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Evaluación reológica y mecánica de un aglutinante asfáltico modificado por polímeros

Rheological and mechanical evaluation of a polymer modified asphalt binder

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Abstract

The paper presents a comparative study between the properties of a conventional binder and a polymer-modified binder, as well as some mechanical properties of hot mix asphalt concrete (HMA) made with these binders. The comparation of binder based on conventional indices and advanced dynamic properties obtained with a dynamic shear rheometer (DSR). These include the dynamic modulus |G|and phase angle (δ) master curves, the fatigue susceptibility in the LAS (Linear Amplitude Sweep) and permanent deformations in the MSCR (Multi Stage Creep Recovery). The asphalt mixtures dosed and compacted according to the Superpave methodology. The mechanical properties explored in concrete asphalt (CA) specimens subjected to moisture-induced damage and static creep tests. The results show the positive effects of polymer addition in the binder's and hot mix asphalt concrete properties, especially with regard to elastic resilience and permanent deformation reduction.*

Keywords: *Modified asphalt; evaluation; rheological; mechanical*

Resumen

El trabajo presenta un estudio comparativo entre las propiedades de un asfalto convencional y un asfalto comercial modificado por polímeros. Se estudia la influencia en las propiedades mecánicas de mezclas asfálticas densas confeccionadas con estos aglutinantes. Los asfaltos son comparados a partir de índices convencionales y propiedades dinámicas obtenidas con un reómetro dinámico de cortante (DSR). Son determinadas las curvas maestras de módulo dinámico |G*| y del ángulo de fase (δ), la susceptibilidad a la fatiga con el ensayo LAS (Linear Amplitude Sweep) y las deformaciones permanente con el ensayo MSCR (Multi Stage Creep Recovery). Las mezclas asfálticas son dosificadas y compactadas según la metodología SuperPave. Las propiedades estudiadas son: daño por humedad inducida y fluencia estática. Los resultados muestran efectos positivos de la adición del polímero tanto en las propiedades analizadas de los asfaltos como en la mezcla, fundamentalmente en la recuperación elástica y la reducción de deformaciones permanentes.

Palabras clave: Asfalto modificado; evaluación; reológicas; mecánicas

1. Introduction

Dense-graded asphalt mixtures are widely used as surfacing for urban and rural roads in Brazil. With the increase in the volume and configuration of traffic in recent years, the use of asphalt mixtures with different granulometries has increased, as well as the use of modified asphalts (Vasconcelos et al., 2011).

The bearing capacity of asphalt concrete is mainly given by the friction generated by the disposition and contact between the aggregates. According to (Kim, 2009) the pathologies of a pavement structure can be mainly classified into two main groups: cracks and permanent deformation. Permanent deformation and crack propagation in asphalt mixtures are affected by several factors such as loading rates, loading time, resting period, temperature, stress state, aging, and moisture. Cracks and fissures can be caused by thermal effects or fatigue. For (Santos, 2012) cracking is related to micro-cracking phenomena in the asphalt mixture and the concentration of stresses at the aggregate-binder interface, while the appearance of permanent deformations is associated with the dissipation of energy caused by the viscoelastic behavior of the asphalt and the accumulation of micro-cracks. While reducing the volumetric fraction of asphalt binder in the mixture reduces the susceptibility to permanent deformation, increasing the volumetric fraction of stone aggregates increases the susceptibility to cracking.

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In order to improve the mechanical behavior of asphalt concrete, the development of asphalt modification by adding polymers has grown. Modifiers give the asphalt greater resistance to fatigue and permanent deformation as well as reducing thermal susceptibility (Domingos and Faxina, 2016); (Pamplona et al., 2012); (Saboo and Kumar, 2015); (Silva et al., 2002). The increased rigidity of the asphalt binder resulting from the incorporation of additives increases the resistance to permanent deformation (Pamplona et al., 2014). In the study of (Domingos et al., 2017), based on the application of dynamic shear rheometer (DSR) tests, the susceptibility of asphalts and asphalt mixtures to permanent deformation is evaluated by studying three types of polymers as asphalt modifiers. The use of modified asphalts in the production of asphalt mixtures provides an increase in resistance to permanent deformation (Onofre et al., 2013).

Tests that simulate long-term aging of the asphalt mixture include the moisture-induced damage test. From this test, several asphalt mixtures produced in Brazil with the addition of modified asphalts are studied and it is proven that modification with SBS polymers becomes more resistant to the action of water (Anitelli, 2013).

Thus, this paper shows the results of the conventional and rheological characterization of polymer-modified asphalt (PMA). In addition, the performance of a dense-graded asphalt mix (CA) produced with PMA is evaluated based on mechanical tests for moisture-induced damage and static creep (Creep Compliance). These results are compared with those of a mixture produced with conventional asphalt under similar conditions and characteristics.

2. Materials and methodos

The tests of this work were conducted at the Infrastructure Laboratory (In-fralab) of the University of Brasília (UnB). The mixtures were produced with dolomitic limestone aggregate frequently used in the Federal District of Brazil, and asphalt modified by elastomer polymers under the trade name Stylink, classified as PG 76-22 Type E 60/85. The aggregates are dosed in a granulometric curve that follows the "C" fraction defined by the National Department of Transportation Infrastructure (from the Spanish Departamento Nacional de Infraestructura de Transporte, DNIT). The limestone material shows Los Angeles Abrasion results of 21%; magnesium sulfate durability of 4.2% and sand equivalent of 68%. On the other hand, asphalt characterization was divided into conventional physical tests and rheological characterization tests. For comparative purposes, petroleum asphalt cement (CAP) with a penetration rate of 50/70, widely used in the production of asphalt mixtures in Brazil, was also characterized. The results of the moisture-induced damage tests and static creep tests are compared with a dense mixture produced under similar conditions and characteristics and using, in addition to the limestone material, 50/70 pure asphalt cement.

2.1 Rheological Characterization

The dynamic shear rheometer (DSR) model SmartPave 102 is used to characterize the rheological parameters of pure and modified asphalt cements. Asphalt cements are tested after aging to verify and compare their rheological properties. For this purpose, the results of the Brookfield viscosity, construction of the dynamic shear modulus master curves |G| and the phase angle (δ), the LAS (Linear Amplitude Sweep) test and the MSCR (Multiple Stress Creep and Recovery) test are shown.*

For the construction of the master curve, the time-temperature superposition principle is applied, which is an inherent characteristic of viscoelastic materials, for a reference temperature which in this case is 25°C. The asphalt samples are subjected to a frequency sweep of 0.1 to 100 rad/s. In this test, the isochrones of the properties of the complex shear modulus (G) and the phase angle (δ) are obtained. In a 15°C to 40°C temperature range of 5°C intervals, the master curve of the complex modulus can be mathematically modeled as a sigmoid function. The sigmoid function and the shift factor are defined by the following formulas:*

$$Log\left|G^*\right| = \mu + \frac{\alpha}{1+\exp(\beta+\gamma.Log(t_r))} \quad \textbf{(1)}$$

$$a(T) = \frac{t}{t_r} = \frac{\omega_r}{\omega} \quad \textbf{(2)}$$

$$Log(a(T)) = a.T^2 + b.T + c \quad (3)$$

Where μ, β, α and γ are coefficients of the sigmoid function, t is the loading time at a temperature of interest, tr is the reduced loading time at the reference temperature, a(T) is the shift factor and a, b and c are second-order polynomial coefficients. The process to obtain the variables defined in equations 1 - 3 is done through the least squares method, using an Excel spreadsheet developed by (Mello, 2008).

Based on this spreadsheet, a similar spreadsheet is developed for the construction of the phase angle master curve. Although the phase angle master curve is constructed with the Christensen Anderson and Marasteanu (CAM) model, the shift factor corresponds to that explained above. According to the authors (Bayane et al., 2017); (Yusoff et al., 2012) the CAM model is effective for both low and high-frequency master curve adjustments. The CAM model is described in formula 4 where β and λ are the model coefficients and ω is the reduced frequency.

$$\delta(\omega) = \frac{90}{\left[1 + (\frac{\omega}{\lambda})^{\beta}\right]} \quad (4)$$

The LAS test was developed by (Johnson, 2010) to quantify fatigue in asphalts using a short process. The test is carried out at a temperature of 25°C using an asphalt sample with a diameter of 8mm and a thickness (gap) of 2mm between the parallel plates. This test is divided into two stages. Initially, a frequency sweep of 0.1 - 30Hz is performed, with a strain amplitude of 0.1%, followed by a strain amplitude sweep in the range of 0.1%-30%, at a frequency of 10Hz and leading the material to break.

The Multiple Stress Creep Recovery (MSCR) test is specified under the AASHTO T 350 standard (AASTHO, 2014) and consists of measuring the viscoelastic properties (through creep compliance) of aged asphalt in an RTFO oven, by applying a 100Pa and 3200Pa stress. The test measures the elastic response in an asphalt binder subjected to shear stress and recovery. Non-recoverable creep compliance is a measure of permanent deformation and is defined as the percentage of a deformed residual unit (%ε) of a specimen after a load and recovery cycle divided by the stress applied.

2.2 Mechanical Evaluation of the Asphalt Mixture.

The test bodies (TBs) of dense-graded asphalt concrete were produced with a diameter of 150 mm in a gyratory compactor with compaction energy of 100 gyrations. Once stabilized at room temperature, 100 mm diameter cores are extracted to adjust the dimensions to the requirements of the mechanical tests. (Figure 1) shows the extraction process.

Figure 1. *Test body preparation process.*

The moisture-induced damage test is used to verify the performance of the modified asphalt used in the dense-graded asphalt mixture. The method for evaluating susceptibility to moisture damage is the method used by AASHTO, which evaluates the long-term action of water AASHTO T 283, (AASHTO 2014). This method estimates the damage from properties because water can separate the asphalt layer that binds the aggregates from the mixture. The TBs produced are separated into two groups. One is a reference group and the other is conditioned by the action of water. In thermal conditioning, the test bodies are partially saturated, packed in a plastic film, and placed in a plastic bag with 10 ml of distilled water, and then they are frozen at -18°C for 16 hours. Once this period is over, the TBs are subjected to a 24-hour bath at a temperature of 60°C. After this thermal conditioning process, the temperature is stabilized up to 25°C and the TBs are brought to break in a diametral compression test. The value of the diametral compression for the unconditioned and conditioned groups is determined by the following equation:

$$\sigma_R = \frac{2F}{\pi . d . h} \quad \textbf{(5)}$$

Where:
σR: tensile strength (Mpa);
F: breaking load in (N);
d: test body diameter (mm);
h: test body height (mm)

The mixture is susceptible to moisture damage when the RTS value (retained tensile strength)—defined as the ratio of the ITS (indirect tensile strength) between the unconditioned and conditioned TBs—is less than 80%. (Figure 2) shows part of the process of the moisture-induced damage test.

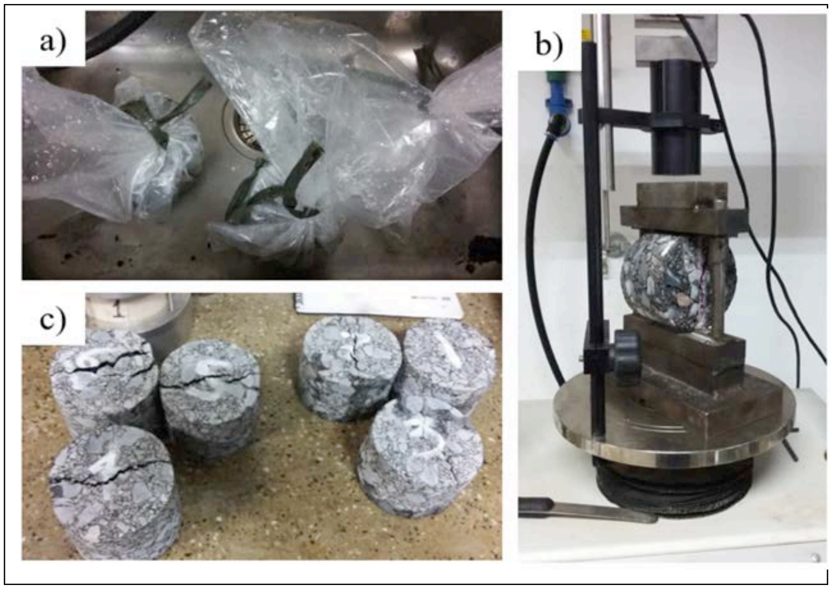

Figure 2. *Moisture-induced damage test. a) TBs during thermal conditioning. b) diametral compression. c) groups of TBs tested.*

2.3 Static Creep Test.

To evaluate the susceptibility to permanent deformation in modified asphalt mixtures, static creep tests are carried out. The test consists in the application of axial compression at a temperature of 25°C, applying a static load at a stress of 100 kPa (1.0 kgf/cm²) for one hour. Then, the test body remains in the unloading phase for 15 minutes to check the elastic recovery of the mixture. (Figure 3) shows the execution of the static creep test.

Figure 3. *Static Creep Test.*

3. Results

This section shows and analyzes the results obtained from tests carried out on conventional and modified asphalts and CA dense-graded asphalt concrete test bodies.

3.1 Conventional Characterization of Asphalts

The conventional properties of asphalt cements, besides being important in the specifications of the auxiliary material itself, together with the rheological characterization, are important when choosing the asphalt to produce the mixture under study in this research. The values obtained in the characterization of the CAP 50/70 asphalt cement and PG 76-22 Type E 60/85 modified asphalt cement are shown in the specifications of each conducted test (Table 1).

Table 1. *Results of characterization tests for asphalt cements.*

Tests	U/M	Limits		Results		Tests methods
		CAP 50-70	AMP	CAP 50-70	AMP	
Density	g/cm^3	-		1.002	1.012	DNER ME 193 (1996)
Penetration(100g, 5s,25°C)	0.1mm	50-70	40-70	56	45	DNER ME 003 (1999)
Softening point	°C	≥46	60, min.	48	65	DNER ME 247 (1994)
Ductility a 25°C, min.	cm	≥60		>100	>100	DNER ME 163 (1998)
Glare point	°C	>235		320	346	DNER ME 148 (1994)
Combustion point	°C	-		380	395	
Elastic recovery at 25°C, 20 cm	%	85 min.		7	90	DNER ME 163 (1998)
Effect of heat and air (RTFOT) a 163° C, 85 min						ASTM D 2872-04 (2004)
Mass variation, max.	% masa	0.5 max.		0.19	0.14	
Brookfield viscosity						ABNT NBR 15184 (2004)
a 135°C, Sp 21, 20 rpm	cP	141, min.	3000, max.	350	1022	
a 150°C, Sp 21, 20 rpm	cP	50, min.	2000, max.	210	520	
a 177°C, Sp 21, 20 rpm	cP	30-150	1000, max.	80	162	

The modified asphalt is "harder", as expressed by the penetration value, and is also less sensitive to the influence of temperature, as shown by the softening point results. The susceptibility under the influence of temperature is determined by the loss of weight during short-term aging (RTFOT). The lower this value, the less sensitive the asphalt cement is to the effects of temperature. This is precisely the case of modified asphalt when compared to CAP 50/70. Another important reference for this work is the significant difference that exists in the elastic recovery value, which is 90% in the case of modified asphalt against only 7% presented by CAP 50/70.

From the Brookfield viscosity results, the mixing and compaction temperatures for conventional asphalt are obtained as specified in ASTM D2493. In this case, the mixing temperature is in the viscosity range of 0.17 ± 0.02 Pa.s and the compaction temperature in the range of 0.28 ± 0.03 Pa.s, resulting in mixing temperatures of 145°C to 150°C and compaction temperatures of 135 to 140°C. This traditional method does not apply to modified asphalts due to the natural increase in viscosity. To obtain a value of 0.17 ± 0.02 Pa.s, the necessary temperature must be higher than 177°C, which is the maximum value applied in the test. In the case of modified asphalt, it is mixed with the aggregates at 165°C and compacted at 155°C, as recommended by the supplier. This recommendation suggests that modified asphalt is produced using CAP 50/70 since, in accordance with specification 5.4.6.4 of the standard (26), the recommended temperature for compacting the asphalt mix must be 140°C +3°C for each 1% of polymer aggregate. From this criterion, it is inferred that an addition of 5% of the polymer was used to modify the asphalt.

3.2 Master Curve Construction

The master curve is widely used to represent the rheological behavior of the material. Rheological properties are expressed for a single reference temperature within a frequency or loading time spectrum. The dynamic shear modulus master curves|G| for CAP 50/70 and AMP asphalts are shown in (Figure 4), for the RTFOT aging condition and a reference temperature of 25°C. This temperature value corresponds to the one used in static creep tests on the prepared mixtures. A spectrum of 15°C to 40°C is used to produce the results at this temperature.*

(Figure 4) shows the variation in stiffness of short-term aged asphalts in relation to a reduced frequency. The results show that for low frequencies or high temperatures, the performance of modified asphalt, in terms of stiffness, is practically equal to that presented by CAP 50/70. On the other hand, for low temperatures or high frequencies, the modified asphalt has a higher complex modulus G, which may indicate lower total strains. (Figure 5) shows the phase angle master curve (°) constructed with the same shift factor used in the dynamic module master curve |G*| and using the CAM model. The modified asphalt has a lower phase angle than CAP 50/70, which indicates a more elastic behavior, also confirming the elastic recovery results. This behavior is more visible for frequencies between 0.1 and 100 rad/s, which correspond to the reference temperature of 25°C.*

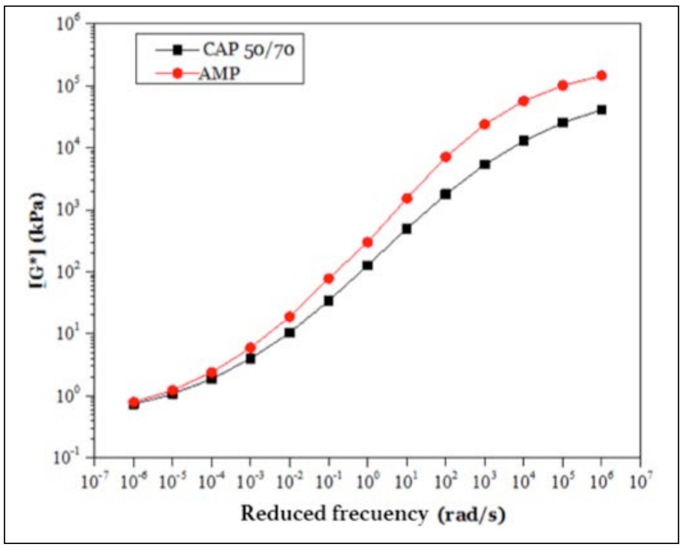

Figure 4. *Dynamic module master curve.*

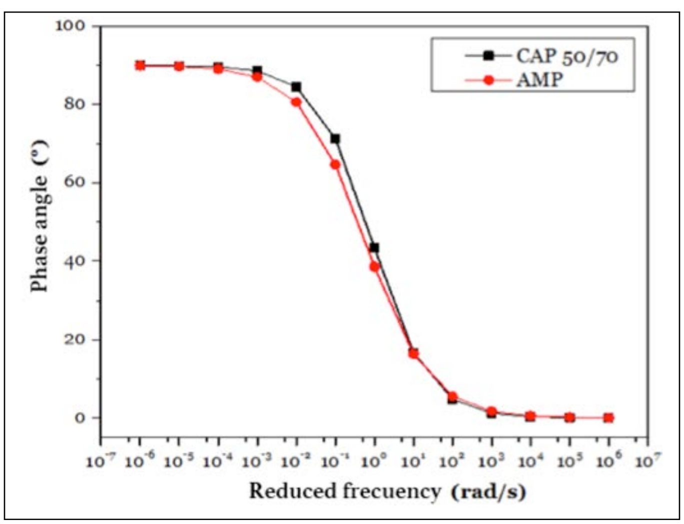

Figure 5. *Phase angle master curve (°).*

3.3 LAS (Linear Amplitude Sweep) Test

The Linear Amplitude Sweep (LAS) test is an accelerated fatigue test in which the tolerance of the material to the cyclic loading process is evaluated. The test results are a comparison of the fatigue susceptibility of the asphalt cements under study.

(Figure 6) shows the comparison of strain versus shear stress curves at a temperature of 25°C for the analyzed asphalts. The results show that despite CAP 50/70 has a higher shear stress value at break, it has a more fragile behavior when compared to the modified asphalt. The shear stress values tend to 0 Pa for a strain rate of 20% and 30% respectively, thus proving the aforementioned statement.

In addition, (Figure 7) details the characteristic curves showing the evolution of damage in the tested asphalt cements. The results show that conventional asphalt is more susceptible to damage than modified asphalt.

The characteristic curves show a lower integrity value for the same damage value in CAP 50/70 compared to modified asphalt, suggesting a relationship between the loss of integrity and the brittle behavior shown in (Figure 6).

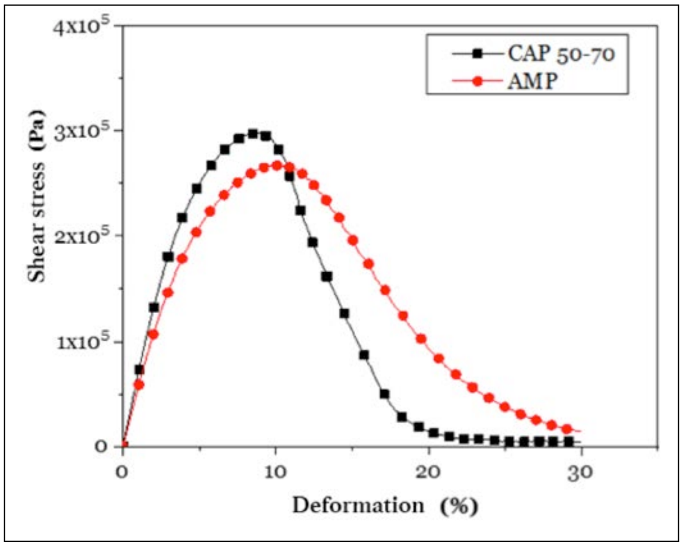

***Figure 6.** Stress-strain curve for the asphalts studied in the LAS test.*

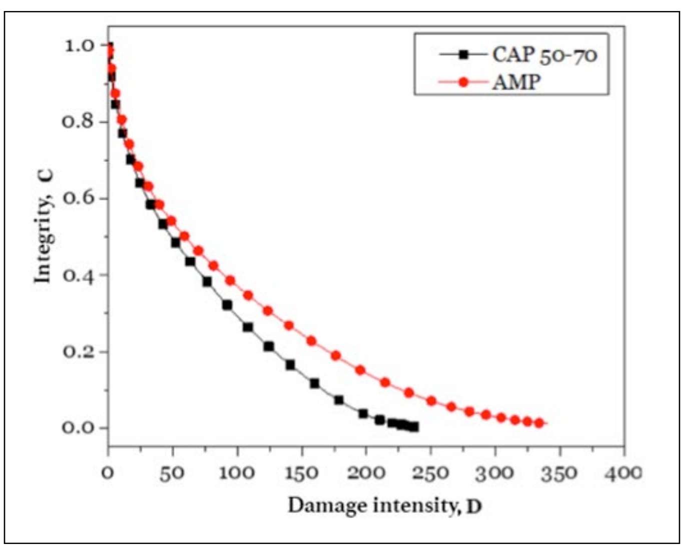

***Figure 7.** Characteristic damage curve in the LAS test for aged asphalts.*

3.4 Multiple Stress Creep Recovery (MSCR)

The results of the MSCR test are shown in (Table 2) and (Table 3). It is important to clarify that the tests were carried out only in the temperatures of 46°C, 58°C and 58 °C since for higher temperatures CAP 50/70 does not show delayed elastic recovery. Another point to be considered with respect to test temperatures is the fact that rheological characterization is carried out with the unique purpose of establishing a performance comparison.

Table 2. *Results of recovery and non-recoverable creep compliance for 0.1 kPa and 3.2 kPa.*

Asphalt	**Recovery 0.1kPa (%)**			**Recovery 3.2kPa (%)**		
	46°C	52°C	58°C	46°C	52°C	58°C
CAP 50/70	15.4	9.76	4.61	11.58	4.14	0.86
AMP	76.8	73.3	69.7	66.3	63.1	46.69
Asphalt	Compliance 0.1kPa (kPa^{-1})			Compliance 3.2kPa (kPa^{-1})		
	46°C	52°C	58°C	46°C	52°C	58°C
CAP 50/70	0.19	0.57	1.4	0.2	0.63	1.54
AMP	0.04	0.12	0.27	0.06	0.17	0.52

Table 3. *Results of the percentage difference between creep compliance 0.1 kPa and 3.2 kPa.*

Asphalt	**$J_{nr,\ diff}$ (%)**		
	46°C	52°C	58°C
CAP 50/70	5.24	9.52	9.09
AMP	33.33	29.41	48.08

Analyzing (Table 2) and (Table 3) it can be concluded that the addition of elastomeric polymers makes modified asphalt a material with greater potential for elastic recovery and less susceptible to the development of permanent deformation. The stress sensitivity and degree of non-linearity of the rheological response ($J_{nr,diff}$) is also shown to be higher for modified asphalt cement. These potentialities of modified asphalt can determine the mechanical behavior of the mixture, especially from the point of view of elastic recovery.

3.5 Result of the Mechanical Behavior of the Mixtures

The asphalt mixtures are prepared according to the Superpave methodology. As a result of the dosage, a mixture with modified asphalt is produced with 4.0% of asphalt, apparent density (Gmb) of 2.352 g/cm^3, Rice Density (Gmm) of 2.466 g/cm^3 and volume of voids (Vv) of 4.6%. The mixture produced with conventional asphalt with 5% of asphalt Gmb=2.329 g/cm^3, Gmm=2.431 g/cm^3, and Vv=4.2%.

The results in (Figure 8) correspond to the moisture-induced damage test. The test is divided into two groups of three specimens for each mixture to which compression is applied. A first group is tested until it breaks without presenting any thermal conditioning, called the control group, and a second group is conditioned according to the procedure described in the AASHTO T 283 standard.

The mixture made with CAP 50/70 has an average RT of 1.21 MPa and a standard deviation of 0.051 MPa for the control group. The conditioned samples have an average of 1.062 MPa and a standard deviation of 0.024 MPa. On the other hand, in the mixture produced with modified asphalt, the control group presents an average value of RT 1,567 MPa with a standard deviation of 0.022MPa. The group of conditioned samples has a mean value of RT of 1,514 MPa with a standard deviation of 0.043 MPa. These values give mixtures produced with "pure" and modified asphalt an RTS of 85% and 96% respectively, thus indicating a lower susceptibility to deterioration by the action of water for the mixture produced with AMP.

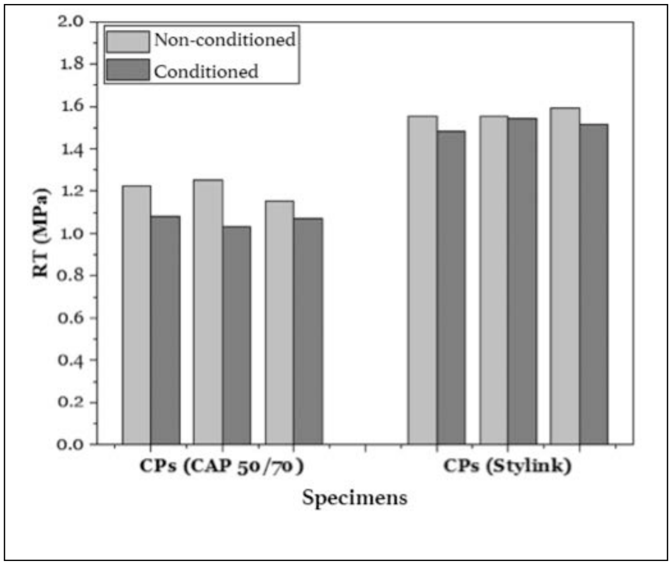

Figure 8. *Results of the Moisture-Induced Damage Test.*

3.6 Static Creep Test Results

(Figure 9) shows the results of the static creep test carried out on the mixtures produced with the modified asphalt. A curve is also shown for comparison with the results of the test carried out on asphalt concrete produced under similar conditions with CAP 50/70.

The results show that the maximum shift in the load application period is in the same order of magnitude for both asphalt concretes. It can also be seen graphically that the mixture produced with AMP has a higher shift recovery when compared to asphalt concrete produced with CAP 50/70 asphalt, giving it a higher elastic potential.

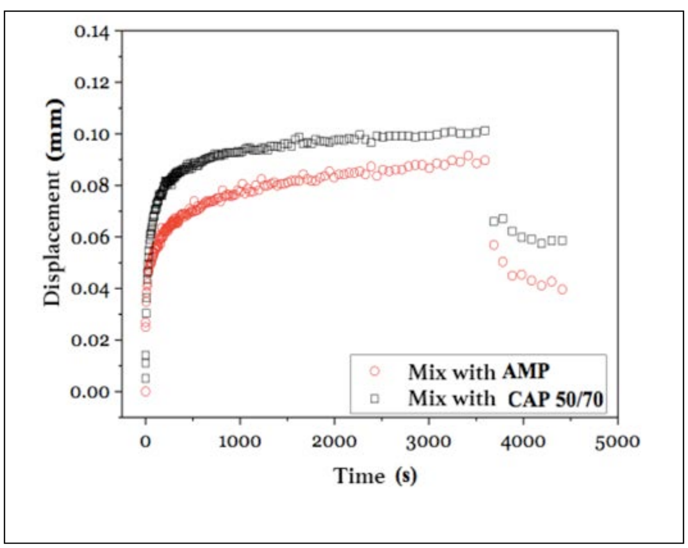

Figure 9. *Static Creep Test Results.*

4. Conclusions

Conventional characterization tests give modified asphalt a superior standard of quality when compared to CAP 50/70. This is supported by the always higher values of the modified asphalt binder. This comparison is also validated against the rheological results.

The master curves constructed for the complex module G and the phase angle also show the distinction of AMP from conventional CAP 50/70 asphalt. LAS (Linear Amplitude Sweep) test results show that modified asphalt is less susceptible to fatigue than conventional asphalt. A relevant aspect for the LAS test is the relationship between the loss of integrity and the intensity of the damage since for the same damage value the AMP has a higher value of integrity than CAP 50/70.*

The modified asphalt also has a lower susceptibility to permanent deformation expressed in J_{nr} values as well as a higher potential for delayed elastic recovery when compared to CAP 50/70 when both are subjected to the Multiple Stress Creep Recovery (MSCR) test.

From a mechanical point of view, the moisture-induced damage tests show that the use of modified asphalt gives asphalt concrete low thermal susceptibility, as demonstrated by the 96% RTS value.

In the case of viscoelastic properties in the time domain, the mixture produced with modified asphalt presents an elastic creep recovery in the order of 56% against 40% in the case of the mixture produced with conventional asphalt CAP 50/70.

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