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Effects of asphalt binder and aggregate gradation on dynamic modulus, resilient modulus and moisture resistance of asphalt concretes

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ABSTRACT

In this paper, the effects of asphalt binder and aggregate gradation on dynamic modulus ($|E^*|$), resilient modulus (M_r) and moisture resistance of asphalt concretes (AC) have been studied. Six different asphalt concretes are designed with two aggregate gradations (nominal maximum aggregate size of 12.5 and 19 mm) and three types of asphalt binders (penetration grades of 40/50, 60/70 and a polymer-modified bitumen PMB3). Dynamic modulus, resilient modulus and Tensile Strength Ratio (TSR) test have been performed on the studied AC. The $|E^*|$ values obtained from dynamic modulus test at various frequencies and temperatures are simulated using a linear viscoelastic model 2S2P1D. Experimental results indicate the clear effect of asphalt binder and aggregate gradation on mechanical properties of tested AC. The 2S2P1D model successfully simulates the $|E^*|$ master curve with high precision (R^2 values from 0.84 to 0.97). The roles of 40/50 and PMB3 asphalt binder in enhancing the performance of asphalt concretes are also clearly demonstrated under each specific temperature condition and mechanical property type.

1 Introduction

Asphalt concrete (AC) is the primary material used for the construction of flexible pavements. The design and construction of asphalt concrete layers in the pavement structures play a crucial role in the durability and longevity of transportation infrastructure. Due to its high performance properties and effective abrasion resistance, asphalt concrete is widely regarded as the material of choice for road pavement construction. However, in the tropical climate zones characterized by significant temperature and humidity fluctuations, the study and evaluation of asphalt concrete's mechanical properties have become increasingly critical. Properties such as dynamic modulus, resilient modulus and moisture resistance

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should be thoroughly assessed to ensure long-term pavement performance, particularly in environments with extreme variations in temperature and moisture. These properties are essential in evaluating material quality and informing the design of pavement structures.

The dynamic modulus ($|E^*|$) is a critical parameter in mechanistic-empirical (M-E) pavement design, used to evaluate the elasticity and deformation resistance of asphalt concretes under dynamic loading. This parameter not only establishes the relationship between material stiffness and loading/environmental conditions but also plays a key role in predicting pavement rutting, fatigue and cracking [1-3]. Additionally, $|E^*|$ is essential for calculating stress and strain within flexible pavement systems [4-5] and serves as an indispensable input for modern M-E design software [6]. However, direct laboratory testing for determining $|E^*|$ is often time-consuming and costly, limiting its application in certain practical scenarios [7]. The dynamic modulus of asphalt concrete depends on the temperature and loading frequency and follows the time temperature superposition principle [8-10]. The change in dynamic modulus as a function of reduced frequency can be modeled by linear viscoelastic models [11-13].

The resilient modulus (M_r) is another fundamental mechanical property that reflects the elastic durability and load-bearing capacity of asphalt concretes under repeated loading. M_r is defined as the ratio between the applied deviator stress (σ_d) and the recoverable strain (ϵ_r) of the material. This parameter is widely used in multi-layer elastic analysis to assess pavement response under traffic loading. The resilient modulus plays a crucial role in mechanistic-empirical pavement design (M-E), where pavement behavior is linked to performance through transfer functions [14-15]. This allows for the determination of new pavement layer thicknesses or the estimation of the remaining service life of existing pavements [16]. Accurate determination of M_r is essential not only for optimizing pavement design but also for ensuring the structural stability and long-term durability of asphalt concretes under real-world traffic conditions.

In addition, moisture resistance is a decisive factor in the long-term durability of asphalt pavements, particularly in regions with high precipitation or humidity. The loss of adhesion between the asphalt binder and aggregates due to water intrusion can cause severe pavement distress, such as stripping and cracking. The Tensile Strength Ratio (TSR) test is a widely used method to assess moisture resistance by comparing the indirect tensile strength of dry and moisture-conditioned specimens. A minimum TSR of 70% has been recommended in numerous studies to ensure adequate moisture resistance. However, more stringent requirements, such as those set by the South Carolina DOT, mandate a minimum TSR of 85% to guarantee pavement durability [17]. Factors such as aggregate moisture content, asphalt binder type and additive composition significantly influence TSR results and the long-term moisture resistance of asphalt concretes [18].

The mechanical properties of asphalt concretes are highly dependent on both the asphalt binder type and aggregate gradation. This study aims to investigate the effects of asphalt binder type and aggregate gradation on key mechanical properties, including dynamic modulus ($|E^*|$), resilient modulus (M_r) and moisture resistance through TSR testing. The research findings will not only identify the critical factors influencing these properties but also provide design recommendations to enhance the durability and cost-effectiveness of asphalt pavements.

2 Materials and experimental methods

2.1 Tested materials

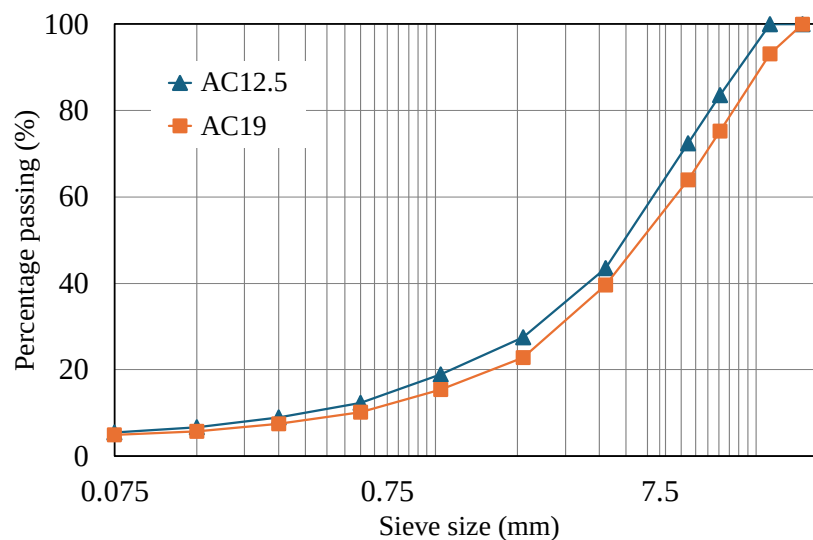
In this study, three different types of asphalt binders were selected, including two conventional ones with penetration grades of 40/50 and 60/70, as well as a polymer-modified bitumen (PMB3). The fundamental properties of these asphalt binders are presented in Table 1.

The two selected gradations use the same type of aggregates and mineral filler sourced from the Houaphanh Quarry in the Lao People's Democratic Republic. One gradation features a nominal maximum aggregate size of 12.5 mm, while the other incorporates a larger size of 19 mm. The gradation curves for both are shown in Figure 1.

The mixtures were designed using the Marshall method. With three asphalt binder types and two gradations, a total of six asphalt concretes were designed. The labeling follows the format ACx y where "AC" represents asphalt concrete, "x" denotes the nominal maximum aggregate size (12.5 or 19 mm) and "y" specifies the asphalt binder type (40/50, 60/70 or PMB3). The optimum asphalt content and air voids for these mixtures are presented in Table 2.

Table 1 - Experimental results of asphalt binder properties (40/50, 60/70 and PMB3).

No.	Experimental Indicator	Unit	40/50 Asphalt	60/70 Asphalt	PMB3 Asphalt
1	Penetration at 25°C, 0.1mm, 5s	0.1mm	46	63	48
2	Penetration Index (PI)	-	-0.28	-0.01	-
3	Softening point (Ring and ball method)	°C	54.1	48.2	89.2
4	Dynamic viscosity at 60°C	Pa.s	695.231	266.525	-
5	Ductility at 25°C, 5 cm/min	cm	>110	>110	-
6	Paraffin content (by mass)	%	1.35	1.69	-
7	Flash point (Cleveland open cup)	°C	301	301	298
8	Solubility in Trichloroethylene	%	99.91	99.89	99.86
9	Density	g/cm ³	1.033	1.027	1.029
10	Mass loss after heating (163°C, 5h)	%	-	-	0.077
11	Retained penetration ratio after heating (163°C, 5h)	%	-	-	90.2
12	Elastic recovery (at 25°C, after stretching 10 cm)	%	-	-	98.0
13	Storage stability (softening point difference between top and bottom, 163°C, 48h)	°C	-	-	1.4
14	Viscosity at 135°C (spindle 21, shear rate 18.6 s ⁻¹ , Brookfield viscometer)	Pa.s	-	-	2.644
15	Adhesion to aggregate	Grade	Grade 3	Grade 3	Grade 4
16	Experimental indicators of asphalt after TFOT test				
16.1	Mass loss	%	0.281	0.088	-
16.2	Retained penetration ratio at 25°C	%	71.72	76.51	-
16.3	Ductility at 25°C, 5 cm/min	cm	>100	>100	-

**Fig. 1 – Gradation curves of AC12.5 and AC19.**

After the design process, the asphalt concrete samples were tested to evaluate their dynamic modulus, resilient modulus and moisture resistance. The results from these tests will be analyzed to assess the influence of asphalt binder type and aggregate gradation on the mechanical properties of the asphalt concretes.

Table 2 – Optimum asphalt contents and air voids for asphalt concretes.

No.	Binder type	Aggregate gradation	AC designation	Optimum asphalt content (% by total mix.)	Air void (%)
1	40/50	12.5	AC12.5 40/50	4.5	4.68
2	40/50	19	AC19 40/50	4.3	4.60
3	60/70	12.5	AC12.5 60/70	4.3	4.85
4	60/70	19	AC19 60/70	4.1	4.96
5	PMB3	12.5	AC12.5 PMB3	4.6	4.31
6	PMB3	19	AC19 PMB3	4.3	4.49

2.2 Experimental program

2.2.1 Dynamic modulus test (E^*)

The dynamic modulus test (E^*) of asphalt concretes was conducted using a frequency and temperature-dependent approach, following the AASHTO TP62 standard [19]. This test evaluates the viscoelastic properties of the material under dynamic loading conditions, which is an important parameter for modeling and predicting the mechanical behavior of flexible pavement structures. The test was performed on cylindrical specimens, including conventional mixes (40/50 and 60/70) and polymer-modified bitumen (PMB3), with two gradations AC12.5 and AC19. The specimens were compacted by a gyratory compactor to the design air void, with a height and a diameter of 100 mm. The specimens were carefully prepared and conditioned in a temperature-controlled chamber to maintain the required temperature before testing. For each mixture type, the dynamic modulus test was conducted on a set of three specimens.

Dynamic modulus test was carried out at temperatures ranging from 10°C to 60°C (with 6 different temperatures), with loading frequencies of 0.1 Hz, 0.5 Hz, 1 Hz, 5 Hz, 10 Hz and 25 Hz. The applied load followed a sinusoidal waveform and varied across test cycles, while specimen deformations were continuously measured and recorded. To ensure linear viscoelastic behavior of the material, stress levels were adjusted to maintain strain values within 50 $\mu\epsilon$ at low temperatures and 150 $\mu\epsilon$ at high temperatures. This testing condition minimized nonlinear effects and ensured accurate and consistent results [20-22].



Fig. 2 – Dynamic modulus test on asphalt concrete using Cooper press.

The dynamic modulus test was conducted using a Cooper testing machine equipped with a vertical force measurement system and axial deformation sensors, as shown in Figure 2. The results were processed and analyzed using specialized software, enabling the determination of $|E^*|$ values under different temperature and frequency conditions. A total of 648 dynamic modulus data points (including 6 asphalt concretes $\times$ 3 specimens $\times$ 6 temperatures $\times$ 6 frequencies) were obtained.

2.2.2 Resilient modulus test (M_r)

The resilient modulus (M_r) test for asphalt concretes was conducted using the repeated load indirect tensile method, following the ASTM D4123-82(1995) standard [23]. This test determines the recoverability of the material under loading, which is a critical parameter influencing the durability and stability of flexible pavements.

During the test, cylindrical specimens were placed in a testing apparatus capable of applying repeated loading. The applied load was selected to range between 10% and 50% of the tensile strength of the specimen. The load was cyclically applied until the specimen's deformations stabilized. The test was performed at 20°C, corresponding to the standard temperature condition for flexible pavement design in Laos [24]. The test was conducted with loading cycles ranging from 50 to 200, after which lateral deformations were measured and recorded. Each mixture type was tested using three specimens.

The results were processed to calculate the resilient modulus (M_r) at 20°C using Equation (1), providing essential data for evaluating the elastic response of asphalt concrete under varying load conditions.

$$M_r = \frac{F \times (v + 0.27)}{z \times h} \quad (1)$$

where:

M_r : Resilient modulus, MPa;

F : Maximum applied load, N;

z : Horizontal deformation, mm;

h : Specimen thickness, mm.

v : Poisson's ratio (a value of 0.35 is assumed for temperature of 20°C) [3, 25-26].

2.2.3 Tensile Strength Ratio (TSR) test

The Tensile Strength Ratio (TSR) test is conducted to evaluate the reduction in the indirect tensile strength of asphalt concretes due to water exposure, thereby assessing its moisture susceptibility. The test method follows the AASHTO T283 standard [27], ensuring accuracy and repeatability of the results.

The specimens are divided into two groups. Each group contains three specimens.

- Dry-conditioned specimens: After fabrication, the specimens are conditioned in air at a temperature of $25 \pm 1^\circ\text{C}$ for 4 hours.
- Wet-conditioned specimens: The specimens are submerged in a $60 \pm 1^\circ\text{C}$ water bath for 24 hours, followed by conditioning in another water bath at 25°C for 2 hours before testing.

Both groups undergo an indirect tensile strength test to determine their average indirect tensile strength. The indirect tensile strength is calculated by the formula given in Equation (2). The TSR index is calculated as the ratio of the average indirect tensile strength of the wet-conditioned specimens to that of the dry-conditioned specimens, representing the material's moisture resistance and given by Equation (3). This procedure not only evaluates the strength degradation due to moisture but also serves as a basis for comparing the effectiveness of moisture resistance enhancement measures, such as the use of anti-stripping additives or modifications to the asphalt binder type.

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \quad (2)$$

where:

S_t : Tensile strength, kPa;

P : Maximum load, N;

t : Specimen thickness, mm;

D : Specimen diameter, mm.

$$TSR = \frac{S_2}{S_1} \quad (3)$$

where:

S_1 : Average tensile strength of the dry-conditioned group, kPa (psi);

S_2 : Average tensile strength of the wet-conditioned group, kPa (psi).

3 Results and discussion

3.1 Dynamic modulus ($|E^*|$) test results

3.1.1 Experimental analysis

The dynamic modulus ($|E^*|$) test results for asphalt concretes reveal a clear relationship between $|E^*|$ values and factors such as temperature, loading frequency, asphalt binder type and aggregate gradation. The experimental analysis was conducted using 648 data points, covering three asphalt binder types (40/50, 60/70, PMB3), two gradations (AC12.5, AC19), six temperature levels (10°C, 20°C, 30°C, 40°C, 50°C, 60°C) and six loading frequencies (25 Hz, 10 Hz, 5 Hz, 1 Hz, 0.5 Hz, 0.1 Hz). From this data, a general full factorial experimental design was created. The ANOVA (Analysis of Variance) and post-hoc analysis using Tukey's standard were conducted to detect significant differences. The input variables for the experimental design included four factors: asphalt binder, gradation, temperature and frequency. The experimental data showed good repeatability. The ANOVA results indicated that all variables had p-values < 0.05 , and the adjusted R^2 was 78.9%. This confirms that the input factors had a statistically significant effect on the dynamic modulus with a good level of confidence.

The dynamic modulus characterizes the viscoelastic behavior of the material, where $|E^*|$ decreases as frequency decreases and temperature increases and is shown as an example for AC12.5 40/50 in Figure 3. At high frequencies and low temperatures, the mixtures exhibit good elastic recovery, whereas at low frequencies and high temperatures, their stiffness decreases, increasing the risk of permanent deformation. This outcome aligns well with the theoretical viscoelastic behavior of materials.

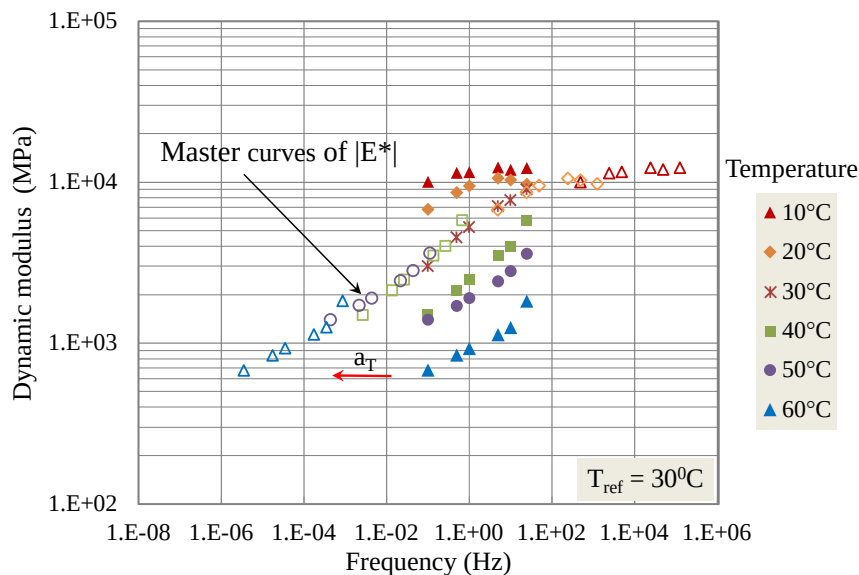


Fig. 3 – Dynamic modulus of AC12.5 40/50.

In general, the effect of asphalt binder, aggregate gradation, temperature and frequency on dynamic modulus are illustrated in Figure 4. In more detail, the change in $|E^*|$ with the asphalt binder and gradation at some tested temperatures (60°C, 30°C and 10°C) is shown in Figure 5. As can be seen in Figure 4 and Figure 5, the asphalt binder type significantly affects $|E^*|$ values. Mixtures with 40/50 asphalt binder exhibit the highest $|E^*|$ values, followed by PMB3 asphalt binder indicating greater stiffness and better resistance to deformation under dynamic loading. Mixtures with 60/70 asphalt binder having lower $|E^*|$ values. It can be seen in Figure 4 that asphalt concrete using 40/50 asphalt binder exhibits significantly

higher stiffness compared to the other two types. Therefore, 40/50 asphalt is recommended for roads with heavy truck traffic and in regions with high average annual temperatures. Aggregate gradation also plays an important role. AC19, with a nominal maximum aggregate size of 19 mm, exhibits significantly higher $|E^*|$ values than AC12.5 especially at high-temperature conditions.

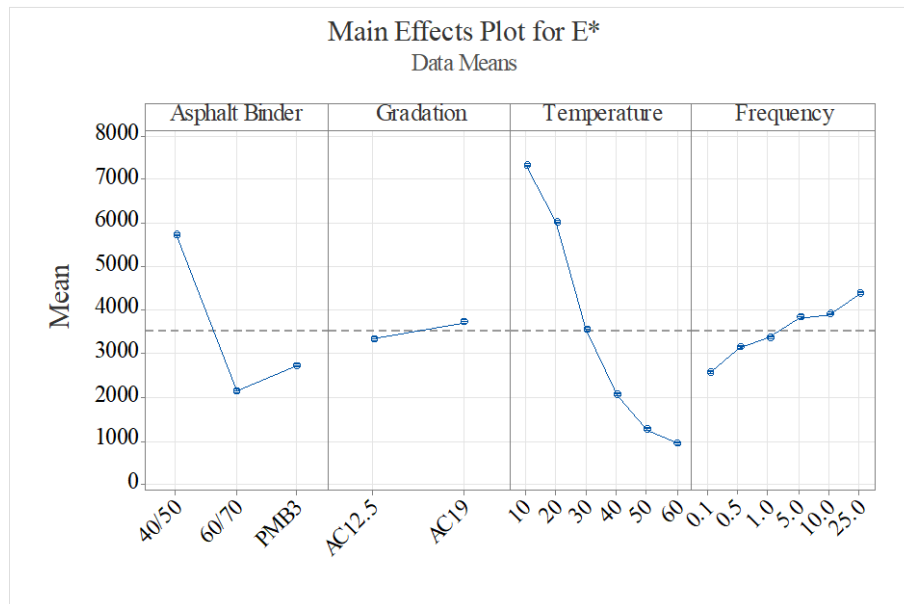
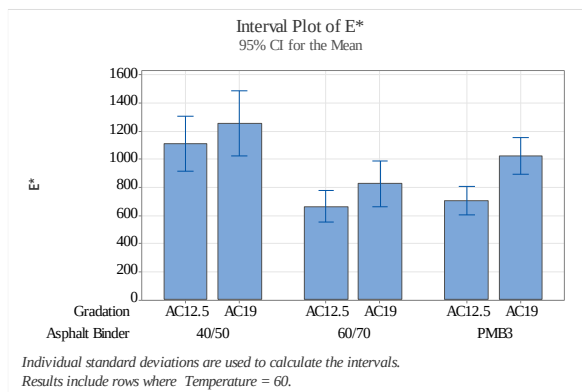
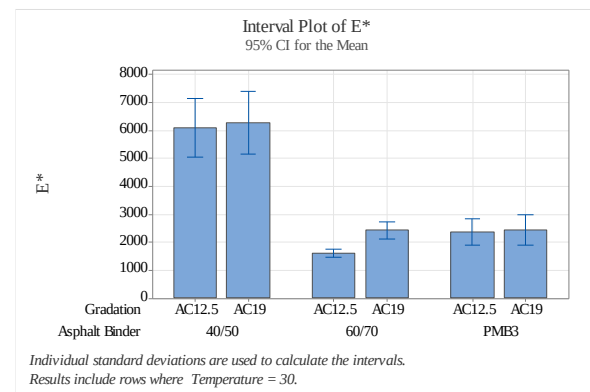


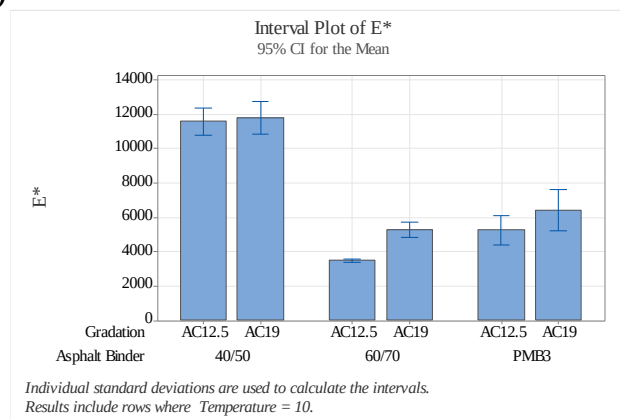
Fig. 4 – Effect of asphalt binder, aggregate gradation, temperature and frequency on $|E^*|$.



(a)



(b)



(c)

Fig. 5 – Change in $|E^*|$ with gradation and asphalt binder at 60°C (a), 30°C (b) and 10°C (c).

The interaction between temperature and frequency strongly reflects the viscoelastic nature of the mixtures, where $|E^*|$ increases at high frequencies and low temperatures but decreases at low frequencies and high temperatures. The interaction between asphalt binder type and temperature shows that PMB3 outperforms at high temperatures, while 40/50 asphalt binder is more effective at low temperatures. The gradation-frequency interaction confirms that AC19 consistently exhibits higher $|E^*|$ values than AC12.5 across all frequency levels.

3.1.2 Master curve of dynamic modulus for asphalt concrete

The dynamic modulus ($|E^*|$) master curve (see Figure 6) for asphalt concrete was built based on experimental results, illustrating the relationship between $|E^*|$, temperature and loading frequency [28–33]. This process employs the time-temperature superposition principle to determine the variation of $|E^*|$ over a wide range of temperatures and frequencies [34–36]. A reference temperature (T_{ref}) of 30°C was selected. $|E^*|$ curves at lower temperatures were shifted to the right, while those at higher temperatures were shifted to the left to form a continuous master curve (see Figure 3, Figure 6). This shifting process used shift factors (aT), ensuring the curves merged smoothly into a single continuous curve [35, 37]. The resulting master curve characterizes the viscoelastic behavior of the material over a broad range of temperatures and frequencies, facilitating the prediction of $|E^*|$ under different loading and temperature conditions [28, 35].

Experiments were conducted at six different temperatures and six different loading frequencies, allowing for the development of a master curve for each type of mixture. The $|E^*|$ master curve results for asphalt concretes incorporating 40/50, 60/70 and PMB3 asphalt binders revealed significant differences in viscoelastic properties and are shown in Figure 6. Specifically, asphalt concrete containing 40/50 asphalt binder exhibited the highest stiffness among the tested mixtures, particularly at high frequencies and temperatures. In contrast, those with 60/70 and PMB3 asphalt binders were observed to have lower stiffness.

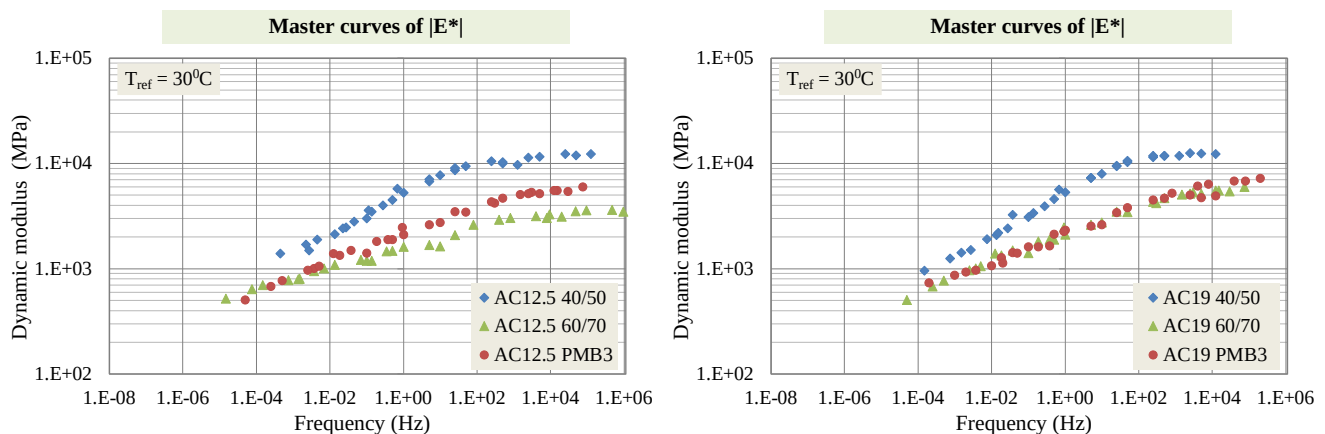


Fig. 6 – Master curves of $|E^*|$ for AC12.5 and AC19 with 40/50, 60/70 and PMB3 asphalt binders at a reference temperature of 30°C.

3.1.3 Modeling the dynamic modulus of asphalt concrete

In this study, the 2S2P1D model (Figure 7) was selected to simulate the master curve of the dynamic modulus $|E^*|$ of asphalt concrete due to its capability to accurately represent the linear viscoelastic properties of both asphalt binder and asphalt concrete over a wide range of frequencies and temperatures.

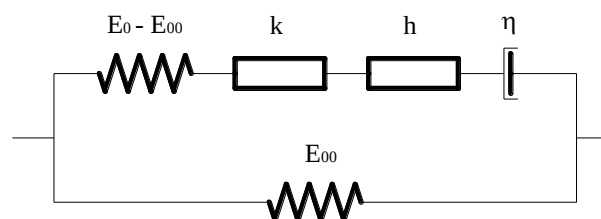


Fig. 7 – Representation of 2S2P1D model.

This model, proposed by Olard and Di Benedetto (2003) [11], consists of physical components such as springs, parabolic elements and a viscous element, requiring seven input parameters to simulate $|E^*|$ [3, 11, 38-39]. The expression of the model is given by Equation (4).

$$E^*(\omega) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(j\omega\tau)^k + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}} \quad (4)$$

where:

j : the imaginary unit of complex number, defined by $j^2 = -1$

ω : The pulsation, $\omega = 2\pi f$ (f is the frequency);

k, h : Exponents such as $0 < k < h < 1$;

β : Constant;

E_{00} : The static modulus when $\omega \rightarrow 0$;

E_0 : The glassy modulus when $\omega \rightarrow \infty$;

η : Newtonian viscosity, $\eta = (E_0 - E_{00})\beta\tau$;

τ : Characteristic time, whose value varies only with temperature T , $\tau(T) = a_T(T) \cdot \tau_0$ where $\tau_0 = \tau(T_{ref})$ is determined at the reference temperature T_{ref} ;

ν_{00} : The static Poisson's ratio when $\omega \rightarrow 0$, ν_0 : the glassy Poisson's ratio when $\omega \rightarrow \infty$.

The 2S2P1D model enables the calculation of the dynamic modulus $|E^*|$ based on parameters such as the modulus at infinite frequency (E_0) and very low frequency (E_{00}), coefficients k and h , as well as viscosity and characteristic time, which are temperature-dependent. These parameters were determined using an optimization method to minimize the error between experimental data and model predictions. The modelling results for different mixtures in Figure 8 demonstrated that this model can accurately simulate the master curve $|E^*|$ with high precision. The simulation results of the master curve $|E^*|$ for AC12.5 and AC19 using the 2S2P1D model showed a good correlation between the predicted values and experimental data. This model proved highly effective in modelling the linear viscoelastic behavior of asphalt concretes with different asphalt binders (40/50, 60/70 and PMB3). To assess the goodness of fit, the Goodness-of-Fit method was applied [36], using statistical indicators and coefficient of determination (R^2). The results indicated an excellent agreement between the 2S2P1D model and experimental data for all asphalt concretes, with high R^2 values ranging from 0.84 to 0.97.

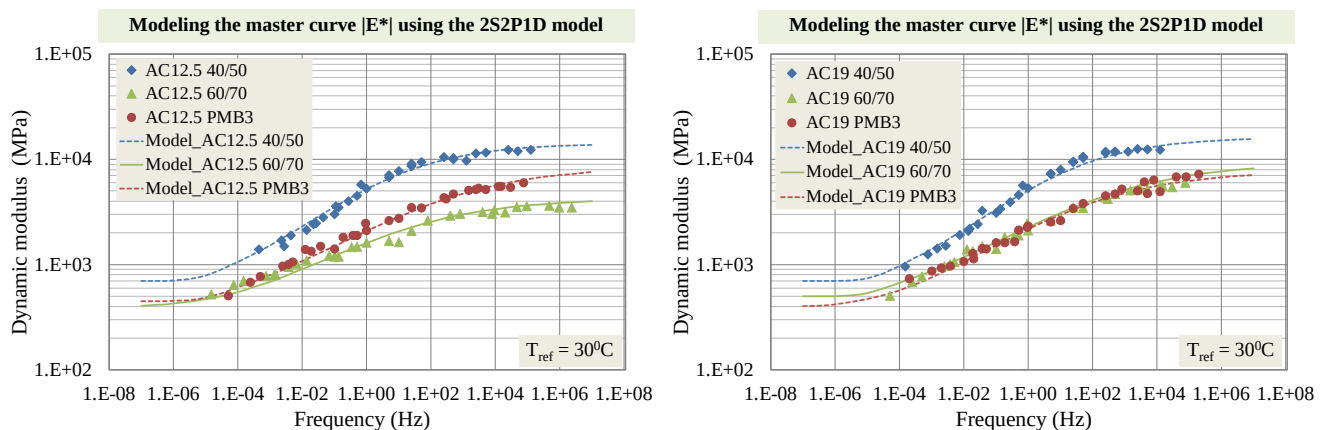


Fig. 8 – Modeling the master curve $|E^*|$ of AC12.5 and AC19 using the 2S2P1D model.

3.2 Experimental results of resilient modulus (M_r)

Resilient modulus (M_r) tests were conducted at a temperature of 20°C on six different types of asphalt concretes. The experimental results show the significant differences in M_r among the various mixtures, depending on the type of asphalt binder used that is shown in Figure 9. The mixture with 40/50 asphalt binder exhibited the highest M_r value compared to other types, indicating superior deformation resistance. This makes it particularly suitable for high stiffness layers in

pavement structures. The Mr value of the mixture with 60/70 asphalt binder is lower than one of 40/50. The PMB3 asphalt concrete has a significantly lower Mr value in comparison with 60/70 asphalt concrete at 20°C. This can be attributed to the polymer-modified nature of PMB3, which is designed to enhance elasticity and deformation resistance at high temperatures. However, at 20°C, the polymer's effect is not fully activated, leading to reduced stiffness compared to conventional asphalt binders. Additionally, the polymer-modified AC contains a higher asphalt content (approximately 0.3–0.5% more) than the 60/70 asphalt concrete, which reduces the Mr stiffness of the mix at moderate temperatures. The average coefficient of variation in the resilient modulus test was 7.8%, with a minimum of 0.6% for AC12.5 PMB3 and a maximum of 14.9% for AC19 PMB3. The standard deviation corresponding to each asphalt concrete type is also shown in Figure 9 (represented by error bars). These results indicate that the Mr test results have good repeatability.

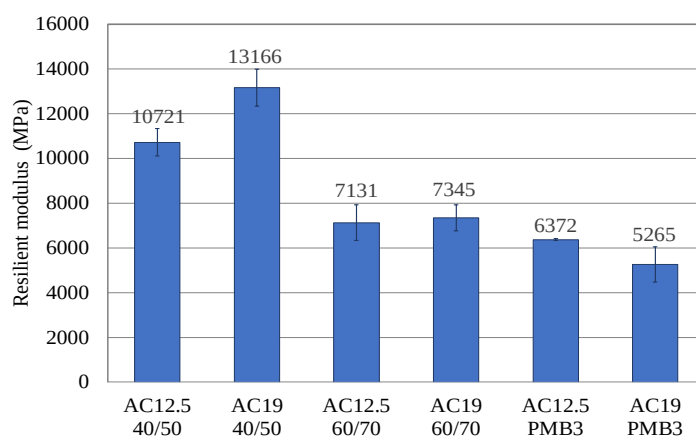


Fig. 9 – Experimental results of Mr for different asphalt concretes.

3.3 Tensile Strength Ratio (TSR) test results

Figure 10 indicates the indirect tensile strength of six tested asphalt concretes while their TSR values are presented in Figure 11. The experimental results showed that the highest tensile strength ratio as well as indirect tensile strength belonged to asphalt concrete using PMB3, followed by 40/50 asphalt concrete and finally 60/70 asphalt concrete. This can be explained by the mechanical and chemical properties of the PMB, which enhance the tensile strength of original bitumen and the adhesion between the asphalt binder and aggregates, thereby significantly improving water resistance of mixture. In addition to increasing the deformation resistance of AC at high temperatures, PMB3 asphalt binder is recommended for surface layers on roads that are heavily affected by high temperature and moisture conditions. Regarding the gradation, AC19 has a higher TSR than AC12.5 but has a similar (for PMB3) or smaller (for 40/50 and 60/70 asphalt binder) indirect tensile strength than AC12.5. The highest coefficient of variation in the TSR test was 5.4%, corresponding to the dry condition test for AC19 60/70. The average coefficient of variation was 2.7% that indicates good repeatability of TSR tests. The standard deviations are illustrated using error bars in Figure 10.

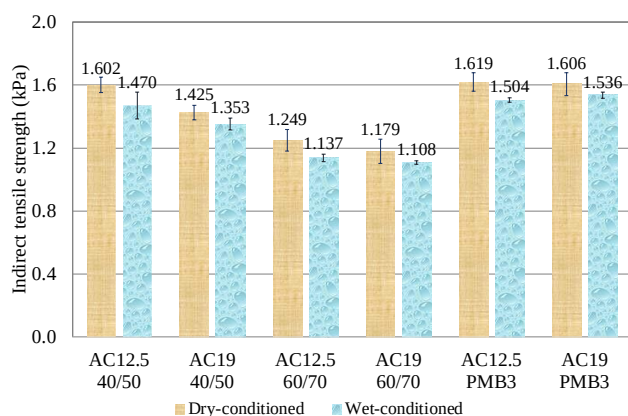


Fig. 10 – Indirect tensile strength for different asphalt concretes.

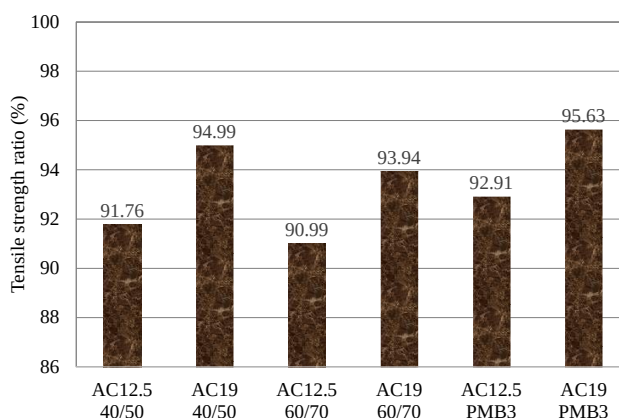


Fig. 11 – Tensile strength ratio for different asphalt concretes.

4 Conclusion

This study conducted experiments to evaluate the key mechanical properties of asphalt concrete (AC), including the dynamic modulus ($|E^*|$), resilient modulus (M_r) and moisture resistance (TSR). The experimental results demonstrated a significant influence of asphalt binder type and nominal maximum aggregate size on the mechanical behavior of the materials.

- Mixtures incorporating 40/50 asphalt binder exhibited the highest $|E^*|$ values, followed by those with polymer-modified asphalt binder (PMB3) and finally those with 60/70 asphalt binder. This demonstrates the role of low penetration asphalt binder (40/50) in enhancing the stiffness of the mixture. Additionally, mixes with a larger aggregate size (19 mm) exhibited significantly higher $|E^*|$ values than those with a smaller aggregate size (12.5 mm), confirming that coarser aggregates enhance the stiffness under varying frequency and temperature conditions.
- The $|E^*|$ values decreased with increasing temperature and decreasing frequency, reflecting the viscoelastic nature of asphalt concrete. The dynamic modulus of all tested materials respects the time-temperature superposition principle and the $|E^*|$ master curves were built.
- The 2S2P1D model successfully simulated the master curve of the dynamic modulus of asphalt concrete, with R^2 range from 84% to 97%, making it a reliable tool for predicting the viscoelastic behavior of these materials under different loading and temperature conditions.
- The experimental results revealed that AC with 40/50 asphalt binder achieved the highest M_r values at 20°C, making them suitable for pavement structures requiring high performance and load-bearing capacity. Meanwhile, mixtures with PMB3 asphalt binder, despite their advantages at high temperatures, exhibited lower M_r values at 20°C due to the polymer component not fully activating at this temperature.
- Mixtures incorporating polymer-modified asphalt binder (PMB3) demonstrated the highest TSR and indirect tensile strength values, due to the superior adhesion between the asphalt binder and aggregates, followed by 40/50 asphalt concrete and then 60/70 asphalt concrete. In terms of aggregate gradation, AC19 exhibits a higher TSR than AC12.5. However, its indirect tensile strength is similar to AC12.5 when using PMB3 and lower when using 40/50 or 60/70 asphalt binder.

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