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Rheological Huet-Sayegh Model Applied for Asphalt Rubber

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ABSTRACT
Asphalt is the main component of asphalt mixtures used as flexible pavements surface. Nowadays, for light and moderate traffic conditions, conventional asphalt performs adequately. However, under severe conditions of heavy traffic and variety climate, road distress as fatigue and permanent deformation prematurely occur. In these conditions, higher mechanical resistance is required, no longer provided by conventional asphalt. This happens because conventional asphalt has a limited capacity under heavy traffic in specific temperature ranges. In this way, the asphalt needs to be modified to improve asphalt mixtures mechanical performance in the field. This study assed the rheological behavior of asphalts modified with crumb rubber from waste tires. The tests were performed through dynamic shear rheometer, with temperature variation and frequency sweep. The rheological tests were performed with modified asphalts contained different crumb rubber content and then, compared to conventional asphalt, used as a reference. The Cole-Cole plan results showed that conventional asphalt is more susceptible to temperature variation and presents higher dissipative modulus in relation to asphalts rubber. The good fit of the modeling to the experimental data confirms the applicability and adequacy of Huet-Sayegh model to describe asphalts rheological characteristics and proved to be consistent to describe asphalt viscoelastic performance.

Keywords - Asphalt Rubber, Huet-Sayegh Model, Rheology

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I. INTRODUCTION

Hot asphalt mixtures (HMA) used as a surface in flexible pavements are, in general, composed of coarse and fine aggregates, filler and conventional asphalt. Asphalt represents the main component due to its viscoelastic properties. As HMA inherit the asphalt performance that composes it, the characteristics of then have a significant influence on HMA rheological properties, affecting mainly the stiffness and thermal susceptibility.

Conventional asphalts have a limited capacity under heavy traffic conditions at specific temperature ranges. Thus, in conditions, conventional asphalts need to be modified to meet the requirements of mechanical performance of asphalt mixtures in the field, related to fatigue and permanent deformation.

For asphalt evaluation, in terms of its viscoelastic behavior, it is necessary to understand the performance of asphalt mixtures in the field. The asphalt viscoelastic characteristics analysis, relative to its stiffness under temperature and frequency variations, could help to explain the appearing of surface distress as fatigue and permanent deformation during the pavement life span. In this way, the knowledge of asphalt rheological performance shows as a useful analysis tool.

Rheology is the science that studies and evaluates the response of time and temperature-dependent materials when subjected to an applied force. The main rheological parameters are the complex shear modulus that can be defined as material resistance to deformation and the phase angle, which represents the lagged time interval between applied stress and the resulting strain. The rheological tests are performed in the dynamic shear rheometer (DSR).

The materials applied in road pavement layers are versatile in terms of the possibility of incorporating by-products and industrial waste. The generation of solid waste represents an environmental problem that, decisively, affects the life quality of the population. Solid wastes that are not collected or improperly deposited in landfills create health problems and water contamination in the places where it is stored. In this scenario, waste tires are included.

Since 1990, in Brazil, waste tires have been reinserted in the productive chain in various ways. The main waste tires use for pyrolysis; as fuel in cement industry ovens and as a ground rubber to introduce into the asphalt, modifying it. The incorporation of rubber in asphalt as a modifying agent presents an alternative to recycling this solid waste, the tire.

Brazil is a country in which high temperatures is predominance. Also, most cargo and people are transported by the road that results in heavy traffic on the main roads. Asphalt rubber mixtures are frequently used and resisted, such as traffic and temperature conditions. However, it is still essential to establish asphalt performance.

This study aims to evaluate the rheological performance of modified asphalt with different rubber contents. The tests were performed in the dynamic shear rheometer (DSR), and Huet-Sayegh rheological models were generated. The modified asphalts results were compared to conventional asphalt, as a reference.

II. BACKGROUND

Asphalt is a product derived from the crude oil residue obtained after a refining process (controlled distillation) in which light fractions (distillates) are firstly removed. One of the main characteristics of the asphalt is its viscoelastic behavior in the service temperatures that means the temperatures that the pavement is subjected in the field. Also, it is sensitive to h high and cold temperatures [1].

The asphalt modification by polymers and other sub-products have been increasingly used. In general, modifiers present capacity to improve asphalt mixtures mechanical resistance by altering asphalt rheological behavior. Modifiers also contribute to enhancing characteristics related to oxidative ageing compared to conventional asphalt [2].

The mechanical or structural improvements of asphalt mixtures through the modified asphalt incorporated are mainly: reduction of permanent deformation; increased fatigue resistance, increased cohesion, reduced thermal susceptibility [1]. However, although these effects positively impact the durability of modified asphalt mixtures, Woo et al. (2006) [2] state that it is necessary to quantify them to order and select the modified binders about the best cost-benefit ratio and, consequently, to efficient use. Several modifiers have been used, for example, polymers such as styrene-butadiene-styrene (SBR), styrene-butadiene rubber (SBS), ethylene vinyl acetate, (EVA), polyphosphoric acid (PPA), crumb rubber from waste tires, among others.

In Brazil, conventional asphalts are specified by penetration following the prescribed by the National Department of Transport Infrastructure (DNIT) [3]. The asphalt rubber is produced by the wet process, terminal blend, with 20% and 15% of crumb rubber content [4].

The wet process consists of the incorporation of crumb rubber with asphalt before mixing the asphalt with the aggregates. The result is modified asphalt that has significantly different properties from the base asphalt [5-6]. The wet process comprises two systems, the continuous blend (no storage) and the blending terminal (storage). In Brazil, asphalt rubber is produced at asphalt distributors through the blend terminal system, at high shear and temperature [6].

According to ASTM D 8 [7], asphalt rubber in the wet process is a mixture of asphalt, crumb rubber and some additives in which the rubber represents at least 15% of the total mass of the mix. The physical characteristics of asphalt rubber are specified by the ASTM D 6114 standard [8], depending on the region where the material will be applied.

Rheology has been a useful tool to characterize and quantify asphalt properties since its properties have a significant influence on pavement performance and the rate of deterioration when subjected to high loads and in adverse environmental conditions [9]. The rheological parameters are determined in tests through the dynamic shear rheometer (DSR). DSR is used to characterize the viscous and elastic asphalt behavior at medium to high temperatures. During the test, shear stress (t) is applied and the asphalt sample response is the shear strain (ε) [10]. Considering the asphalt viscoelasticity, the response (strain) is out of phase concerning the applied stress for a specified time lag (Δt), measured by phase angle (δ) in degree, as illustrated in Fig. 1.

DSR measures the complex shear modulus (G*) and the phase angle (δ) and the tests are performed in temperature variation and frequency sweep. The phase angle (δ) represents the difference between stress and strain in harmonic oscillation. If δ equals 90^0, the material can be considered purely viscous, while, when δ is 0^0 corresponds to purely elastic behavior. The complex modulus magnitude and phase angle are often the two parameters that represent the asphalt viscoelastic properties [10]. The parameters G* and δ are highly dependent on the temperature and frequency loading.

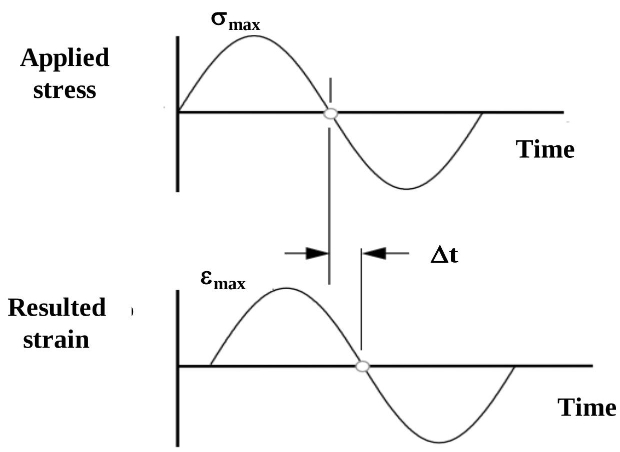


Fig.1. Applied stress and resulted strain for viscoelastic materials (Based on SHRP [10]).

Thereby, it is essential to determine the temperature of the project where the pavement will be implanted, as well as the traffic speed (frequency). From Fig. 1, the complex shear modulus is calculated by Equation (1):

$$G^* = \frac{\sigma_{max}}{\varepsilon_{max}} \quad (1)$$

Where G* is the complex shear modulus; σ_{max} is maximum applied shear stress; ε_{max} is the resulted shear strain.

The complex shear modulus represents the total material resistance to deforming when repeatedly sheared and consists of elastic and a viscous component (Fig. 2).

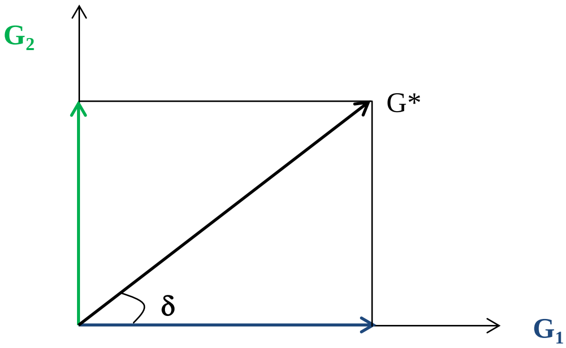


Fig. 2. Complex shear modulus components.

The storage modulus (G_1), which is the recoverable or elastic component, represents the amount of energy stored in a sample during each load cycle. On the other hand, the dissipative or loss modulus (G_2) is the non-recoverable component or viscous that represents the energy lost during each load cycle. Measuring G* and δ, the DSR provides a complete analysis of the behavior of the asphalt at service temperatures to which the pavement is subjected [11-14]. The complex shear modulus components, storage modulus (G_1) and loss modulus (G_2) are calculated by Equation (2) and Equation (3), respectively. The norm for the complex modulus is called dynamic modulus and the phase angle refers to the phase shift between the deformation and the measured stress on a material in rheological tests [7]. Dynamic modulus represents the absolute value of the shear complex modulus |G*|. In oscillatory tests, the complex shear modulus is defined mathematically as Equation (4) and Equation (5).

$$G_1 = \frac{\sigma}{\varepsilon} \times \cos\delta \quad (2)$$

$$G_2 = \frac{\sigma}{\varepsilon} \times \sin\delta \quad (3)$$

$$G^* = \sqrt{G_1 + G_2} \quad (4)$$

$$G^* = G_1 + iG_2 \quad (5)$$

Where σ is the shear stress; ε is the strain; δ is the phase angle; G_1 is the storage modulus; G_2 is loss modulus (imaginary part of G*, the out of phase component amplitude); i is the complex number (x^2 = -1).

The asphalt rheological data can be presented in terms of complex modulus, phase angle and its components, such as, isochrones, isotherms, black diagram, Cole-Cole plan and master curves. The isotherm curves express the evolution of the complex modulus and its phase angle for each test temperature at the tested loading frequencies. The complex modulus norm increases with the decrease of temperature, while the opposite is observed for the phase angle. The Cole-Cole plan represents the relation between the storage (G_1) and loss (G_2) components of modulus. Black diagram states the relation between the material stiffness and its viscosity [15].

Considering that G* depends on the loading frequency as well as the temperature, the time-temperature superposition principle stands that a unique reduced variable, the equivalent frequency, can be introduced to describe the evolution of the complex modulus for every frequency/temperature loading condition, called master curve. Thus, the same complex modulus norm (|G*|) value can be obtained at different combinations of loading frequency and temperature [15]. From complex modulus test including various temperatures, the evolution of the shift factor can be fitted by the Williams-Landel-Ferry (WLF) equation (Equation 6).

$$\mathrm{Log}a_{T_R} = \frac{C_1(T - T_R)}{C_2 + T - T_R} \qquad (6)$$

Where a_{TR} is the shift factor from an isotherm curve to reference temperature TR; T is a temperature of an isotherm curve (K); C_1 and C_2 are the constants of the WLF equation.

Viscoelasticity is a phenomenon that describes materials that have characteristics as fluid and as an elastic solid at the same time. To better understand the viscoelastic behavior of the materials, mechanical models are used that consist of springs and dashpots coupled in series and parallel. The spring represents the elastic behavior and follows Hooke law, while the dashpot is in line with Newton law as a mechanical model with a viscous element. Several rheological models were developed that can be treated mathematically, i.e., Maxwell; Kevin-Voigt; Huet; Huet Sayegh, 2S2P1D [16].

Rheological tests and models are used to describe and evaluate the asphalt viscoelastic behavior [9]. In a linear viscoelastic behavior, the material properties are assumed independents of the applied stress or strain levels [17]. The Huet-Sayegh rheological model is an improved version by Sayegh [18] in relation to the Huet model [19]. The Huet model components are one spring and one dashpot connected in series. The model is characterized by an infinite number of Kelvin-Voigt models in series or Maxwell models in parallel with continuous spectrum [17]. The express of complex modulus G* by the Huet model is done by Equation 7.

$$G^* = \frac{G_\infty}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \qquad (7)$$

Where i is the complex number defined by $i^2 = -1$; ω is 2π, frequency, pulsation; G∞ is the limit of the complex shear modulus when $\omega\tau \to \infty$ or infinite modulus; h, k are exponents such that $0 < 1 < k < h$; δ is a dimensionless constant; τ: is the relaxation time whose characteristics varying only with the temperature.

However, Huet model is limited at high temperatures and low frequencies because it has not a static modulus G_0 [20]. In this case, Sayegh improved Huet model with the addition of a spring parallel to the model. In the Huet-Sayegh model (Fig. 3), the spring represents the static modulus (G_0) and is shown through Equation 8, in terms of the complex shear modulus. The adjustment experimental data from Cole-Cole plan is presented in Fig. 4.

$$G^* = G_0 + \frac{G_\infty - G_0}{1 + \delta\left(i\omega\tau(\theta)\right)^{-k} + \left(i\omega\tau(\theta)\right)^{-h}} \qquad (8)$$

Where i is the complex number defined by $i^2 = -1$; ω is 2π, frequency, pulsation; G∞ is the limit of the complex shear modulus when $\omega\tau \to \infty$ or infinite modulus; h, k are exponents such that $0 < 1 < k < h$; δ is a dimensionless constant; τ is the relaxation time whose characteristics varying only with the temperature (θ), G_0 is the static modulus.

The dashpots relaxation time is given by Equation 9 in function of the temperature (θ) and three scalar parameters A_0, A_1 and A_2, constants.

$$\tau(\theta) = e^{(A_0 + A_1\theta + A_2\theta^2)} \qquad (9)$$

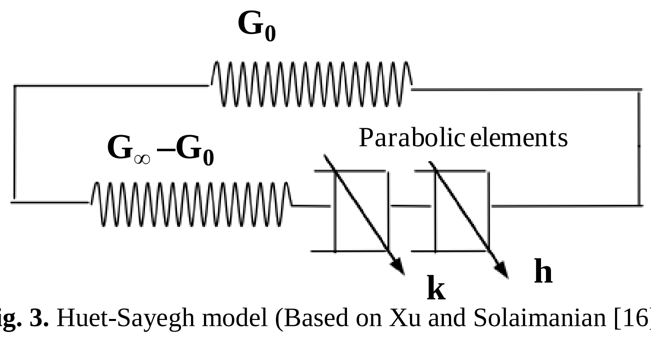


Fig. 3. Huet-Sayegh model (Based on Xu and Solaimanian [16]).

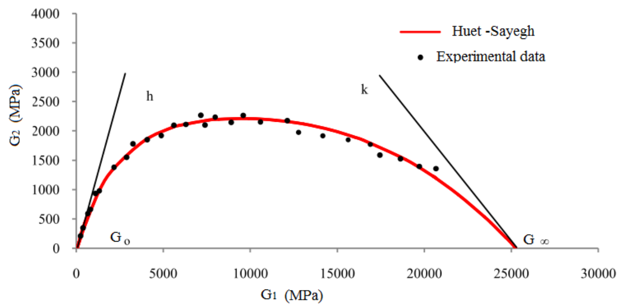


Fig. 4. Huet-Sayegh model adjusted in Cole-Cole plan (Based on Quintero [21]).

Several researchers [16-17; 20; 22-24] have obtained consistent results based on experimental and modeling results using the Huet-Sayegh model, without the need for a large number of complex terms or calculations. The model proved to be a useful tool for the construction of the modulus master curve. Furthermore, the Huet-Sayegh model proved to be adequate, and for the calculation of the modulus and the phase angle, it showed accurate precision. After that, Olard and Di Benedetto developed the 2S2P1D model, which is obtained by adding a linear dashpot in series to the Huet-Sayegh model. The 2S2P1D model added improvements to the Huet-Sayegh model concerning high temperatures and low frequencies [25].

III. METHODOLOGY

In this study, the rheological behavior of three asphalt rubber and Brazilian conventional asphalt (CAP 50/70, classified by penetration) as a reference were evaluated. For the asphalts the Huet-Sayegh model was generated through ViscoAnalyse software. Fig. 5 shows the phases of the experimental methodology.

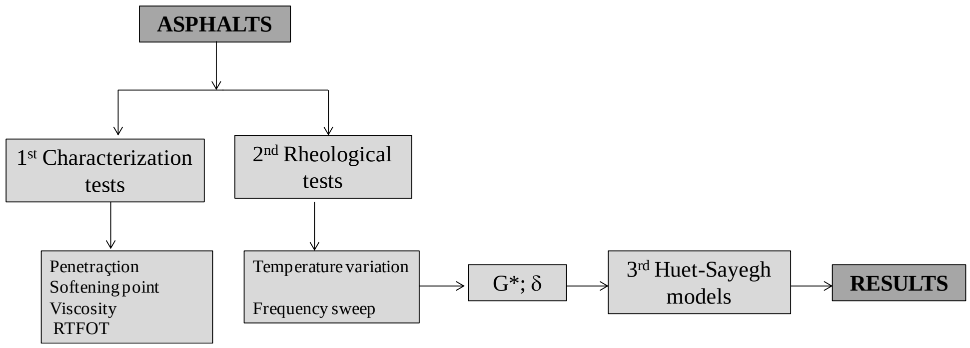


Fig. 5. Phases of the methodology.

In the 1st phase, the asphalts were characterized by the conventional tests, such as penetration, softening point, apparent viscosity with Brookfield viscometer and, ageing test using Rolling Thin Film Oven Test (RTFOT). Table 1 presents the types of asphalts tested in this study.

The rheological tests were performed in 2nd phase. The tests to obtain the parameters, complex shear module (G*) and phase angle (δ) were carried out in the dynamic shear rheometer (DSR). A scan of twenty-five frequencies between 0.01 and 10 Hz at five temperatures (20ºC, 30ºC, 40ºC, 50ºC and 60ºC) was performed. The tests were conducted in Reologica StressTech HR rheometer using parallel plates with 40 mm in diameter and sample thickness of 8 mm. Also, the tests were carried out through dynamic measurements, that is, an oscillatory deformation of a sinusoidal nature, of low amplitude, under controlled conditions.

In the 3rd phase, the Huet-Sayegh models were generated using ViscoAnalyse software, which is a tool that allows you to view measurements of complex modules, interpret data in terms of temperature, build master curves and calibrate analogue models (Huet, Huet-Sayegh). The Viscoanalyse inputs are the complex shear modulus |G*|, and phase angle measured in several temperatures and frequencies for each temperature [22].

Table 1. Asphalt types.

Denomination	Asphalt base	Type	% of rubber	System
CAP	CAP 50/70	Conventional	-	-
AB15	CAP 50/70	Asphalt rubber	15	Terminal blend
AB20	CAP 50/70	Asphalt rubber	20	Terminal blend
AB17	CAP 50/70	Asphalt rubber	17	Continuous blend

IV. RESULTS

Table 2 presents the characterization tests results of the conventional asphalt (CAP 50/70), in which can be observed that CAP 50/70 meets into Brazilian specifications [3] and can be used to asphalt mixtures production. The asphalts rubber test results fit according to ASTM D 6114 specifications [8], as shows in Table 3.

Table 2. Characterization tests results of conventional asphalt.

Tests	Standard	Specification[3]	CAP
Penetration (0.1 mm), 100g, 25ºC, 5s	[26]	50 to70	51.5
Softening point[1] (º)	[27]	46 (min)	51.5
Apparent viscosity[2] (cP)			
135º C	[28]	274 (min)	580
150ºC		115 (min)	150
177ºC		57 to 285	112
RTFOT (163ºC, 85 minutes)			
Change mass (%)	[29]	0.5 (max)	0.3
Softening point elevation (ºC)		8 (max.)	4,3
Apparent viscosity[2] (cP), 175ºC		-	95.8
Penetration (0,1 mm), 100g, 25ºC, 5s		-	22.3
Retained penetration (%)		55 (min)	56

[1]Ring and ball method; [2]Brookfield viscometer; [3]Brazilian specification [3].

Table 3. Characterization tests results of asphalts rubber.

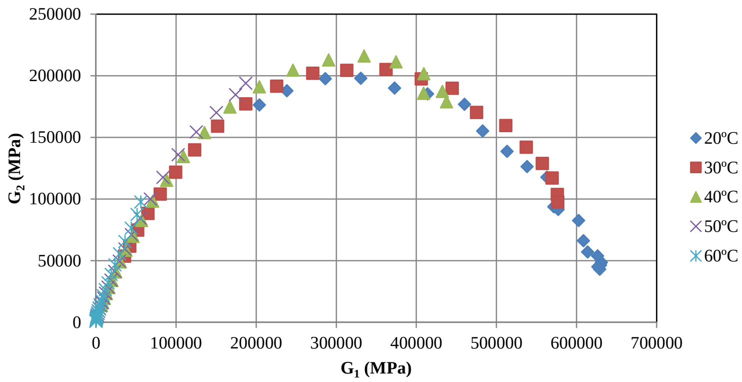
Tests	Standard	Specification[3]	Asphalt rubber		
			AB15	AB20	AB17
Penetration (0,1 mm), 100g, 25ºC, 5s	[26]	25 to 75	42	40	26
Softening point[1] (º)	[27]	54.4 (min)	67.7	68.0	65.0
Apparentviscosity[2] (cP), 175º(cP)	[28]	1,500 (min)	1,644	2,179	2,829
RTFOT (163ºC, 85 minutes)					
Change mass (%)	[29]	-			
Softening point elevation (ºC)		0.6 (max)	0.3	0.3	0.3
Penetration (0.1 mm), 100g, 25ºC, 5s		-	25.3	28.8	18.5
Retained penetration (%)		-	30.2	72.0	71.7
Apparent viscosity[2] (cP), 175ºC		-	1,962	5,350	4,800

[1]Ring and ball method; [2]Brookfield viscometer; [3]ASTM specification [8].

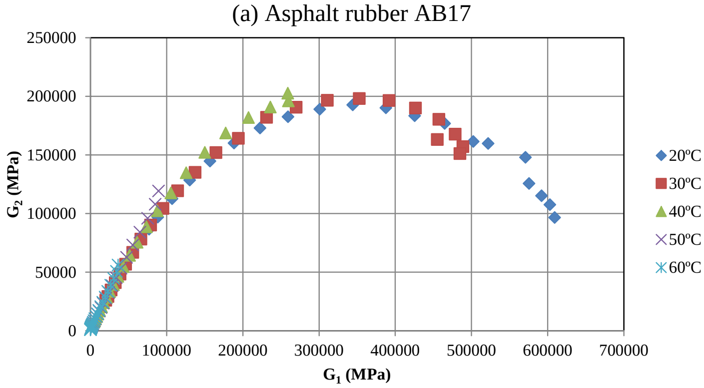
The rheological parameters, complex shear modulus (G*) and phase angle (δ) were obtained through the dynamic shear rheometer (DSR). The rheological behavior was represented through the Cole-Cole Plan and master curve. The master curves parameters were obtained using ViscoAnalyse software for the reference temperature of 20ºC. This temperature was chosen because in general, is used in asphalt mixtures fatigue tests and the dynamic modulus in the pavement design.

Fig. 6 shows that the curves in the Cole-Cole plane of asphalt rubber are similar in terms of storage and dissipative modulus. However, the representation in the Cole-Cole plane for conventional asphalt (Fig. 7) shows that this asphalt has a higher dissipative modulus than modified asphalts, which is indicative of lower performance in the field. On the other hand, asphalt rubber AB15 presented lower dissipative module, which may indicate better fatigue behavior in the field. Conventional asphalt obtained a higher dissipative modulus, and thus, it would tend to have worse mechanical performance in the field when compared to rubber asphalt.

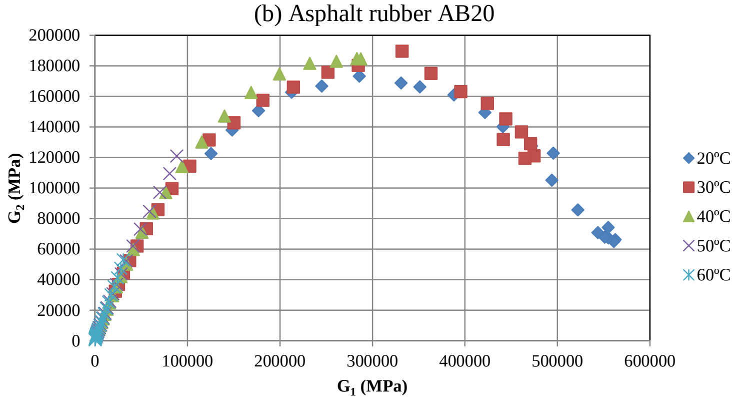
Fig. 8 illustrates the master curves of the asphalts, which indicated that all asphalt rubbers in relation to conventional asphalt presented in a range of frequencies and temperatures, a higher stiffness.



(a) Asphalt rubber AB17



(b) Asphalt rubber AB20



(c) Asphalt rubber AB15

Fig. 6. Curves in the Cole-Cole plane for asphalt rubber.

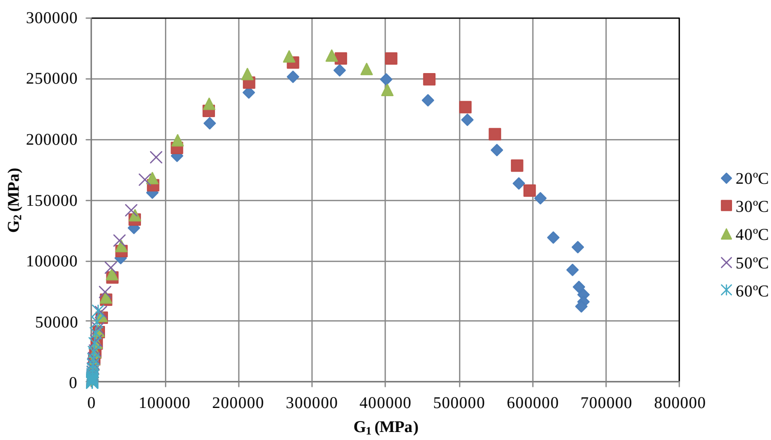


Fig. 7. Curve in the Cole-Cole plane for conventional asphalt (CAP).

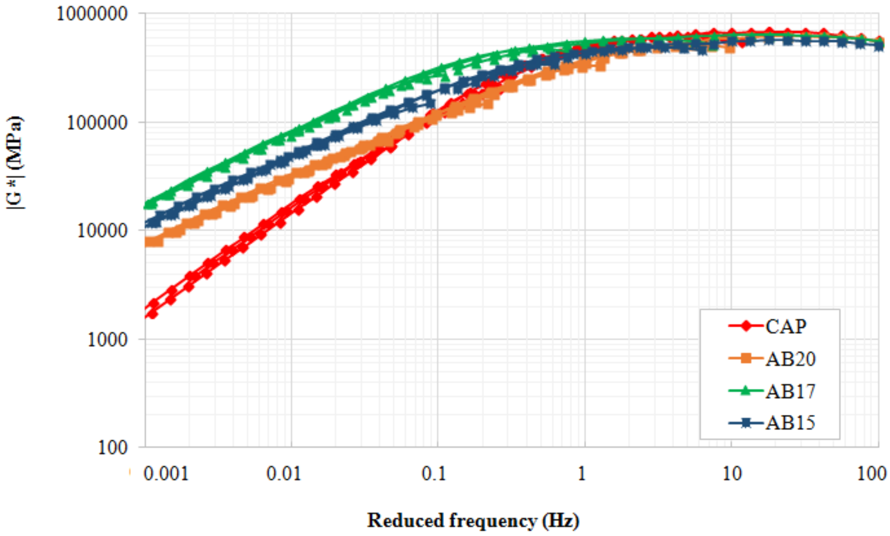


Fig. 8. Master curves of the asphalts.

The parameters of Huet-Sayegh rheological model, obtained through ViscoAnalyse software, are present in Table 4. Huet-Sayegh proved to be consistent for modeling the asphalt, viscoelastic behavior, once the sum of the standard deviation was minimal. The adjustment results of parameters "k" and "h" (parabolic elements) showed that being the parameter "h" characterizing the viscous behavior of the material; it is observed to be higher for conventional asphalt (CAP). The "k" parameter (describes the elasticity) was higher for AB15 asphalt.

Table 4. Huet-Sayegh parameters.

Parameters	Asphalts			
	CAP	AB15	AB20	AB17
G_0 (static modulus), MPa	811.40	433.42	152.72	134.28
G_∞ (infinit modulus), MPa	58,893.3	119.126.0	346.063.0	672,282.8
δ (constant)	0.3834	1,2263	0.1955	0.8209
k (parabolic element)	1.1313	1.6116	0.07526	0.1778
h (parabolic element)	0.2483	0.1490	.	0.0726
β (constant)	5.7835	2.2817	1.6136	1.1346
τ (Relaxation time)	1,732.48	1,690.32	1,238.47	1,131.45
Standard deviation	0.00120	0.000198	0.00096	0.0049

From the data obtained, the asphalt would be ordered as the best fatigue prediction (AB15), permanent deformation (AB20), followed by AB17 and CAP. The good fit of the curves to the experimental data confirms the applicability and adequacy of the Huet-Sayegh model to describe linearity. However, the mechanical behavior of asphalt mixtures in the field is also influenced by the asphalt content and gradation.

V. CONCLUSION

In this study, viscoelastic characteristics of different modified asphalt with rubber were evaluated in relation to conventional asphalt. Two asphalts rubber come from terminal blend system containing 15% (AB15) and 20% (AB20) of crumb rubber content. An asphalt rubber produced in the laboratory by continuous blend system with 17% (AB17) of crumb rubber was also tested. The conventional reference asphalt (CAP) was a Brazilian CAP 50/70, classified by penetration, being the same asphalt base for asphalts rubber production.

Characterization tests were carried out for all the asphalts, and the rheological parameters were evaluated through DSR varying temperature and frequency. From the master curve and Cole-Cole plan construction and; Huet-Sayegh model generated, the analysis of viscoelastic behavior was assessed.

The complex modules measured in a range of frequencies and temperatures met the conditions in the theory of linear viscoelasticity in which the stiffness and phase angle are dependent parameters. As for stiffness, it was observed that rubber asphalt presented less penetration and a higher softening point compared to conventional asphalt, which was expected by the presence of rubber.

The complex modulus variation data in different frequency and temperature was used to build the master curves based on the parameters of the WLF equation and, allowed to classify the asphalts. In this case, conventional asphalt was more susceptible to temperature variation. The WLF model provides the possibility of building master curves at any temperature based on the relationships between C_1 and C_2 constants at different reference temperatures. The experimental data represented in Cole-Cole plane presented well adjust when Huet-Sayegh models were generated.

Also, the good fit of the curves from the experimental data confirms the applicability and adequacy of the Huet-Sayegh model to describe linearity. As for asphalts ordination, AB15 asphalt would be the most suitable for fatigue resistance while AB20 asphalt for permanent deformation. However, the mechanical behavior of asphalt mixtures depends on several factors, including aggregates and mixture gradations, asphalt content and void volume. In this way, the prediction of asphalt behavior must be verified from mechanical tests of asphalt mixtures.

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