values, but with the default binder properties defined in the M-E design guide for all binder grades [18].

There are several ways of obtaining the available Dynamic Elasticity Modulus(E*) for HMA mixtures. The most accurate one is by direct laboratory testing of HMA samples at various loading frequencies at various temperatures. However, laboratory testing is generally more expensive and time consuming than other methods [19].

2. Methodology

There are many research programmes about determining the mechanistic empirical behavior of asphalt pavements. Determination of the properties of asphalt layers are complex and challenging, because of mixtures visco-elasto-plastic and thermo-plastic properties. In this research four prediction models were used to find dynamic elasticity module property of same asphalt layer. Level 3 analysis have used for predictions and the results have compared with each other.

2.1. Witczak and Fonseca's E* prediction model in 1996

The accurate prediction of the E* of an asphalt mixture plays a critical role in the pavement design and its performance. The model developed by Fonseca and Witczak allows for the evaluation of dynamic elasticity modulus for a wide variety of asphalt mixtures/properties. This model also considers any degree of aging. Due to this model's sigmoidal mathematical structure, it can be used to predict the E* of the asphalt mixture at extreme climatic conditions for load associated distress. At the extreme climatic points, many other models are giving highly irrational results. The Witczak-Fonseca predictive model equation is shown in Equation 1. [20].

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

Tr = reduced loading time at reference temperature.

δ =minimum E* value,

δ + α = maximum E* value.

Witczak and Fonseca evaluated the reliability of the Dynamic Modulus of Elasticity estimation equation on a new database different from the one in which the model was calibrated. For developing this model various input data used within statistical principles. But there are also some limitations in this prediction equation shown in Equation 2 that only conventional asphalt cements have been used for developing and calibrating the model. As a result, the precision of the model in estimating the modified asphalt mixtures are unknown [20].

$$logE^* = \left[\begin{array}{c} -0{,}261+0{,}008225.p_{200}-0{,}00000101.(p_{200})^2 \\ +0{,}00196.p_4-0{,}03157.V_a-0{,}415.\left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ +\frac{1{,}87+0{,}002808.p_4+0{,}0000404.p_{38}-0{,}0001786.(p_{38})^2+0{,}0164.p_{34}}{1-e^{(-0{,}716.log(f)-0{,}7425.log(\eta))}} \end{array}\right] \quad (2)$$

Where the variables represent:

E	Asphalt Mix Dynamic Modulus, in 105 psi
F	Load frequency in Hz
η	Bitumen viscosity in 106 poise (at any temperature, degree of aging)
VBEFF	% effective bitumen content, by volume
VA	% air voids in the mix, by volume
P34	% retained on the ¾ inch sieve, by total aggregate weight (cumulative)
P38	% retained on the 3/8-inch sieve, by total aggregate weight (cumulative)
P4	% retained on the No. 4 sieve, by total aggregate weight (cumulative)
P200	% passing the No. 200 sieve, by total aggregate weight, [20,21]

2.2. Andrei, Witczak and Mirza's NCHRP 1-37A Revised model in 1999

Andrei, Witczak and Mirza's prediction model estimates the E* of the mixture for a wide range of temperatures and loading frequencies using volumetric property data of asphalt mixture. This model has been developed by using a very large database. This experimental prediction equation shown in Equation 3, uses a sigmoidal function due to binder stiffness as a function of viscosity for expected temperatures [22].

Viscosity tests performed in the laboratory can be more effective at high temperatures where the bitumen is fluid. The viscosity-temperature sensitivity (VTS) method allows to predict the viscosity of bitumen at various temperatures [22].

And this predicted VTS values can be used in E* predictions [22,23].

$$\log E^* = \left[\begin{array}{c} 3.750063+0.029232.p_{200}-0.001767.(p_{200})^2 \\ +0.002841.p_4-0.058097.V_a-0.802208.\left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ +\frac{3.871977-0.0021.p_4+0.003958.p_{38}-0.000017.(p_{38})^2+0.00547.p_{34}}{1+e^{(-0,603313-0,313351.\log(f)-0,393532.\log(\eta))}} \end{array}\right] \quad (3)$$

2.3. The Witczak's NCHRP 1-37A model in 2006

The model developed by Witczak 1-37A (2006) gives the estimated E * value for Level 2 and Level 3 input parameters in the ME Design software. The model has been implemented by using both modified and unmodified asphalt binders. This model is a sigmoidal function of the available parameters in the asphalt mixture. This model considers the binder viscosity (temperature dependent) and the volumetric data of the asphalt mixture as shown in Equation 4 [24].

Asphalt binder data is required for all three input levels. Tests performed on the asphalt binder are generally: viscosity dynamic shear rheometer (DSR) at different temperatures to assign the complex shear modulus and phase angle, low-temperature beam bending rheometer, penetration class and performance class. To determine viscosity-temperature relationship of an asphalt binder, laboratory test can be used according to ASTM D2493M-09 [24].

$$\log E^* = \left[\begin{array}{c} -1.249937+0.029232.p_{200}-0.001767.(p_{200})^2 \\ +0.002841.p_4-0.058097.V_a-0.802208.\left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ +\frac{3.871977-0.0021.p_4+0.003958.p_{38}-0.000017.(p_{38})^2+0.00547.p_{34}}{1+e^{(-0,603313-0,313351.\log(f)-0,393532.\log(\eta))}} \end{array}\right] \quad (4)$$

2.4. Georgouli Model in 2015

Georgouli et al. also enhanced a prediction model, which is similar to Witczak 1-37A model, for estimating the E* values accurately. Numerous nationally used asphalt base mixes were considered to develop the model shown in Equation 5. This model has been validated with high statistical precision for estimating the performance of local asphalt mixtures [25].

$$\log E^* = \left[\begin{array}{c} 3,9+3,7437.p_{200}-0,0298.(p_{200})^2 \\ -0,01221.p_4-0,08686.V_a-0,94215.\left(\frac{V_{beff}}{V_{beff}+V_a}\right) \\ +\frac{3,04483-0,01124.p_4+0,0024.p_{38}+0,00025.(p_{38})^2+0,00111.p_{34}}{1+e^{(-1,07682-0,47006.\log(f)-0,62593.\log(\eta))}} \end{array}\right] \quad (5)$$

3. Results and Discussion

Table 1 and Table 3 show the material parameters calculated according to the loading period of both 4 Hz and 10 Hz in a valid pavement infrastructure model on the highway section of 21 km, which is the 3rd part of the 715-05 highway between Cumra-Karaman cities.

Table 1. Model input parameters for the 4 Hz frequency of the selected highway on the Cumra-Karaman highway

Karaman	Cumra	15 km from Karaman city				Highway No	Part No	Length (km)
						715-06	3	21
Opening to traffic date						2015		
						Performance Grade	64	-40
Layer thicknesses			CBR	Mr (MPa)	Mr (Psi)	E*(MPa)	E*(psi)	f (Hz)
Surface		5 cm				7459,2	1081860	
Binder		6 cm				7309,4	1060143	4 Hz
Bituminious base		8 cm				7030,0	1019614	
Base		20 cm	188,6	307,6	44617	A-1-a		
Subbase		20 cm	188,6	307,6	44617	A-1-a		
Natural Subgrade		100 cm	25	112,0	16244	A-7-5		

Table 2. Model input parameters for the 10 Hz frequency of the selected highway section on the Cumra-Karaman highway

Karaman	Cumra		15 km from Karaman city			Highway No 715-06	Part No 3	Length (km) 21
Opening to traffic date							2015	
						Performance Grade	64	-40
Layer thicknesses			CBR	Mr (MPa)	Mr (Psi)	E*(MPa)	E*(psi)	f (Hz)
Surface		5 cm				8063,0	1169438	
Binder		6 cm				7901,0	1145940	10 Hz
Bituminious base		8 cm				7598,9	1102126	
Base		20 cm	188,6	307,6	44617	A-1-a		
Subbase		20 cm	188,6	307,6	44617	A-1-a		
Natural Subgrade		100 cm	25	112,0	16244	A-7-5		

The last layer of this highway section, which consists of six layers, was completed in 2015 and the highway was put into service. In the pavement model of this highway section, layer types and thicknesses, CBR values of surface, binder and bituminous base layers and aggregate gradation and bituminous binder test results of these layers were obtained from General Directorate of Highways regional directorate. By using these data, Mr values of base, subbase and natural subgrade and E* values of surface, binder and bituminous base layers were calculated.

Table 2 shows the data required for calculating the E * value from the material properties to be used in the analysis to be made for the Cumra-Karaman highway. In this table, in the top row, the parameters are considered for the BSK layers used in the pavement, and the values of these parameters are given in the following lines. These data are given separately from top to bottom for 4 Hz and 10 Hz loading, as in the same Table 3, including surface, binder and bituminous base. Table 4 shows the Pba and Pbe data required for calculating the E * value from the material properties to be used in the analysis to be made for the Cumra-Karaman highway and the material parameters used during the calculation of these data. In this table, you can write which parameters are considered in the top row, and the values of these parameters are given in the bottom lines. These data are given in order from top to bottom for 4 Hz loading, as in the same Table 1 and Table 3, including surface, binder, and bituminous base layers.

In Table 5, it is calculated according to four different formulas by using a valid highway pavement model on the highway section of 21 km, which is the 3rd segment of the highway section 715-05 between Cumra and Karaman cities, using 4 Hz loading periods at five different temperatures. E* values are shown. The values obtained by using the 70 Fahrenheit temperature value give the values closest to the values obtained from the basic curve. The E * values calculated for this temperature in the table give very similar results in all 4 formulas. In addition, as seen in the table, while E * modulus values are high at low temperatures in all 4 formulas, E * values decrease with increasing temperature.

In Table 6 E* values are shown, which calculated according to 4 different formulas by using a valid highway pavement model and using 10 Hz loading periods at 5 different temperatures on the highway section between Cumra-Karaman cities at 21 km in the 3rd zone of the highway section of 715-05.

The results obtained at 70 Fahrenheit temperature have given the values closest to the values obtained from the master curve. The E * values calculated for this temperature in the table give very similar results in all 4 formulas. In addition, as seen in the table, while E * modulus values are high at low temperatures in all 4 formulas, E* values decrease with increasing temperature. In addition, in 10F and 40 F temperatures the E* results have shown significant differences between models as seen in Table 5 and Table 6.

Table 3. Data required for E * calculation on the selected highway section on the Karaman-Cumra highway

ρ200	ρ4	ρ38	ρ34	Va	Vbeff	f	log(f)	A	VTS
5.4	48.4	82.6	100	3.56	74.7	4	0.60206	8.524	-2.798
4.5	42.8	61.4	91.1	4.46	68.1	4	0.60206	8.524	-2.798
4.1	38.6	54.8	81	4.93	63.7	4	0.60206	8.524	-2.798
5.4	48.4	82.6	100	3.56	74.7	10	1	8.524	-2.798
4.5	42.8	61.4	91.1	4.46	68.1	10	1	8.524	-2.798
4.1	38.6	54.8	81	4.93	63.7	10	1	8.524	-2.798

Table 4. Material parameters of the selected highway section on Karaman-Cumra highway

Pb Bitumen (%)	**Ps Aggregate (%)**	**Gb Bitumen specific gravity**	**Gse Mix. Effective specific gravity kgf/m3**	**Gsb Mix. Bulk Specific Gravity. kgf/m3**	**Air Void (%)**	**Gsa Mix. Apparent Specific Gravity. kgf/m3**	**Pba Absorbed aggregate by bitumen (%)**	**Pbe Effective. Binder ratio (%)**
4.9	95.1	1.033	2.693	2.666	4.04	2404	0.3885	4.5305
4.05	95.9	1.031	2.692	2.673	5.11	2404	0.2722	3.7887
4.05	95.9	1.031	2.692	2.673	5.11	2404	0.2722	3.7887

Table 5. E * results for 4 Hz for the selected highway section on Karaman-Cumra highway

Karaman Cumra highway		15 km from Karaman				
	Georgouli E*(MPa)	Witczak 1-37A E*(MPa)	Witczak 1999 E*(MPa)	Witczak 1996 E*(MPa)	Temperature	
Surface	11290,3	18200,5	17429,8	8035,531		
Binder	11062,5	16729,0	16032,2	7679,831	10 F	
Bituminious base	10639,3	16438,0	15757,7	7608,103		
Surface	9830,4	11591,6	11100,7	6885,897		
Binder	9632,4	10656,2	10212,4	6581,226	40 F	
Bituminious base	9264,0	10471,7	10038,4	6519,891		
Surface	7459,2	6454,7	6181,4	4874,912		4 Hz
Binder	7309,4	5935,1	5687,9	4659,437	70 F	
Bituminious base	7030,0	5833,0	5591,7	4616,224		
Surface	4811,5	3348,1	3206,3	2804,411		
Binder	4715,5	3079,4	2951,1	2680,656	100 F	
Bituminious base	4535,3	3026,8	2901,5	2655,988		
Surface	2711,0	1731,0	1657,7	1458,720		
Binder	2657,2	1592,5	1526,2	1394,472	130 F	
Bituminious base	2555,8	1565,5	1500,7	1381,759		

Table 6. E * results for 4 Hz for the selected highway section on Karaman-Cumra highway

Karaman Cumra		15 km from Karaman				
	Georgouli E*(MPa)	Witczak 1-37A E*(MPa)	Witczak 1999 E*(MPa)	Witczak 1996 E*(MPa)	Temperature	
Surface	11424,5	19239,4	18424,7	8153,079		
Binder	11193,9	17683,6	16947,0	7792,160	10 F	
Bituminious base	10765,7	17375,7	16656,6	7719,369		
Surface	10177,0	12820,0	12277,1	7245,878		
Binder	9972,0	11785,0	11294,2	6925,231	40 F	
Bituminious base	9590,5	11580,8	11101,5	6860,645		10 Hz
Surface	8063,0	7514,9	7196,7	5521,932		
Binder	7901,0	6909,6	6621,9	5277,769	70 F	
Bituminious base	7598,9	6790,6	6509,6	5228,735		
Surface	5533,8	4087,8	3914,7	3489,501		
Binder	5423,1	3759,4	3602,9	3335,414	100 F	
Bituminious base	5215,9	3695,1	3542,2	3304,626		
Surface	3339,2	2192,7	2099,8	1945,057		
Binder	3272,9	2017,0	1933,0	1859,317	130 F	
Bituminious base	3147,9	1982,7	1900,7	1842,296		

The results between Witczak 1999 model and Witczak 1-37A model have shown close results in every temperature. The results have shown increase in E* values from bottom to top between pavement layers in all models. The E* values between pavement layers become closer by the increase in temperature in all models.

For comparing the results for 70 F which is closer to normal weather conditions, surface and bituminous base results are more linear than binder layer at 4Hz frequency as seen in Figure 1, but at 10 Hz binder layer gives the most linear results as seen in Figure 2. In 4 Hz surface and bituminous base layer results showed similar linearity, but in Figure 2 bituminous base results gave more linear results than surface layer.

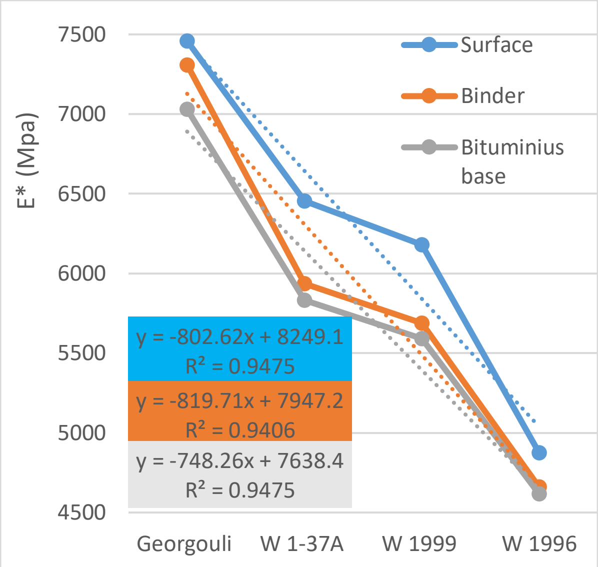

Figure 1. E * results for 70 F and 4 Hz on the selected highway section between Cumra-Karaman

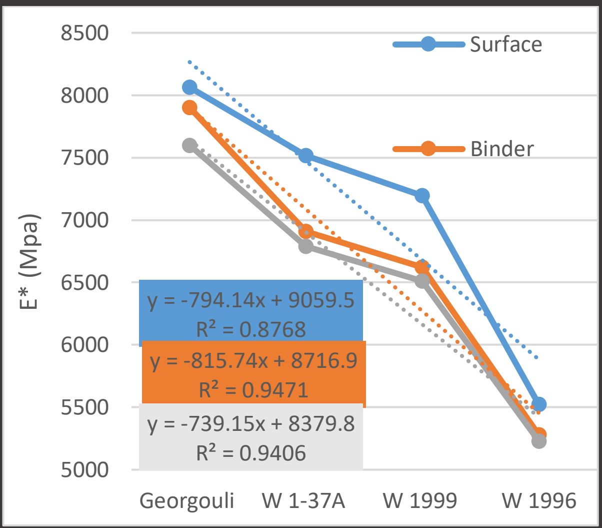

Figure 2. E * results for 70 F and 10 Hz on the selected highway section between Cumra-Karaman

4. Conclusion

This study has focused on the results of mechanistic empirical design prediction methods for a given highway section at 4Hz and 10 Hz frequencies. Four different equations have used for comparison of prediction approaches. And the following conclusions can be drawn from this paper.

The first prediction equation, which is developed by Witczak and Fonseca in 1996 has given the lowest Dynamic Elastic Modules results.

The second and third prediction equations of Witczak and his colleagues have given closer results to each other.

Between 1999 and 2006 models, there is not much change, so it can be said that consideration of more data can change the results for similar prediction equation to these equations. Higher frequency used in these prediction equations gives higher E* results.

As seen in Figure 1 and Figure 2, by the quality increase in material properties, the E* results from prediction models also increases.

The fourth equation gives the highest results and not very close to 2. and 3. equation results. This should because of the region selection, traffic inputs and the climatic condition consideration of the selected equation.

The results from Equations 1, 2 and 3 have risen comparing to age of invention. The newest model of the Witczak and his colleagues have given the highest results. This should be because of the consideration of the section wideness of all USA regions, climatic conditions, traffic loading changes and test results for all these huge amount of property inputs. While the more results have considered, higher accuracy can be obtained from these E* predictions.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution Statement

K. Armagan: Investigation, Methodology, Project Administration, Resources, Software, Visualization, Writing – Original Draft – **M. Saltan:** Supervision, Validation, Writing – Review & Editing – **S. Terzi**: Supervision, Validation, Writing – Review & Editing – **N. Kirac**: Supervision, Validation, Writing – Review & Editing

References

[1] Audu, H. A. P., Oghorodje, E. E., & Oviri, D. E. (2016). Sensitivity Analysis On Flexible Road Pavement Life Cycle Cost Model. *Nigerian Journal of Technology*, 35(2), 278-289. https://doi.org/10.4314/njt.v35i2.7

[2] Scheving, A. G. (2011), Life Cycle Cost Analysis of Asphalt and Concrete Pavements, Master of Science, School of Science and Engineering, Reykjavík University, Iceland.

[3] AASHTO. 1972. Interim Guide for the Design of Pavement Structures. American Association of State Highway and Transportation Officials.

[4] AASHTO. 1986. Guide for the Design of Pavement Structures. American Association of State Highway and Transportation Officials.

[5] AASHTO. 1993. Guide for the Design of Pavement Structures. American Association of State Highway and Transportation Officials.

[6] Guclu, A., Ceylan, H., Gopalakrishnan, K., & Kim, S. (2009). Sensitivity analysis of rigid pavement systems using the mechanistic-empirical design guide software. *Journal of Transportation Engineering*, 135(8), 555-562. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000036

[7] Shahji, S. (2006). Sensitivity Analysis of AASHTO's 2002 Flexible and rigid pavement design methods.

[8] Liu, P., Wang, D., & Oeser, M. (2015). Application of semi-analytical finite element method coupled with infinite element for analysis of asphalt pavement structural response. *Journal of Traffic and Transportation Engineering (English Edition)*, 2(1), 48-58. https://doi.org/10.1016/j.jtte.2015.01.005

[9] Liu, P., Wang, D., & Oeser, M. (2017). Application of semi-analytical finite element method to analyze asphalt pavement response under heavy traffic loads. Journal of traffic and transportation engineering (English edition), 4(2), 206-214. https://doi.org/10.1016/j.jtte.2017.03.003

[10] Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (NCHRP 1-37A), 2004.

[11] Li, X. Y., Zhang, R., Zhao, X., & Wang, H. N. (2014). Sensitivity analysis of flexible pavement parameters by mechanistic-empirical design guide. In Applied Mechanics and Materials, 590, 539-545. https://doi.org/10.4028/www.scientific.net/AMM.590.539

[12] 2002 Mechanistic-Empirical Pavement Design Guide (MEPDG), Federal Highway Administration, USA.

[13] Kannekanti, V., & Harvey, J. (2006). Sensitivity analysis of 2002 design guide rigid pavement distress prediction models.

[14] Nam Tran, P. E., Robbins, M. M., & Rodezno, C. (2017). Pavement ME Design–Impact of Local Calibration, Foundation Support, and Design and Reliability Thresholds.

[15] Zhang, C., Wang, H., You, Z., & Ma, B. (2015). Sensitivity analysis of longitudinal cracking on asphalt pavement using MEPDG in permafrost region. *Journal of Traffic and Transportation Engineering (English Edition),* 2(1), 40-47. https://doi.org/10.1016/j.jtte.2015.01.004

[16] Wu, Z., Yang, X., & Sun, X. (2017). Application of Monte Carlo filtering method in regional sensitivity analysis of AASHTOWare Pavement ME design. *Journal of traffic and transportation engineering (English edition),* 4(2), 185-197. https://doi.org/10.1016/j.jtte.2017.03.006

[17] Ali, Y., Irfan, M., Ahmed, S., Khanzada, S., & Mahmood, T. (2015). Sensitivity analysis of dynamic response and fatigue behaviour of various asphalt concrete mixtures. *Fatigue & Fracture of Engineering Materials & Structures*, 38(10), 1181-1193. https://doi.org/10.1111/ffe.12297

[18] Shu, X., & Huang, B. (2009). Predicting dynamic modulus of asphalt mixtures with differential method. *Road materials and pavement design*, 10(2), 337-359. https://doi.org/10.1080/14680629.2009.9690198

[19] Shu, X., & Huang, B. (2008). Dynamic modulus prediction of HMA mixtures based on the viscoelastic micromechanical model. *Journal of Materials in Civil Engineering*, 20(8), 530-538. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:8(530)

[20] Final Document Appendix CC-1, (2001), Correlation of CBR Values with Soil Index Properties, Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structures, NCHRP 1-37A.

[21] Marasteanu, M. O., Clyne, T. R., Li, X., & Skok, E. L. (2003). Dynamic and Resilient Modulus of Mn/DOT Asphalt Mixtures.

[22] Hou, H., Wang, T., Wu, S., Xue, Y., Tan, R., Chen, J., & Zhou, M. (2016). Investigation on the pavement performance of asphalt mixture based on predicted dynamic modulus. *Construction and Building Materials*, 106, 11-17. https://doi.org/10.1016/j.conbuildmat.2015.10.178

[23] Plati, C., Georgouli, K., & Loizos, A. (2013). Asphalt concrete stiffness modulus estimation utilizing an algorithm approach. In *Airfield and Highway Pavement 2013: Sustainable and Efficient Pavements* 1219-1228.

[24] M-E Pavement Design Manual, (2015), Colorado Department of Transportation.

[25] Georgouli, K., Plati, C., & Loizos, A. (2016). Assessment of dynamic modulus prediction models in fatigue cracking estimation. *Materials and Structures*, 49(12), 5007-5019. https://doi.org/10.1617/s11527-016-0840-6