An evaluation of Pavement ME Design dynamic modulus prediction model for asphalt mixes containing RAP

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ABSTRACT

Dynamic modulus is a measure of stiffness of an asphalt concrete (AC) mix when subjected to cyclic sinusoidal compressive stresses. In the AASHTOWare Pavement ME Design (ME Design) program, dynamic modulus (E*) value is an essential parameter for the prediction of asphalt pavement distresses such as rutting and fatigue cracking.

Several empirical models have been developed by researchers to estimate the E* from the asphalt mix properties when the laboratory measured E* values are unavailable. Witczack model has been integrated into the ME Design program to estimate the E* values when Level 2 and Level 3 inputs for AC mixes are used in the pavement analysis and design. Although Witczack model was developed based upon test data from a different combination of asphalt mixes, the representative data for AC mixes containing reclaimed asphalt pavement (RAP) was not adequate. The study presented in this paper examines the applicability of the Witczack E* prediction model to Manitoba AC mixes containing RAP.

For the analysis presented in this paper, asphalt mixes containing different amounts (varied from 0% to 50%) of RAP were prepared in the laboratory. Virgin aggregates and RAP sources remained the same for all mixes to minimize the variability in the laboratory measured E* values. The test for the E* was conducted on the prepared AC specimens at different temperatures and frequencies, E* master curve was then constructed for each AC mix. The developed master curve was compared with the Witczak prediction model. The analysis showed that for Level 2 AC inputs, the Witczak model underestimates the E* by 100% at high temperature but overestimates the E* by 50% at low temperature. For Level 3 AC inputs, Witczak model underestimated the E* by 30% to 70% at high temperature and overestimated the E* by 150% to 200% at low temperature. These indicate that Witczak model may not be appropriate for E* prediction for Manitoba AC mixes. For the use of the ME Design program in Manitoba, Level 1 inputs for Manitoba asphalt mixes may be required.

INTRODUCTION

Like many other highway agencies, Manitoba Infrastructure Transportation (MIT) is planning to implement the Mechanistic-Empirical Pavement Design Guide (MEPDG) software, currently called the AASHTOWare Pavement ME Design program, to advance the pavement design and analysis process.

Based upon the quality and quantity of the available data for each material properties, there are three levels of input options in the Pavement ME Design program [1]. Level 1 input option generally requires site specific material properties data which are obtained through laboratory or field testing. These data have the highest level of accuracy and is expected to provide the most reliable design and analysis. Level 2 inputs have the intermediate level of accuracy. These input data are generally obtained through limited laboratory or field testing or estimated from the correlations with other measured properties. Level 3 inputs have the lowest level of accuracy since the typical agency data or software default data are used [2].

The dynamic modulus (E*) of the AC mix is used to predict AC pavement distresses such as rutting and fatigue cracking in all three input levels. In the Level 1 inputs for the AC mix, the dynamic modulus measured in the laboratory in accordance to the AASHTO T342 test method is required [3]. This test is usually conducted at five different temperatures and six different frequencies. The test starts at a low temperature and high frequency and ends at a high temperature and low frequency to consider possible range of temperature and traffic speed which an in-service pavement AC mix is expected to experience. Although the Level 1 inputs for the AC mix provide more reliable results than the Level 2 and Level 3 inputs, the comprehensive laboratory testing required to obtain them is time consuming and expensive. When the Level 1 inputs for the AC mix cannot be obtained because of the unavailability of the equipment and/or limitation in time and budget, dynamic modulus can be estimated from correlations with other properties of the AC mixes [4]. The Witczak model has been incorporated into the Pavement ME Design program to estimate the E* when Level 2 and Level 3 inputs for asphalt mix and asphalt binder are used in the design and analysis.

RELEVANT PAST STUDIES

The accuracy of the estimated E* from the Witczak model was evaluated by several researchers [5-7]. Clyne et. al. [6] found that Witczak model provides fairly accurate estimate of the dynamic modulus values at intermediate temperatures. However, the estimated dynamic modulus values at high temperatures were shown to be lower than those obtained through the laboratory testing. Kim [7] also found that the estimated E* from the Witczak model show a better fit with the measured values at the low temperature than at the high temperature. Yu and Williams [8] assessed the influence of recycled asphalt shingles (RAS) in the AC mix on the E*. The authors found that RAS can significantly influence the E* values. The Witczak model was found not to be very efficient in the estimation of E* for AC mixes containing RAS [8]. Studies in Idaho, Arizona and Argentina showed that Witczak model is relatively accurate in estimating the E*[9-12].

OBJECTIVES AND SIGNIFICANCE

The objectives of the study presented in this paper are: 1) to investigate the applicability of the Pavement ME Design program default model (Witczak model) for estimating the dynamic modulus to Manitoba AC mixes containing RAP, and 2) to provide an estimate of the difference in dynamic modulus values between the ME Design model and the laboratory for each of these AC mixes. The analysis presented in this paper will provide an understanding of the need for Level 1 i.e., laboratory determined dynamic modulus data for these special mixes. The laboratory determined dynamic modulus is also expected to be useful in the design and analysis of pavement using the ME Design program for asphalt mix containing RAP.

DESCRIPTION OF INVESTIGATED AC MIXES

MIT has been conducting various tests on asphalt mixes and asphalt binders that are being used in the construction and rehabilitation of provincial highways and roads in order to develop a comprehensive database. These include laboratory tests on samples 1) extracted by coring from asphalt pavements, 2) prepared in the laboratory using loose mixes collected from the project site during the paving operation and 3) prepared in the laboratory using the laboratory prepared asphalt mixes. For the analysis presented in this paper, the dynamic modulus tests were conducted on the laboratory prepared samples using loose asphalt mixes collected from Provincial Trunk Highway (PTH) 8 located at 100 km north of Winnipeg, Manitoba. The testing was performed by the Pavement Research Group at the University of Manitoba. Asphalt mixes containing different amounts of RAP (0% to 50%) were compacted using a Gyratory compactor. Specimens for the dynamic modulus testing were then prepared from the gyratory compacted samples. Three AC mixes that were tested and analyzed in this study are: 1) MIT-0, 2) MIT-10, and 3) MIT-50. MIT-0, MIT-10 and MIT-50 contain 0% RAP, 10% RAP, and 50% RAP by weight of the total mix, respectively. All the mixes contained PG 58-28 (Pen 150-200 grade) virgin binder. The aggregate gradation and volumetric properties of design asphalt mixes are summarized in Table 1. Figure 1 graphically shows the variation in aggregate gradation of the AC mixes included in this study.

Table 1: Volumetric properties and aggregate gradations of asphalt mixes

	Mix ID		
Properties	**MIT-0 (0% RAP)**	**MIT-10 (10% RAP)**	**MIT- 50 (50%RAP)**
V_a, %	2.7	3.7	3.6
VMA, %	13.3	14.1	12.3
VFA, %	79.6	73.6	70.9
G_{mm}	2.484	2.486	2.520
AC Binder, %	5.3	5.4	5.3
Aggregate gradation	Percentage Passing		
19 mm (3/4")	100	100	100
16 mm (5/8")	98.6	96.8	98.8
12.5 mm (1/2")	91.5	90.9	93.8
9.5 mm (3/8")	81.3	80.9	84
4.75 mm (#4)	60.3	62.4	67.4
2.00 mm (#10)	45.7	47.5	51.4
0.425 mm (#40)	28	28.3	27.9
0.18 mm (#80)	8.1	8.6	9.9
0.075 μm (#200)	5.3	5.7	6.8

V_a = percent air voids; VMA= voids in minerak aggregates; VFA= voids filled with binder; G_{mm}= maximum theoretical spesific gravity; AC binder= total AC binder in the mix

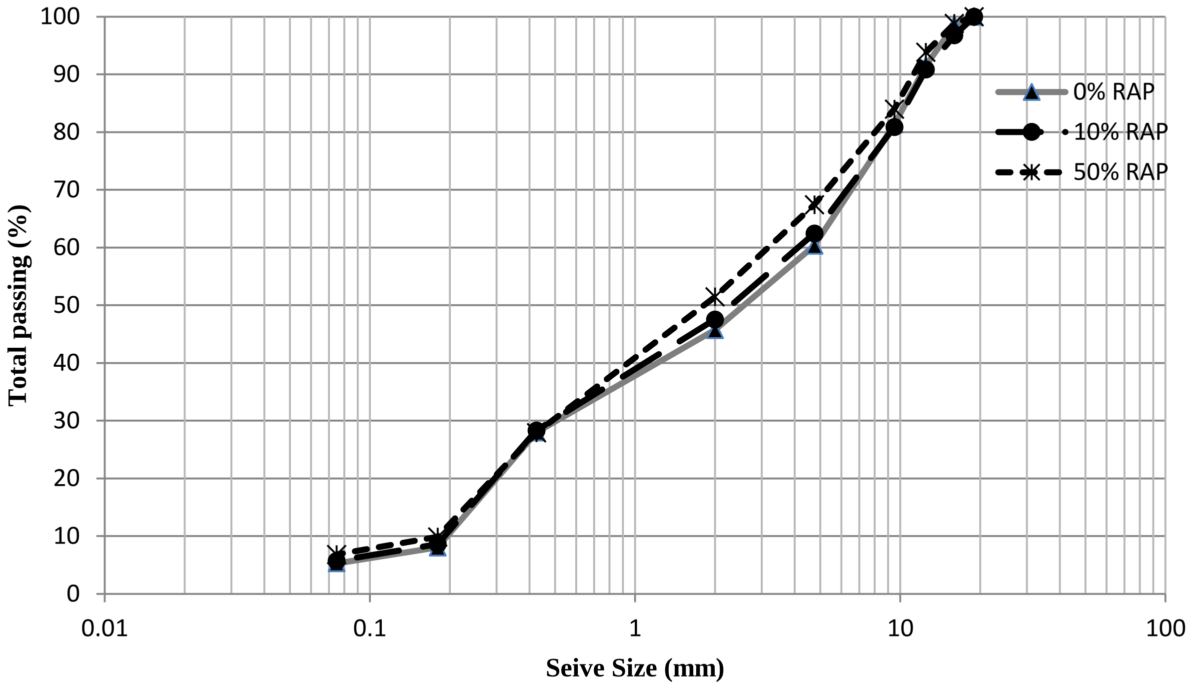


Figure 1: Aggregate gradation of the AC mixes

ESTIMATING DYNAMIC MODULUS USING THE WITCZAK MODELS

The model developed by Witczak provides the estimate of the E* when Level 2 and Level 3 asphalt mix and binder data are entered in the ME Design program. This model was developed based upon many dynamic modulus data points from asphalt mixes containing unmodified asphalt binders and AC mixes containing modified asphalt binder. The Witczak model is a sigmoid function of inputs for the AC mix. It is constructed based upon asphalt binder viscosity (which is dependent on temperature) and asphalt mix volumetric properties [1]. Equation 1 shows the Witczak model.

$$\mathrm{Log}_{10} E^* = -1.249937+0.02923\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\,\rho_4 - 0.058097V_a -$$

$$0.802208\frac{V_{beff}}{V_{beff}+V_a} + \frac{3.871977-0.0021\rho_4+0.003958\,\rho_{38}-0.000017(\rho_{38})^2+0.00547\rho_{34}}{1+e^{(-0.603313-0.313351(\log f)-0.393532(\log\eta))}} \qquad (1)$$

Where:

E* = dynamic modulus of the mix, Psi.

η = bitumen (asphalt binder) viscosity, 10^6 Poise.

f = loading frequency, Hz.,

V_a = air voids content, %.

V_{beff} = effective bitumen content, % by volume.

ρ_{34} = cumulative % retained on the 3/4 in. (19 mm) sieve.

ρ_{38} = cumulative % retained on the 3/8 in. (9.5 mm) sieve.

ρ_4 = cumulative % retained on the #4 sieve.

ρ_{200} = % passing the #200 sieve.

For all three input levels, asphalt binder data is required. The asphalt binder tests usually are: viscosity dynamic shear rehometer (DSR) at various temperatures (after short-term and long-term aging) to determine the complex shear modulus and phase angle, bending beam rehometer at low temperature, penetration grade and performance grade. The binder test data is used to determine the viscosity at any temperature using viscosity-temperature relationship recommended by ASTM [13]. The linear regression is performed to obtain the regression parameters in Equation 2.

$$\log \log \eta = A + VTS \log T_R \qquad (2)$$

Where

η = binder viscosity, cP.

T_R = temperature, Rankine.

A = regression intercept.

VTS = regression slope of viscosity temperature susceptibility.

For the Level 1 inputs, the complex shear modulus and phase angle of the asphalt binder at different temperatures are required (when the SuperPave Binder System is selected). The following equation (Equation 3) is used to compute the viscosity of asphalt binder at different temperatures.

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

Where

G^* = complex shear modulus, Pa.

δ = phase angle, degrees.

η = binder viscosity, cP.

It should be noted that in Level 2 inputs for asphalt concrete mixes, Level 1 binder test data and volumetric properties of asphalt mixes (same as Level 3 inputs) are required.

In the Level 3 inputs, the default value of VTS and A parameters are used to calculate the viscosity of the selected asphalt binder grade (penetration or performance grade). Table 2 shows the default VTS and A parameters for the SuperPave Performance Grade (PG) asphalt binders [1].

Table 2: Default VTS and A parameters based on asphalt PG grade [1]

High Temperature Grade	**Low Temperature Grade**									
	-10		-16		-22		-28		-34	
	VTS	**A**	**VTS**	**A**	**VTS**	**A**	**VTS**	**A**	**VTS**	**A**
52	-4.570	13.386	-4.541	13.305	-4.342	12.755	-4.012	11.840	-3.602	10.707
58	-4.172	12.316	-4.147	12.248	-3.981	11.787	-3.701	11.010	-3.350	10.035
64	-3.842	10.690	-3.822	11.375	-3.680	10.980	-3.44	10.312	-3.134	9.461
70	-3.566	10.059	-3.548	10.641	-3.426	10.299	-3.217	9.715	-2.948	8.965

Table 3 shows the performance grades of the asphalt binders for the three asphalt mixes that were used in this study. 150-200 penetration (PG 58-28) grade virgin asphalt binder was used for all three asphalt mixes. As shown on the table, 10% RAP was not sufficient to change the PG grade of the combined binder (virgin binder plus binder from the RAP). However, the high temperature performance grade of the combined binder was one grade higher while the low temperature performance grade was two grades higher for the MIT-50 mix compared to the MIT-0 mix. The VTS and A parameters for the PG 58-28 binder are -3.701 and 11.010, respectively. These parameters are -3.822 and 11.375, respectively, for the PG 64-16 binder (Table 2).

Table 3: Performance grade of extracted binders for the tested AC mixes

Mix type	**RAP %**	**Virgin binder pen. grade**	**Extracted binder performance grade**
MIT-0	0	150/200	58-28[1]
MIT-10	10	150/200	58-28[1]
MIT-50	50	150/200	64-16[1]

[1] (Hajj, E.Y., et al., 2011)

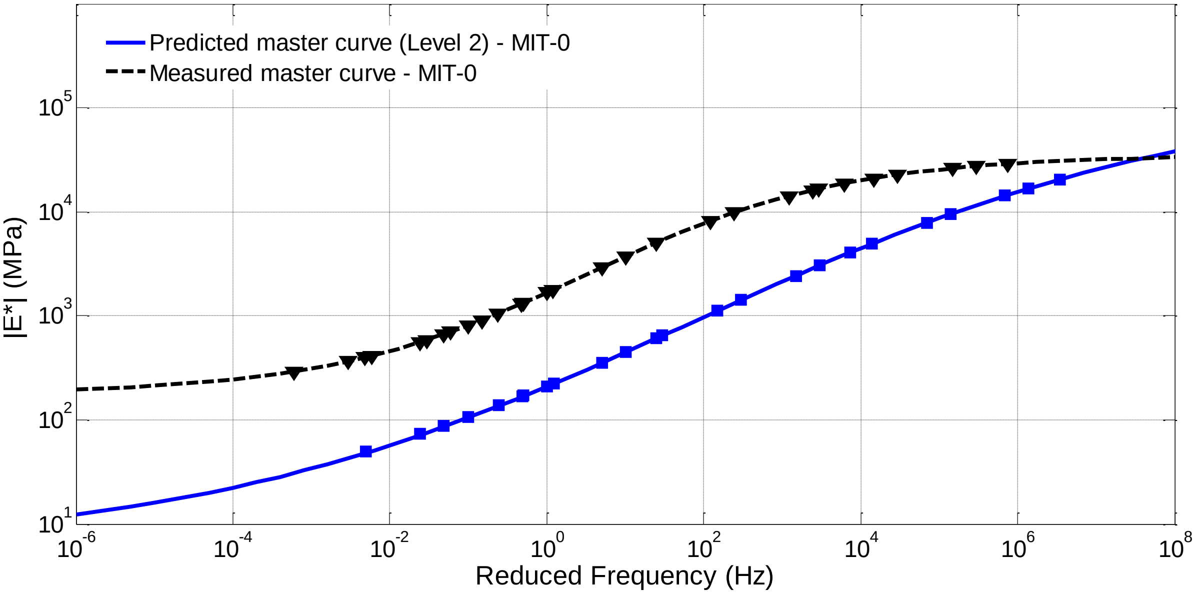
For the Level 2 inputs, VTS and A were calculated using Equation 3. The viscosity-temperature parameters for Level 2 and Level 3 inputs are summarized in Table 4. As shown on the table, lower VTS and higher A values were obtained for Level 2 inputs than the default (Level 3) values in the ME Design program. Table 4 also shows no or small differences in VTS and A parameters between MIT-0, MIT-10 and MIT-50 mixes for the Level 3 inputs. This reflects a very low accuracy of the inputs at level 3 for these mixes.

Table 4: Selected VTS and A parameters for AC mixes containing RAP

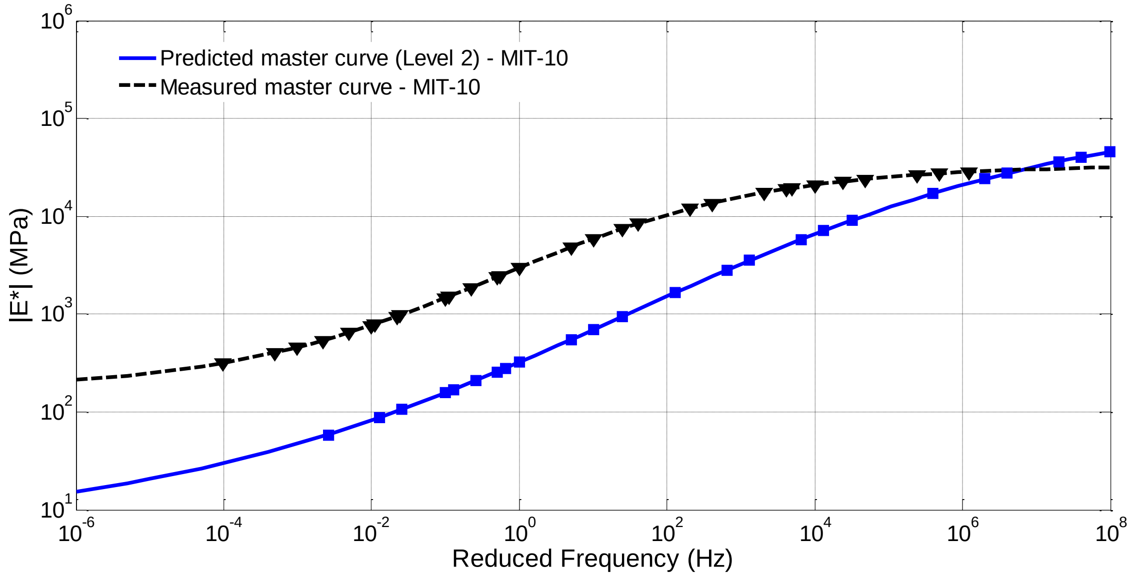
	Level 2		Level 3	
Asphalt mixes	**VTS**	**A**	**VTS**	**A**
MIT-0	-4.8405	13.906	-3.701	11.010
MIT-10	-5.4616	15.639	-3.701	11.010
MIT-50	-5.6257	16.103	-3.822	11.375

RESULTS AND ANALYSIS

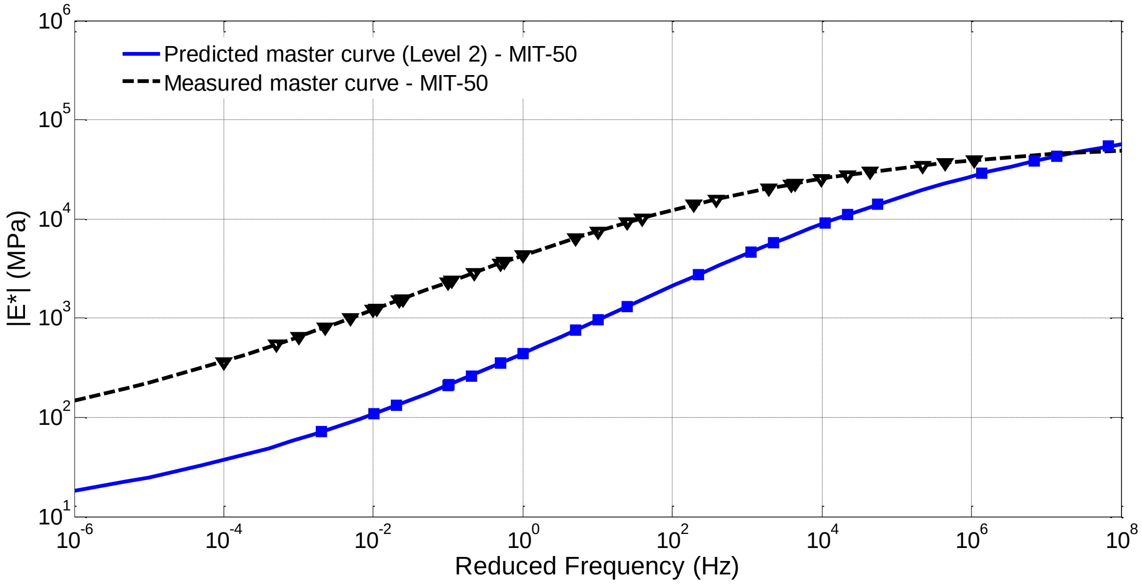
Dynamic modulus was estimated using the Witczak model for Level 2 and Level 3 inputs for all three asphalt mixes. Figure 2 and Figure 3 show the comparison between the master curves for the measured and estimated (predicted) E* values for Level 2 and Level 3 inputs, respectively. Figure 2 shows a slight difference between the measured and Level 2 predicted E* values at low temperature (high frequency) and a significant difference between the measured and Level 2 predicted E* values at high temperature (low frequency) for all three RAP contents. Figure 3 shows that regardless of the amounts of RAP in the AC mixes, Witczak model in Level 3 tends to over predict the E* value at high frequency or low temperature for Level 3 inputs. In Level 3, Witczak model produces lower dynamic modulus values at low frequency or high temperature as compared to the measured values.



a) Mix containing 0% RAP



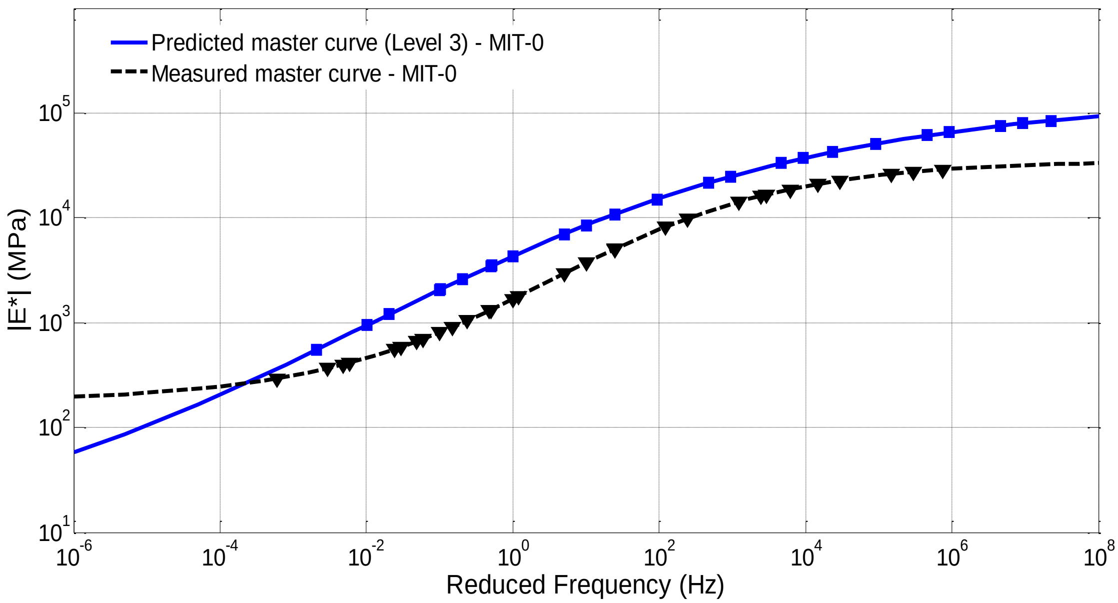
b) Mix containing 10% RAP



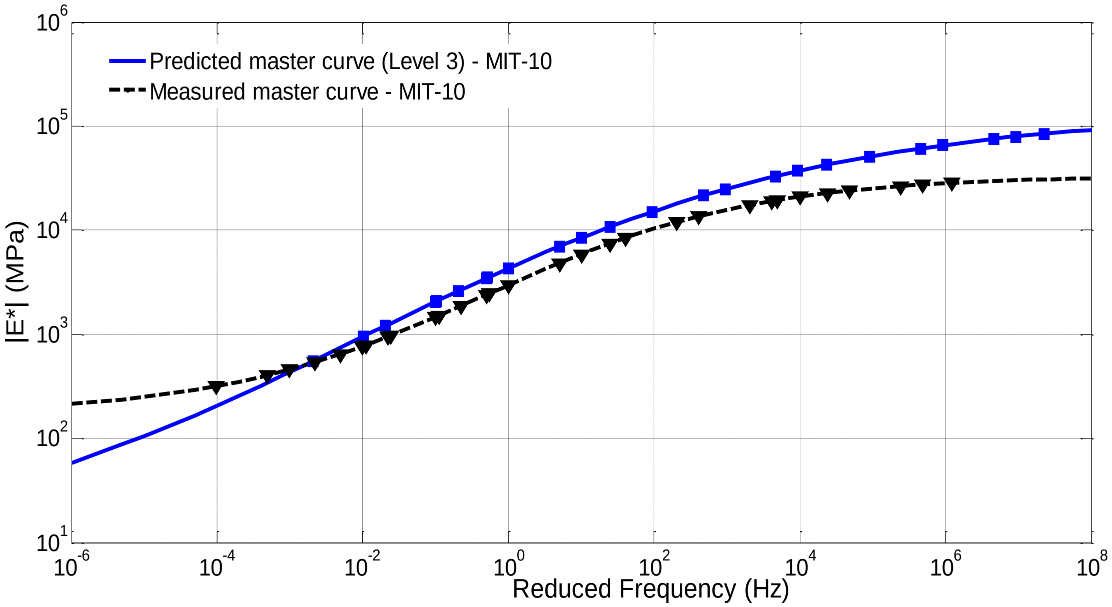
c) Mix containing 50% RAP

**MIT-0 mix contains 0% RAP, MIT-10 mix contains 10% RAP, MIT-50 mix contains 50% RAP*

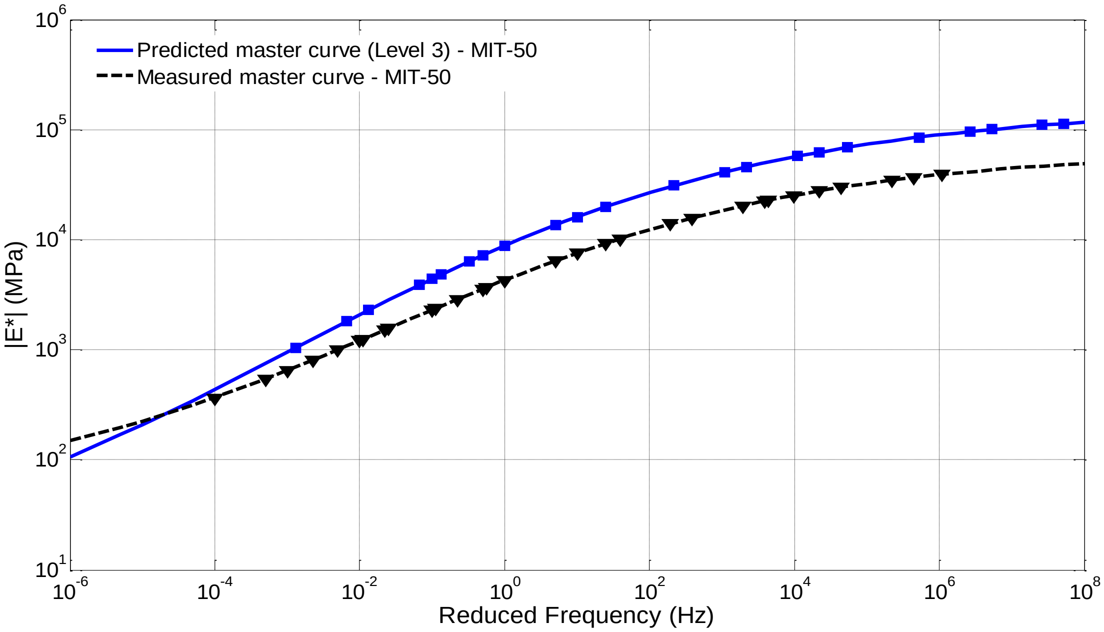
Figure 2: Comparison of measured E* and Witczak model (Level 2) master curves for different asphalt mixes.



a) Mix containing 0% RAP



b) Mix containing 10% RAP

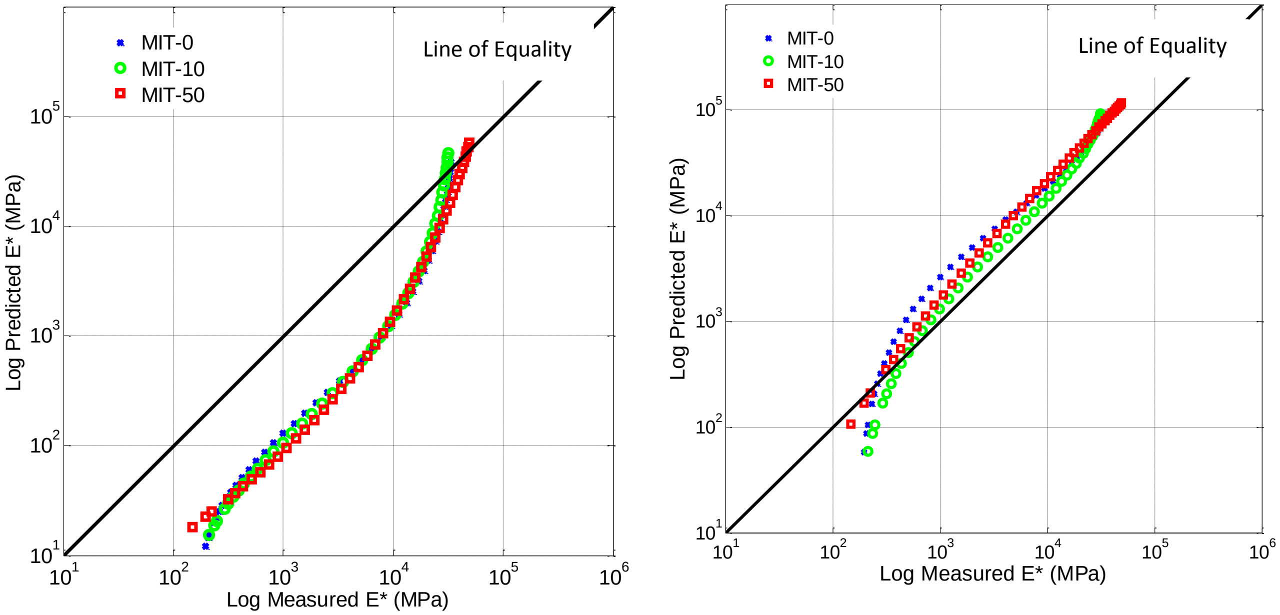


c) Mix containing 50% RAP

**MIT-0 mix contains 0% RAP, MIT-10 mix contains 10% RAP, MIT-50 mix contains 50% RAP.*

Figure 3: Comparison of measured E* and Witczak model (Level 3) master curves for different asphalt mixes.

Figure 4 shows comparison of the laboratory measured and the estimated dynamic modulus values from the Witczak model for Level 2 and Level 3 inputs. The goodness of fit between the estimated and measured E* values was evaluated with reference to the line of equality. Statistical parameters such as the R^2 values, the standard error of predicted dynamic modulus (S_e) and the standard deviation of the measured dynamic modulus (S_y) were calculated.



a) Level 2 Inputs b) Level 3 Inputs

**MIT-0 mix contains 0% RAP, MIT-10 mix contains 10% RAP, MIT-50 mix contains 50% RAP*

Figure 4: Fitness between the Witczak model predicted E* values for Level 2 and Level 3 inputs and the measured E* values.

The S_e/S_y and R^2 are used as indicators for model accuracy. The R^2 value indicates strength of the correlation (goodness of model fit) between measured E* and predicted E*. The S_e/S_y indicates the relative improvement in model accuracy. Higher R^2 and lower S_e / S_y show higher accuracy in the fitness of the model. Table 5 shows the statistical criteria of correlation between measured value and predicted value [11]. Table 6 shows the statistical evaluation of the Witczak model.

The results of the statistical analysis show that the accuracy of the Witczak model prediction is “very poor” at Level 2 and “good” at Level 3. The possible reason for this noticeable difference in accuracy between two Levels is the viscosity of the asphalt binders. At Level 2, viscosity of the asphalt binders was found to be very different from the default (Level 3) values. This indicates that changes in the binder grade and viscosities have significant influence on the predicted E*.

Table 5: Statistical criteria for correlation between measured value and predicted value [11]

Criteria	**R^2**	**S_e / S_y**
Excellent	≥0.9	≤0.35
Good	0.70-0.89	0.36-0.55
Fair	0.40-0.69	0.56-0.75
Poor	0.20-0.39	0.76-0.90
Very poor	≤0.19	≥0.90

**R^2 and S_e / S_y: goodness of fit*

The R^2 values for the correlation between the measured E* and the predicted E* at Level 2 were found to be close to zero for MIT-10 and very low for MIT-0 and MIT- 50 mixes. This indicates that Witczak model is unable to provide a reasonable estimate of the E* values for Manitoba AC mixes. The correlation between the measured E* and the predicted E* at Level 3 showed good R^2 values for all three AC mixes. However, such good correlation does not mean that the E* can be predicted accurately using the Witczak model for the Level 3 inputs (see further discussion below).

Table 6: Statistical evaluation of the Witczak model

	Level 2		Level 3	
Asphalt mixes	R^2	S_e / S_y	R^2	S_e / S_y
MIT-0	0.112	0.993	0.847	0.409
MIT-10	0.001	1.001	0.875	0.365
MIT-50	0.082	1.009	0.860	0.392

*R^2 and S_e / S_y: goodness of fit

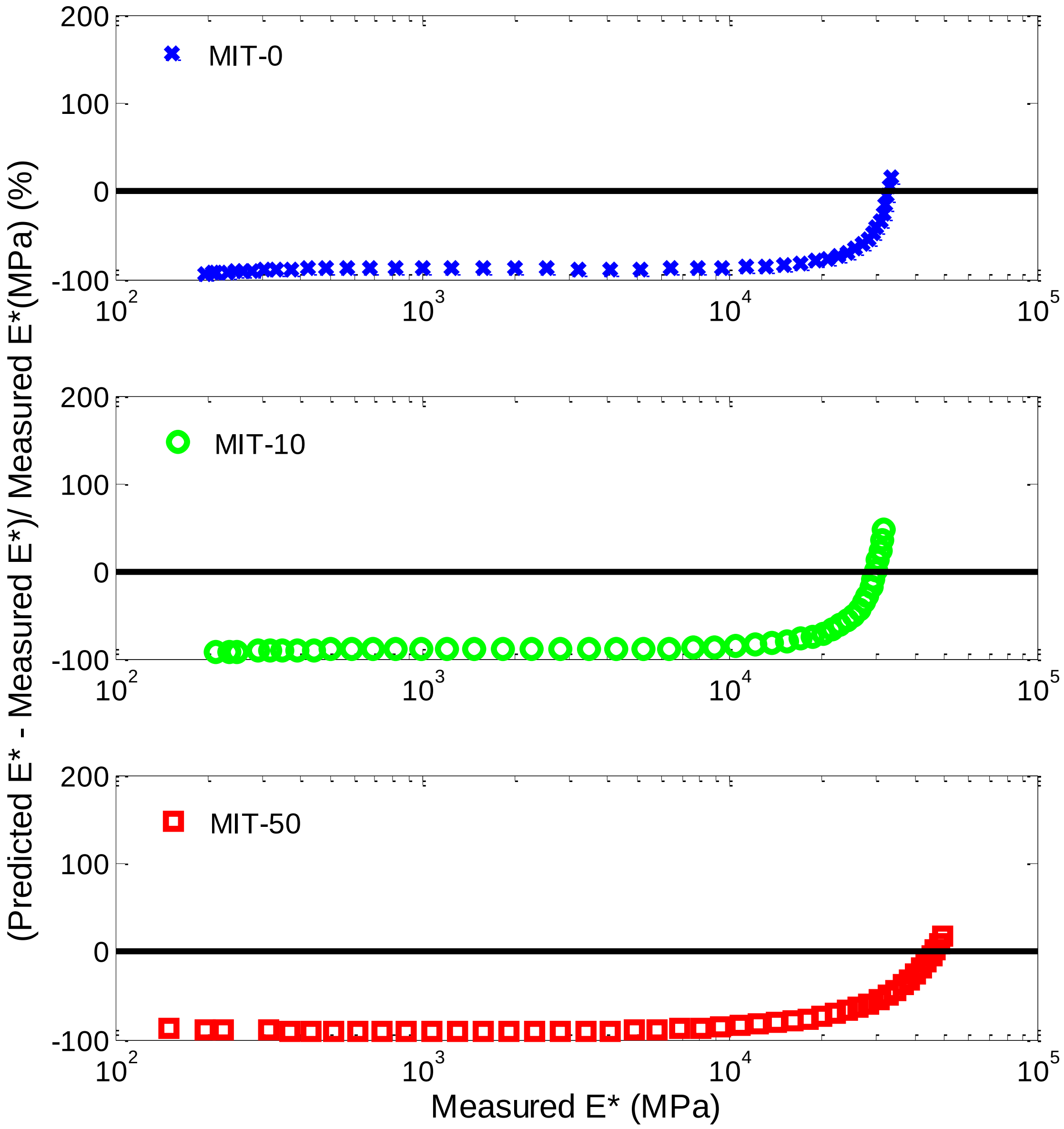
In order to quantify the perdition error, the difference between the measured and predicted E* values was calculated and presented as a percentage of the measured E* value for each mix. Figure 5 shows the prediction error for all the asphalt mixes included in this study. As shown on the figures, the prediction errors for both Level 2 and Level 3 inputs are negative at high temperature (low E*). This means that the Witczak model underestimated the E* at high temperature. The value of dynamic modulus at high temperature is crucial since it has a direct influence on the rutting performance of the AC mix. At high temperature, asphalt binder becomes soft and prone to rutting. Therefore, a high E* at high temperature is desirable for good rutting resistance. Underestimating the E* at high temperature means underestimating the rut resistance of the mix.

For the Level 2 inputs, Witczak model showed up to 100% underestimation of the E* values (i.e., the predicted E* values were approximately 50% of the measured E* values) at high temperature for all the AC mixes. At low temperature, this model showed up to 50% overestimation of the E* values for the Level 2 inputs.

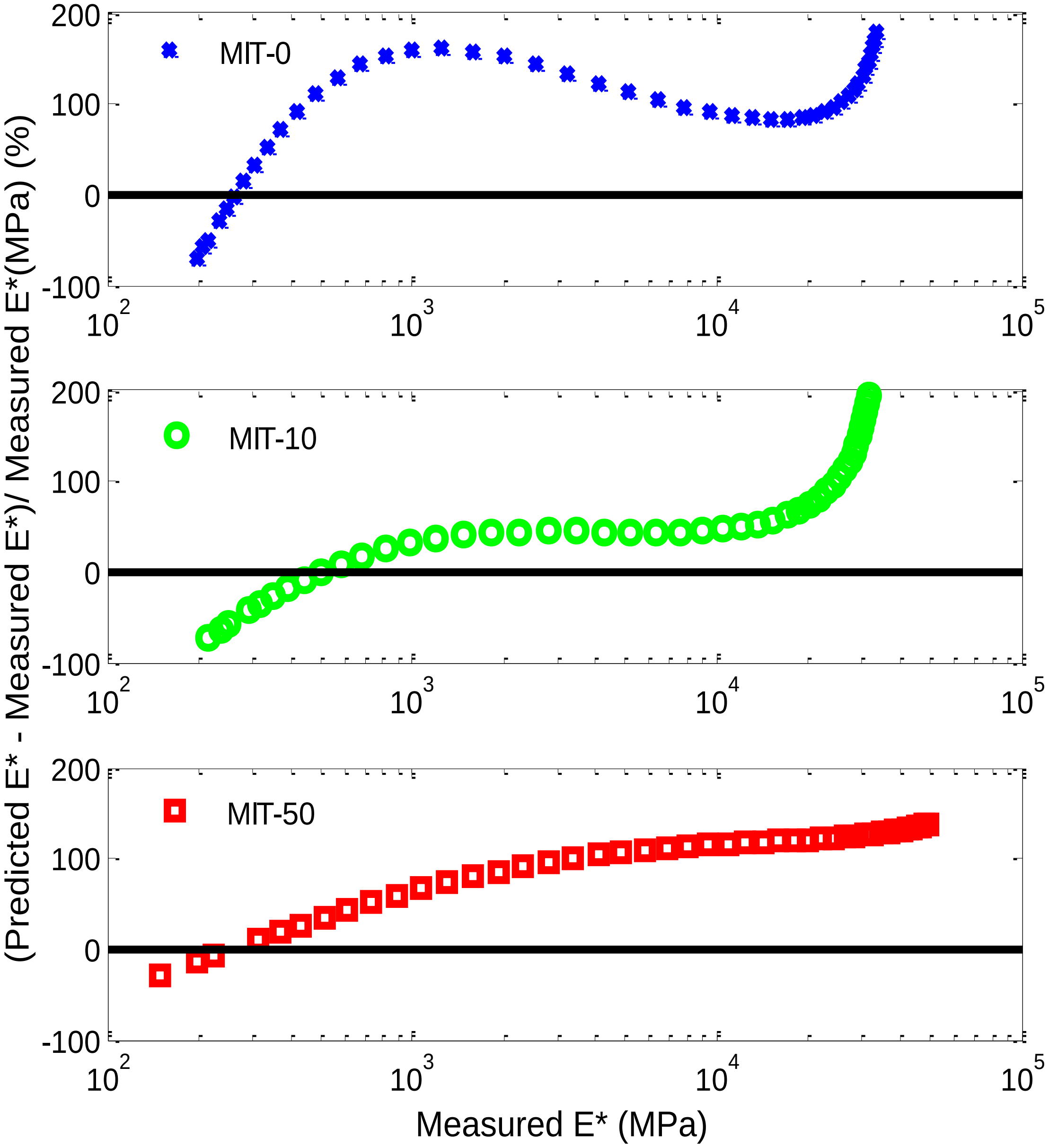
For the Level 3 inputs, Witczak model showed 70% underestimation of the E* values for both MIT-0 and MIT-10 mixes at high temperature. The predicted E* value was approximately 30% less than the measured E* value at high temperature for the MIT-50 mix. At low temperature, this model overestimated the E* by approximately 200% for the MIT-0 and MIT-10 mixes and by approximately 150% for the MIT-50 mix.

Underestimation of the E* at high temperature leads to an increase in the AC layer thickness, wastage of valuable materials and an increase in the cost due to a overdesign. Overestimation of the E* at low temperature shows a decrease in the thermal cracking resistance of the AC mix (an increase in thermal cracking) than the actual.

The above analysis shows an inconsistent variation of the predicted E* values using the Witczak model for both Level 2 and Level 3 inputs. These results indicate that Witczak model may not be appropriate for Manitoba AC mixes. For the use of the AASHTOWare Pavement ME Design program in Manitoba, Level 1 inputs for Manitoba asphalt mixes may be required.



a) Level 2 inputs



b) Level 3 inputs

**MIT-0 mix contains 0% RAP, MIT-10 mix contains 10% RAP, MIT-50 mix contains 50% RAP*

Figure 6: The E* prediction error compared to the measured E*

SUMMARY AND CONCLUSIONS

For calibrating the MEPDG distress prediction models and for a reliable pavement design or analysis, Level 1 asphalt materials inputs are required. Level 2 and Level 3 inputs may be used when Level 1 data are not available. The Pavement Research Group, University of Manitoba was engaged to develop the Level 1 dynamic modulus inputs and to verify the applicability of the dynamic modulus prediction model for Level 2 and Level 3 inputs. This paper presented the comparison of the ME Design default model i.e., Witczak model (Level 2 and Level 3) predicted dynamic modulus and laboratory measured (Level 1) dynamic modulus for Manitoba asphalt mixes containing different percentages of RAP. In order to examine the reliability of the dynamic modulus prediction model, aggregate type, RAP source and virgin binder were kept the same for all the AC mixes used in the analysis. Based on the analysis, the following conclusions were made:

- For the Level 2 inputs, the Witczak model showed up to 100% underestimation of the E* and up to 50% overestimation of E* at high and low temperatures, respectively, as compared to the measured E*.

- For the Level 3 inputs, the predicted E* values were approximately 70% lower for two AC mixes and approximately 30% lower for one AC mix than the measured E* at high temperature. At low temperature, Witczak model overestimated the E* by approximately 200% for two AC mixes and by approximately 150% for one AC mix as compared to the measured E*.

- Although the variation of the predicted E* values (using the Witczak model), for both Level 2 and Level 3 inputs, from the measured E* was inconsistent (the difference varied from -30% to +200%), the correlation between the measured E* and the predicted E* for Level 3 inputs showed a good R^2 values for all three AC mixes. This indicates that a good correlation (a high R^2 value) is not necessarily an indicator of the accuracy of the model prediction.

- Witczak model may not be appropriate for E* prediction for Manitoba AC mixes. For the use of the AASHTOWare Pavement ME Design program in Manitoba, Level 1 inputs for Manitoba asphalt mixes may be required.

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