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A Study on Dynamic Modulus of Epoxy Asphalt Concrete: Experiment and Modeling

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ABSTRACT

Epoxy asphalt concrete (EAC) has been applied as a surface layer for heavy-load pavements and as a coating layer on steel bridge decks in many countries such as Japan, the UK and the US. EAC exhibits several superior properties, including enhanced resistance to rutting and fatigue cracking, compared to conventional asphalt concrete (AC). The dynamic modulus ($|E^*|$) is a key parameter used to evaluate the performance of EAC in flexible pavement structures. This paper presents laboratory experimental results of the dynamic modulus of EAC across a broad range of temperatures and loading frequencies. Based on these results, master curves of $|E^*|$ were constructed to investigate viscoelastic properties of EAC mixtures. Moreover, in order to simulate $|E^*|$ master curves of EAC, the model “2S2P1D” was chosen because it has been proven to be suitable for all types of asphalt mixtures. The experimental and simulation results of $|E^*|$ master curves of EAC mixtures compared with those of polymer modified asphalt concrete (PMAC) showed that EAC have been retained the viscoelastic properties of asphalt materials.

1 Introduction

Dynamic modulus ($|E^*|$) is a main parameter of asphalt concrete (AC) for Mechanical-Empirical Pavement Design Method [1]. Dynamic modulus is measured through a uniaxial compression test or tensile test on cylindrical samples. The load applied to the specimens has the form of a sinusoidal harmonic function (Eq. (2)). With sinusoidal loading, the viscosity of asphalt mixture is indicated by a phase angle (Φ) between stress and strain (see Fig. 1).

$$\varepsilon(t) = \varepsilon_0(t)\sin(\omega t) \quad (1)$$

$$\sigma(t) = \sigma_0(t)\sin(\omega t + \Phi) \quad (2)$$

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where: ε_0 - amplitude of strain, σ_0 - amplitude of stress and ω - angular velocity.

Dynamic modulus of AC is calculated according to the following formula

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \quad (3)$$

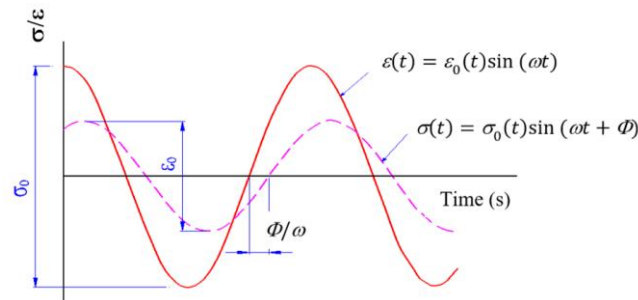


Fig. 1 – The shape of stress and strain in complex modulus tests

Uniaxial compression tests performed on cylindrical specimens, conducted according to AASHTO TP62, are been widely used to measure the complex modulus of AC mixtures [2]. Base on the results of $|E^*|$ measured across a broad scope of loading frequencies and temperatures, the master curves of $|E^*|$ are built using frequency-temperature superposition principle. These master curves are utilized to assess viscoelastic properties and forecast $|E^*|$ of AC mixtures at any frequency and temperature. Moreover, the model “2S2P1D” for linear viscoelastic asphalt materials is investigated to simulate $|E^*|$ master curve of AC mixtures [3-6].

EAC is a type of modified asphalt mixtures with epoxy asphalt (EA) as a binder, in which EA is produced by mixing asphalt binder and epoxy with designed proportion. Therefore, EA is a thermoset material with both the hardness of epoxy and the flexibility of asphalt binder [7-9]. Due to the modification of conventional asphalt binder with epoxy, some mechanical properties of EAC mixtures are significantly improved. Some researches on the properties of EAC mixtures show outstanding advantages of these mixtures such as better rutting and fatigue resistance and higher dynamic modulus compared to conventional AC mixtures. However, there has been few studies aimed at finding out suitable models to simulate the viscoelastic properties of EAC [9-16].

In this study, dynamic modulus tests based on AASHTO TP62 are conducted on two EAC mixtures with two different epoxy contents and compared with a reference PMAC mixture. In addition, the model “2S2P1D” is also fitted to $|E^*|$ master curves of the EAC mixtures. The result shows EAC mixtures still retain viscoelastic properties of asphalt materials and this property is revealed differently depending on epoxy content in EA binder.

The epoxy content in this study was selected in accordance with the research results of Tran Thi Cam Ha [11, 12]. In order to choose the appropriate epoxy content, epoxy was mixed into grade 60-70 asphalt in different proportions, respectively 0 %, 15 %, 20 %, 30%, 35%, 40% and 50% by binder mixture weight. Their penetration and softening point were performed after curing EA at different temperature conditions and curing duration. Experimental data have shown that the decrease in penetration and increase in softening temperature of BE were not much with epoxy content less than 30%, however, when epoxy content was 35% or more, the reduction in penetration and the rise in softening point of EA were superior compared with 60-70grade asphalt binder. In addition, the study on rheological properties of EA also showed a significant increase in their dynamic shear modulus (G^*) of EA binder at high temperatures. EA binders with 35% and 50% epoxy contents by weight reached PG 76 and PG 82 respectively according to AASHTO M320.

Moreover, the research on mechanical properties on EAC mixtures using two types of epoxy asphalt binders with two epoxy contents of 35% and 50% respectively has also been conducted [13-15], showing their outstanding advantages as follow:

- Marshall stability of EAC is 2 to 3 times greater than that of PMAC.

- Static elastic modulus of EAC 50 is significantly higher than PMAC at all experimental temperatures in the range from 15°C to 60°C. The highest increase in static elastic modulus of EAC 50 is 64% at 15°C.
- Flexural strength of EAC 50 is superior, approximately 2 times greater compared to PMAC.
- Both EAC 50 and EAC 35 have outstanding rutting resistance. Test outcomes at the temperature of 50°C in water have shown that wheel rutting depth of EAC 50 and EAC 35 are only approximately 1/3 and 1/2 of that of PMAC respectively (see Fig.2).

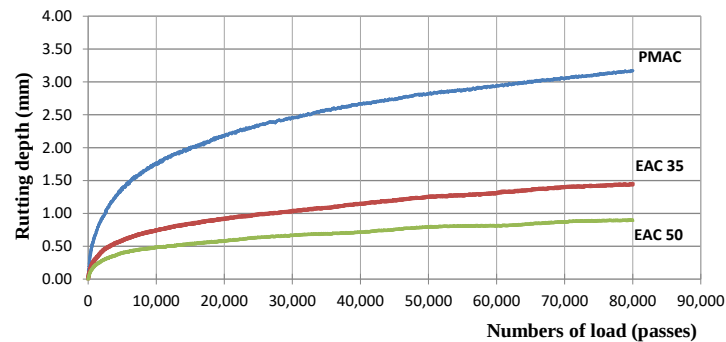


Fig. 2 – Outputs of Wheel rutting test of EAC at 50°C in water

- At specified experimental conditions (at 10°C, 10Hz frequency, and a strain level of $300\mu\epsilon$), the number of repetitive load cycles that reduce the hardness modulus to 50% of the initial value (N_{f50}) of EAC 50 is greater than that of EAC 35 and PMAC. N_{f50} of EAC 50 reaches 975,500 cycles, 1,34 times higher than 728,500 cycles of EAC 35 and 1,48 times higher than 660,500 cycles of PMAC (see Fig. 3).

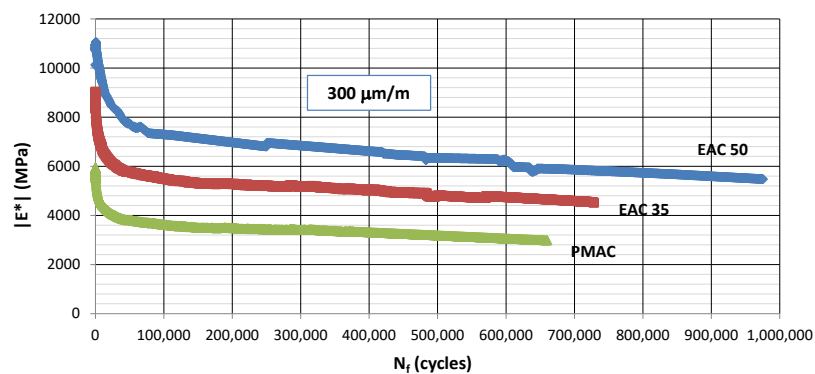


Fig. 3 – Complex modulus in relation to the number of cycle for EAC 50, EAC 35 and PMAC at $300\mu\epsilon$

It can be seen that these researches have shown the outstanding mechanical properties of EA binders and EAC mixtures with 35% and 50% epoxy by weight of mixed binder. Therefore, the two epoxy contents of 35% and 50% by weight of the mixed binder were selected for the researches on dynamic modulus of EAC mixtures.

2 Materials and Specimen preparation

In this study, component materials of EAC mixtures include:

- The two types of asphalt binders, including 60-70 grade asphalt binder and polymer modified asphalt binder were provided by Petrolimex, Vietnam.

- Epoxy was made from 56% main resin and 44% hardener by weight. The component materials of epoxy were provided by Taiyu Kensetsu Co. Ltd, Japan.
- All coarse aggregate and fine aggregate were exploited and processed at Sunway quarry, Hanoi city, Vietnam.

Three types of mixtures including two EAC mixtures with different epoxy asphalt binder and a PMAC mixture with polymer modified asphalt were used in this study (see Table 1). The types of aggregate and grading curve were identical for all three mixtures (see Fig. 4). The optimal EA binder contents of these mixtures determined by the Marshall method were shown in Table 1 [13, 14].

Table 1 – Epoxy content in EA binders and EA binder contents in mixtures by weight

Type of asphalt mixture	Content of binder	Epoxy content in binder by weight
EAC35	6.0	35
EAC50	6.0	50
PMAC	5.2	0

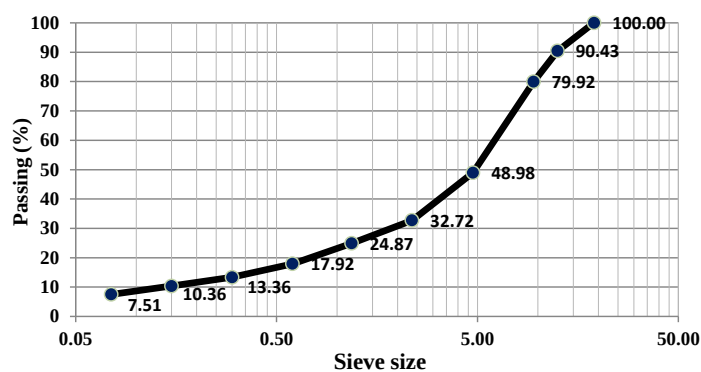


Fig. 4 – Aggregate grading curve

Table 2 – Number of specimens for each asphalt mixture

Type of asphalt mixture	Number of samples	Temperature (°C)	Frequency (Hz)
EAC35	3	10, 20, 30, 40, 50, 60	10, 5, 1, 0.5, 0.1
EAC50	3	10, 20, 30, 40, 50, 60	10, 5, 1, 0.5, 0.1
PMAC	3	10, 20, 30, 40, 50, 60	10, 5, 1, 0.5, 0.1



a) Gyratory compactor



b) Specimens

Fig. 5 – Specimen preparation by a gyratory compactor

All specimens of all 3 types of the mixtures (EAC 35, EAC 50 and PMAC) was produced using a gyratory compactor in accordance with AASHTO T312. The compaction was carried out in a mold with a 100 mm diameter under a pressure of 600 KPa (see Fig. 5). EAC and PMAC specimens were cured at room temperature with different curing time were for 7 days (168 hours) and 01 day (24 hours) respectively. The experimental plan is presented in Table 2.

3 Dynamic Modulus Test

Dynamic modulus experiments were carried out on Cooper compression testing machine at University of Transport and Communications (see Fig. 6). All specimens are kept in a thermostatic chamber at experimental temperature for at least 4 hours to ensure the specimen reaches a uniform temperature throughout, from the outside to the inside. Stress levels should be controlled depending on temperature so that the compression strain was within the linear viscoelastic region of AC. According to AASHTO TP62, micro-strain range of AC mixtures is from 50 to 150 $\mu\epsilon$.

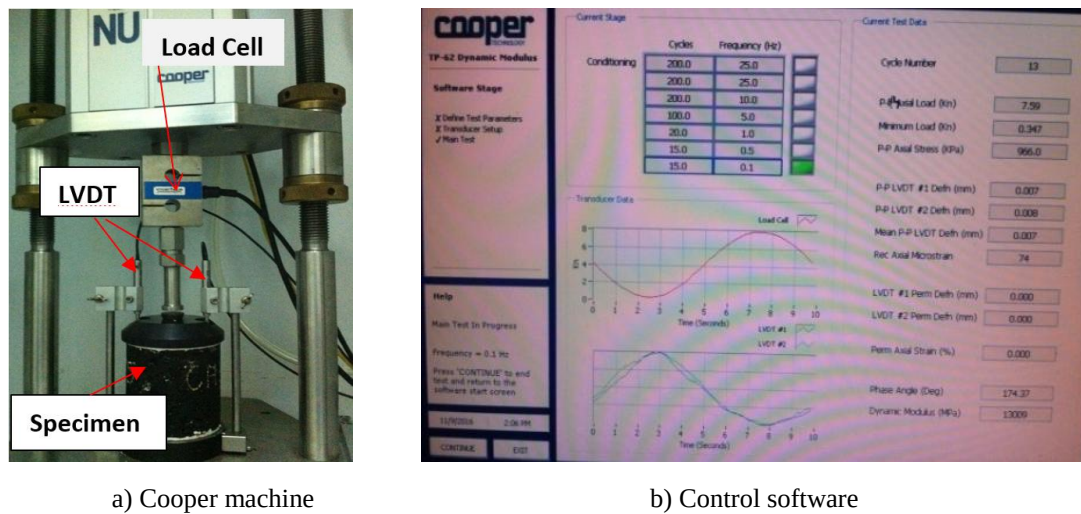


Fig. 6 – Dynamic modulus test on Cooper compression testing machine

4 Experimental Outcomes and Analysis

The test outcomes of dynamic modulus $|E^*|$, which were determined at five different loading frequencies and six distinct temperatures for each of the three types of mixtures studied, are presented in the following charts (see Fig. 7). These results provide a comprehensive view of how dynamic modulus responds to changes in frequency and temperature.

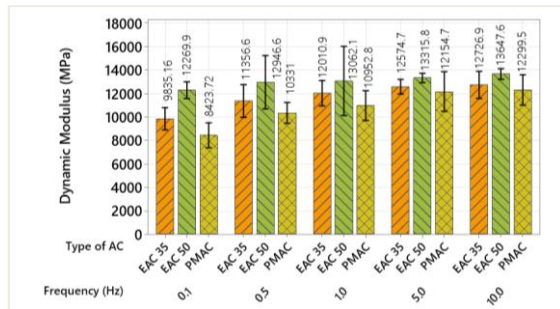
Experimental conditions including temperature and loading frequency greatly have an effect on $|E^*|$ of all three types of mixtures measured. At the same frequency, $|E^*|$ decreases significantly when the temperature increases. In case of the same temperature, $|E^*|$ also decreases with the reduction of loading frequency. This can be explained by the viscoelasticity of both EAC mixtures and PMAC mixtures.

At all tested temperatures (from 10°C to 60°C) and loading frequencies, $|E^*|$ of EAC 50 and EAC 35 determined are higher than those of PMAC and those of EAC 50 are highest in all 3 types of all mixtures. At higher temperatures, $|E^*|$ values of EAC is significantly higher than that of PMAC due to the presence of a hardener in the epoxy binder.

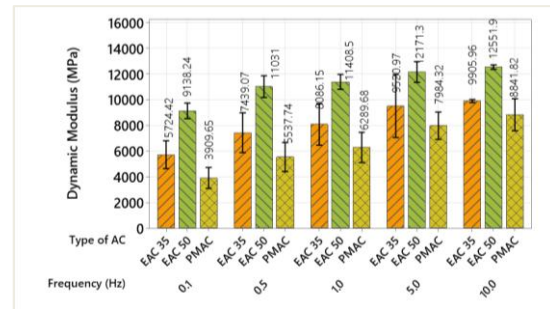
The dynamic modulus ($|E^*|$) master curve of AC is built from time-temperature shift principle. Master curve of $|E^*|$ is a characteristic curve for the viscoelastic properties of asphalt materials in a wide range of frequency and temperature. These curves are applied to predict $|E^*|$ at various temperatures and loading frequencies. The reference temperature at 30°C is chosen to develop the master curves of $|E^*|$. The curves corresponding to lower temperatures than 30°C will be shifted to the right and that corresponding to higher temperatures than 30°C will be shifted to the left by the shift factors (a_T) to create a continuous smooth curve.

For each type of AC mixture, $|E^*|$ values measured at 6 temperatures and 5 frequencies were used to build the master curve. Fig. 8, Fig. 9 and Fig. 10 respectively illustrates the method and the result of constructing the $|E^*|$ master curves of

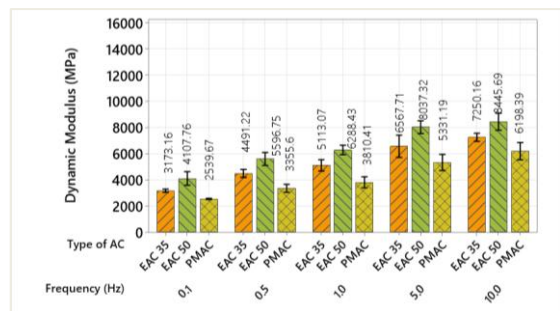
EAC 35, EAC 50 and PMAC at reference temperature (30°C). Summary of $|E^*|$ master curves of EAC 35, EAC 50 and PMAC is shown in Fig. 11.



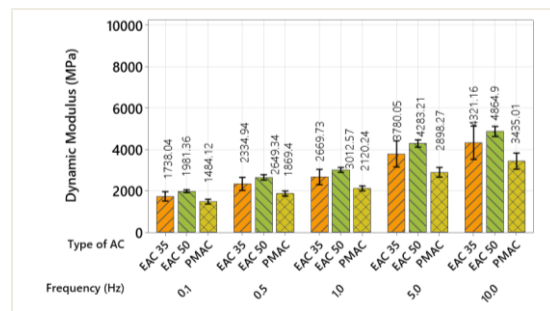
Experimental results of $|E^*|$ at 10°C



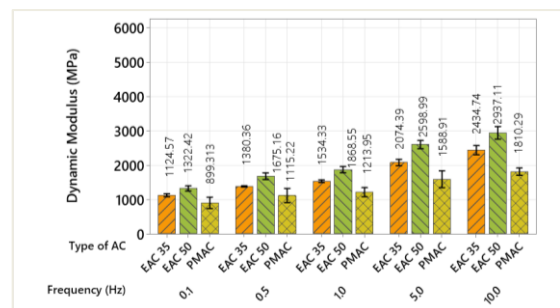
Experimental results of $|E^*|$ at 20°C



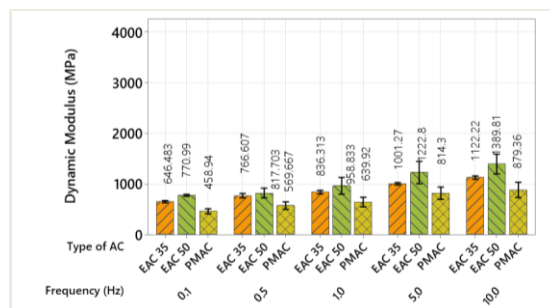
Experimental results of $|E^*|$ at 30°C



Experimental results of $|E^*|$ at 40°C



Experimental results of $|E^*|$ at 50°C



Experimental results of $|E^*|$ at 60°C

Fig. 7 – Dynamic modulus ($|E^*|$) of EAC 35, EAC 50 and PMAC

The graph in Fig.11 shows the $|E^*|$ master curves of the three mixtures at a set temperature of 30°C, in which $|E^*|$ master curve of EAC 50 is at the highest position and that of PMAC is at the lowest position. This proves $|E^*|$ of EAC 50, EAC 35 is higher than PMAC at all frequencies and temperatures. However, on the right side, $|E^*|$ master curves of three mixtures are located very close to each other. This proves that the difference between $|E^*|$ of EAC and PMAC is not much at high frequency and/or low temperature. Nevertheless, there are significant differences between $|E^*|$ of EAC and PMAC at low frequencies and/or high temperatures, which is demonstrated by wide separation of the master curves on the left side. In other words, $|E^*|$ of EAC mixtures is significantly higher than that of PMAC at low temperatures and/or low frequencies.

The correlation between shift factor (a_T) and temperature is found out by Williams, Landel and Ferry. The WLF formula allows the estimation of a_T at any temperature [3-5].

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + T - T_{ref}} \quad (4)$$

where: C_1 , C_2 are constants for fitting the values of the shift factor (a_T), determined by the least squares method. These coefficients are determined using “Solver” function in Microsoft Excel.

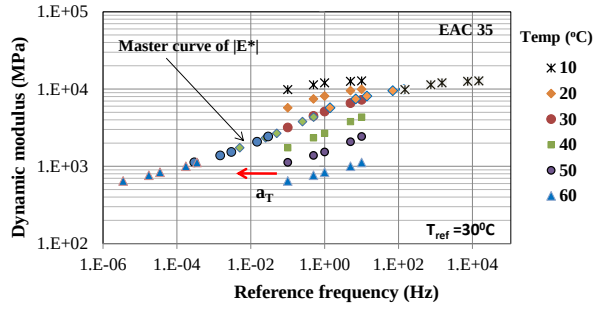


Fig. 8 - Construction of $|E^*|$ master curve of EAC 35

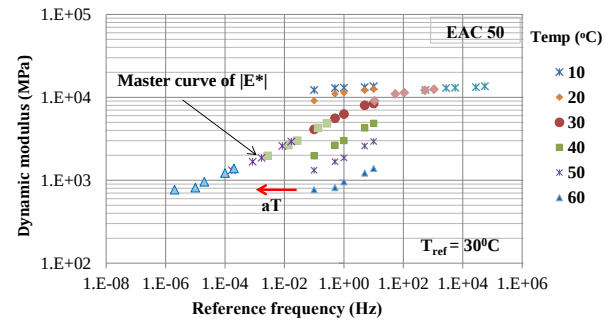


Fig. 9 - Construction of $|E^*|$ master curve of EAC 50

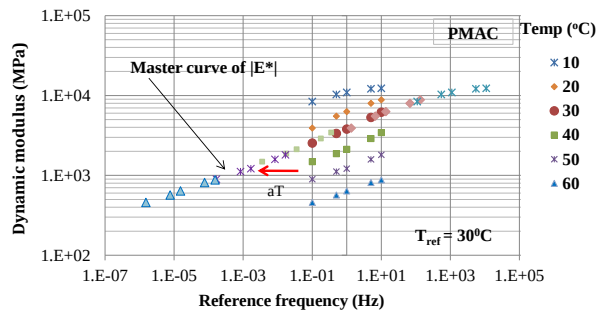


Fig. 10 - Construction of $|E^*|$ master curve of PMAC

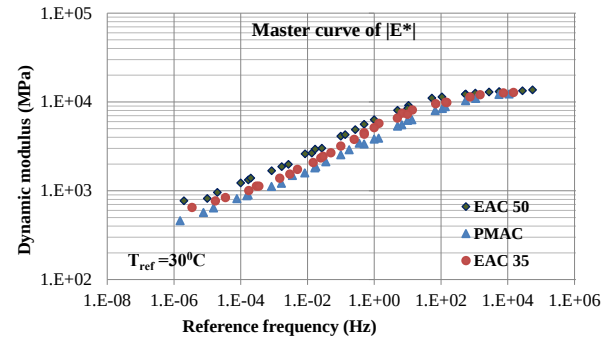


Fig. 11 - $|E^*|$ master curves of three mixtures (EAC 35, EAC 50 and PMAC)

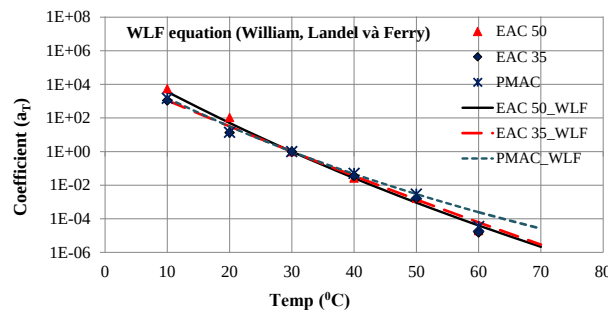


Fig. 12 – WLF equation (William, Landel and Ferry)

The results of determining the coefficients C_1 , C_2 using WLF equation of all three types of mixtures are presented in Table 3.

Table 3 – Coefficients of the WLF equation

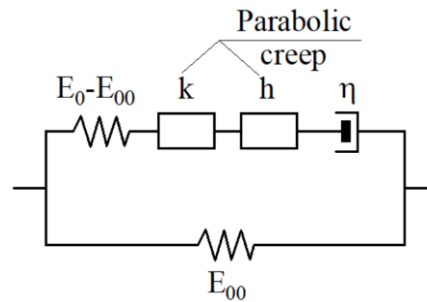
Types of AC	C ₁	C ₂
PMAC	93.25	633.20
EAC 35	24.76	175.92
EAC 50	41.94	256.13

5 Simulation for the viscoelasticity property of EAC mixture

5.1 Model selection

Currently, there are several different models, such as the Huet model, Huet-Sayegh model, and 2S2P1D model, used to simulate the $|E^*|$ of bitumens and their mixtures [3-6]. Each of these models has its own advantages and disadvantages when used to simulate the viscoelastic properties of asphalt materials. Huet model can appropriately simulate the linear viscoelastic behaviour at all frequencies and temperatures but not suitable for that of asphalt mixtures at low frequencies and/or high temperatures. On the other hand, the Huet-Sayegh model cannot accurately describe the behavior of asphalt binders at low temperatures [3].

To avoid the disadvantages of the two models mentioned above, the general model “2S2P1D” was researched and proposed by Olard, F., & Di Benedetto [3]. The model “2S2P1D” was developed to solve describe the shortcomings of the above two models when describing the viscoelastic properties of bitumens and their mixtures. This model was created by a combination of physical components: 2 Springs, 1 Dashpot and 2 Parabolic creep elements. This model includes 07 constants (E_{00} , E_0 , δ , β , τ , k và h) illustrated in Fig 13 [3, 7].

**Fig. 13 – The general model “2S2P1D” with 7 constants (E_{00} , E_0 , δ , β , τ , k và h)**

When using this model, the complex modulus of bitumens and AC mixtures is determined by the equation (5)

$$E^*(\omega) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}} \quad (5)$$

where: k , h -parabolic creep elements ($0 < k < h < 1$); δ , β - constant; E_0 - dynamic modulus value in which $\omega\tau \rightarrow \infty$; E_{00} - dynamic modulus value in which $\omega\tau \rightarrow 0$; η -Newtonian viscosity, $\eta = (E_0 - E_{00})\beta\tau$ and τ -parameter depends on temperature, $\tau(T) = a_T(T)\tau_0$ and τ_0 is found out at T_{ref} .

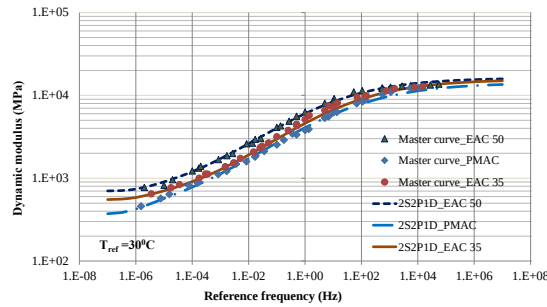
From advantages of the model “2S2P1D”, it was chosen to simulate $|E^*|$ master curves of all three mixtures. The suitability of this model for EAC mixtures can be evaluated through these simulation results.

5.2 Modeling

The 2S2P1D model parameters were determined by trial and error to minimize the error between the experiment and the model. The seven 2S2P1D model parameters for all three mixtures (EAC 35, EAC 50 and PMAC) are shown in Table 4. The modeling results for these mixtures are presented in Fig. 14.

Table 4 – The parameters of 2S2P1D model

Type of AC	E ₀₀ (MPa)	E ₀ (MPa)	k	h	δ	τ (s)	β
PMAC	370	20000	0.24	0.33	4.25	5.00E-01	2500
EAC 35	550	22000	0.25	0.37	4.00	4.00E-01	2000
EAC 50	700	23000	0.25	0.40	4.40	1.80E+00	500

**Fig. 14 – Modeling of $|E^*|$ master curve by the 2S2P1D model**

5.3 Evaluating “Goodness of fit” of 2S2P1D model

The Goodness of Fit [16] is used to assess the suitability of the 2S2P1D model in relation to the experimental data ($|E^*|$). In this approach, the standard error (Se) and standard deviation (Sy) are determined using the following formulas

$$S_e = \left[\frac{1}{(n-p-1)} \sum_{i=1}^n \left(\log |\hat{E}^*|_i - \log |E^*|_i \right)^2 \right]^{0.5} \quad (6)$$

$$S_y = \sqrt{\frac{\sum_{i=1}^n \left(\log |E^*|_i - \overline{\log |E^*|} \right)^2}{n-1}} \quad (7)$$

The determination coefficient (R^2) is given by the following expression

$$R^2 = 1 - \frac{(n-p-1) S_e^2}{(n-1) S_y^2} \quad (8)$$

The results of calculating R^2 and Se/Sy are shown in Table 5. For 3 types of mixtures, $R^2 > 0.90$ and Se/Sy < 0.35 demonstrate that the model “2S2P1D” is suitable to simulate the $|E^*|$ master curve of both EAC and PMAC.

Table 5 – The results determined the parameters of Goodness-of-fit

Type of AC	R^2	Se/Sy	Goodness-of-fit
PMAC	0,9894	0,118	Excellent
EAC 35	0,9944	0,086	Excellent
EAC 50	0,9801	0,162	Excellent

6 Conclusions

The dynamic modulus of EAC increases with higher epoxy content in the epoxy asphalt binder. At the same temperature and loading frequency, the dynamic modulus of EAC 50 is the highest among the three mixtures. The dynamic modulus of both EAC 50 and EAC 35 is significantly higher than that of PMAC at high temperatures and/or low loading

frequencies, though the increase in dynamic modulus decreases at even higher temperatures and/or lower loading frequencies.

Master curves of $|E^*|$ were developed for EAC 35 and EAC 50 mixtures, and 2S2P1D model was found to effectively simulate the $|E^*|$ master curves for these mixtures. This result demonstrates that EAC mixtures retain the viscoelastic and thermal sensitivity characteristics of asphalt binders. However, the thermal sensitivity of EAC is significantly reduced compared to that of PMAC mixtures.

The findings from this research provide dynamic modulus values for EAC layers, which can be used in flexible pavement structural analysis following the Mechanistic-Empirical Pavement Design Method. These results are also used to forecast the dynamic modulus of EAC across various temperature and frequency conditions.

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