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Mechanical performance of asphalt mixture composed of asphalt binder modified with sunflower oil

Desempenho mecânico de misturas asfálticas compostas por ligantes asfálticos modificados com óleo de girassol

Jeovanesa Régis Carvalho[1], Ablenya Grangeiro de Barros[2], Adriano Elísio de Figueiredo Lopes Lucena[3], Rita Flávia Régis Queiroz[4], Daniel Beserra Costa[5], Antonio Leomar Ferreira Soares[6], Érika Vitória de Negreiros Duarte[7]

[1]Federal University of Campina Grande, Paraíba – Brazil, jeovanesaregis@gmail.com
[2]University of Antwerp, Flandres – Belgium, ablenyagb@gmail.com
[3]Federal University of Campina Grande, Paraíba – Brazil, lucenafb@uol.com.br
[4]Federal University of Campina Grande, Paraíba – Brazil, flaviarq18@gmail.com
[5]Federal University of Campina Grande, Paraíba – Brazil, daniel.beserra@gmail.com
[6]Federal University of Campina Grande, Paraíba – Brazil, antonioleomar@msn.com
[7]Federal University of Campina Grande, Paraíba – Brazil, erika__vitoria@hotmail.com

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ABSTRACT
Warm Mix Asphalt (WMA) refers to a variety of asphalt mixtures produced at lower temperatures than those conventionally used to produce hot mixture asphalt. These reductions in the production temperatures provide social, economic, and environmental gains. This study aimed to investigate the mechanical properties of asphalt mixtures composed of asphalt binders modified with sunflower oil at the addition contents of 1%, 2%, and 3%. Indirect tensile strength, resilient modulus, water sensitivity, dynamic modulus, rutting resistance, and fatigue life of the asphalt mixtures were evaluated. Results showed that the mechanical performance of asphalt mixtures composed of oil-modified asphalt binder decreased compared to that of the mixture with neat asphalt binder, even though all of them are suitable for application in surface courses according to the current technical requirements for asphalt concretes. However, asphalt mixtures with sunflower oil-modified binders presented enhances in adhesion, which indicates less susceptibility to moisture than their equivalent non-modified.

RESUMO
Misturas Asfálticas Mornas (MAMs) referem-se a uma variedade de misturas asfálticas produzidas a temperaturas mais baixas do que as convencionalmente utilizadas para produzir misturas asfálticas a quente, que proporcionam ganhos econômicos, ambientais e sociais. Este estudo investigou as propriedades mecânicas das misturas asfálticas compostas por ligantes asfálticos modificados com óleo de girassol nos teores de adição de 1%, 2%, e 3%. Foram avaliadas a resistência à tração indireta, o módulo de resiliência, o dano por umidade induzida, o módulo dinâmico, a resistência à deformação permanente, e a vida de fadiga das misturas asfálticas mornas. Os resultados evidenciaram que o desempenho mecânico das misturas asfálticas compostas por ligantes asfálticos modificados com óleo reduziu em comparação com o da mistura com ligante asfáltico puro, apesar de todas serem adequadas para aplicação em camadas superficiais de pavimento de acordo com os atuais requisitos técnicos para misturas asfálticas. No entanto, as misturas asfálticas com ligantes modificados com óleo de girassol apresentaram uma maior adesividade, que indica uma menor susceptibilidade à ação deletéria da água do que a sua equivalente não modificada.

1. INTRODUCTION

The increasing concern regarding global warming has led to the introduction of environmental-friendly and sustainability-related practices and criteria in various industries, including the asphalt production industry (Jalali, 2016).

During the production process of asphalt pavements, emissions of greenhouse gases into the atmosphere occur mainly due to the high temperatures of mixing and compaction used to produce asphalt mixtures (Thieves and Ghisi, 2017). Taking it into consideration, researchers have been exploring new alternatives to the conventional production process of asphalt mixtures, including Warm Asphalt Mixtures (WMAs). This type of mixture is produced and compacted at temperatures 20°C to 40°C lower the typical production temperature range of hot mix asphalt (Vaitkus et al., 2016).

The decrease in mixing and compacting temperatures provided by WMA can bring benefits such as: lower greenhouse gases emissions; reduced exposure of workers to asphalt fumes; lower fuel consumption; possibility of reducing asphalt aging, thus increasing flexibility and durability of the surface course; drop in temperature with time are significantly lower, allowing transport distances and longer paving season; possibility to incorporate a larger quantity of reclaimed asphalt pavement into the mixture (Podolsky et al., 2016; Rodríguez-Alloza and Gallego, 2017; e Yu at al., 2018).

The existing technologies to produce WMA can be divided into: foaming technologies, organic or wax additives technologies, and chemical additives technologies (Omari et al., 2016). The main objective of these technologies is to reduce the asphalt working temperatures without compromising the performance of neat asphalt binders. Organic additives and foaming asphalt decrease the viscosity of asphalt binders, resulting in improved workability and compactability at lower temperatures of asphalt mixtures. Whereas chemical additives facilitate the wetting of particle aggregate, modifying and controlling the internal friction of the mix, which improves the workability of the asphalt mixture (Ferrotti et al., 2017).

Organic additives were one of the first additives to produce WMA developed in Europe. Among the organic additives, it is worth highlighting the use of oils. In Brazil, several studies (Pilati, 2008; Ribeiro, 2011; Lucena et al., 2016; Rodrigues et al., 2017; Portugal et al., 2017; Luz et al., 2019) have been conducted to analyze the influence of the addition of vegetable oils in asphalt binders and asphalt mixtures. Overall, these authors verified that even though the oil addition leads to increased permanent deformation and reduces elastic recovery of asphalt binders, it enables decreases in temperatures mixing and compaction of asphalt mixtures, besides increasing storage stability and adhesion between aggregates and the asphalt binders.

Sunflower is cultivated especially for the high oil content of its seeds (about 50 wt.%). Oil represents up to 80% of its economic value (Salgin et al., 2005; Evon et al., 2007). It is ranked fourth among the most consumed oilseeds and accounts for 8.74% of total world demand for vegetable oils for food and industrial uses (USDA, 2016).

Silva (2016) studied the rheological properties (performance grade, multiple stress creep recovery, and master curve) of a sunflower oil-modified asphalt binder aiming to achieve warm mixture, obtaining 11.3°C and 14.8°C reductions in the mixing and compaction temperatures.

Within this context, the objectives of this work are: (i) to quantify the reduction in mixing and compaction temperatures of asphalt binders modified with different contents of sunflower oil; (ii) to evaluate the mechanical properties of an asphalt mixture composed of sunflower oil-modified asphalt binder.

2. MATERIALS AND METHODS

2.1. Sunflower oil

Commercial sunflower oil supplied by local markets was used as an organic additive due to its potential to promote reductions in viscosity of the asphalt binders. Addition contents of 1%, 2%, and 3% by total weight of the asphalt binder were added to the base binder. These addition contents were chosen based on the research of Silva (2016), who analyzed the effects of adding sunflower oil at contents ranging from 1% to 2.5% on the rheological properties of asphalt binders. At the addition content of 1%, the author observed reductions in mixing and compacting temperatures without negatively affecting the rheological performance of the binder. However, with 2.5% of sunflower oil, the decreases in viscosity were the greatest. In this study, a higher content than those used by Silva (2016) was investigated to verify to what extent the mechanical properties of asphalt mixtures are affected by these ranges of oil addition in the base asphalt binder.

2.2. Asphalt binders

An asphalt binder of 50/70 penetration grade was used in this research. Asphalt binder modification with sunflower oil was carried out using a low shear mechanical mixer (FISATOM, Model 72) at 135°C. The mixture of neat 50/70 asphalt binder and sunflower oil was mixed for 20 minutes at 410 rpm, according to the methodology defined by Silva (2016).

Penetration, softening point, rotational viscosity, and rolling thin film oven test were performed per standards DNIT-ME 155/2010, DNIT-ME 131/2010, ASTM D 4402, and ASTM D 2872, respectively, as shown in Table 1. For the neat binder, all results attended the DNIT-EM 095/2006 requirements for 50/70 penetration grade asphalt binders.

Table 1 - Properties of the neat and modified asphalt binders and mixing and compaction temperatures

	Asphalt binder			
Characteristic	**Neat asphalt binder**	**+1% sunflower oil**	**+2% sunflower oil**	**+3% sunflower oil**
Penetration (100g, 5s, 25°C), dmm	64	77	94	122
Softening point, °C	48	47	46	44
Rotational viscosity (135°C SP 21 20 rpm), cP	458	429	380	341
Rotational viscosity (150°C SP 21 50 rpm), cP	224	214	194	176
Rotational viscosity (177°C SP 21 100 rpm), cP	81	79	73	68
Mass variation after short term ageing, %	0.072	0.025	0.046	0.098
Retained penetration, %	65.9	58.6	58.1	58.1
Softening point variation, °C	+4.5	+4.5	+3.0	+5.0
Thermal susceptibility index, °C	-1.1	-0.9	-0.6	-0.5
Average mixing temperature, °C	157	156	154	151
Average compacting temperature, °C	146	145	142	140

The addition of sunflower oil increased penetration of the neat binder, thus decreased its stiffness. Softening point decreased slightly with the increase in the addition content of sunflower oil.

Average mixing and compacting temperatures presented in Table 1 were determined from the viscosity chart. The largest reduction in production temperatures of the modified binders compared to the neat binder is observed for the sunflower addition content of 3%, which was 6°C.

As this reduction does not allow the modified binder to be classified in a typical WMA, a new mixture was produced, with 2% of sunflower oil (optimum content) and a 20°C. It is important to mention that these temperatures do not comply with the viscosity recommended by the regulatory body; in this manner, it was decided to evaluate the mechanical properties of the asphalt mixtures to verify if the non-compliance with this viscosity could compromise the performance of the mixtures.

2% of sunflower oil was used as the optimum content because, in addition to meeting the criteria recommended by the standards for the indirect tensile stregth, resilient modulus, dynamic modulus and fatigue life tests, it promoted greater adhesion with the asphalt binder, considering that granitic aggregates, used in this research, are kown for having weak adhesion. Among the studied sunflower oil contents, the 2% content also showed a higher resistance to permanent deformation.

Although the reduction of mixing and compaction temperatures were not relatively considerable, the possibility of using lower temperatures than the established by the viscosity test can be studied (Rodrigues et al. 2017). The addition of oil promotes physicochemical changes that affect not only the consistency: they can also provide increase in the wetting capability of asphalt binders. This characteristic is not measured through the viscosity test, but it can be observed via increases in workability of the binder at lower temperatures. Such an increase in wetting is reported by (Portugal et al. 2017).

2.3 Aggregates

Crushed granite stones were used as coarse aggregates and stone powder from granitic stones was used as fine aggregates. Physical properties of the aggregates are shown in Table 2. Also, Figure 1 shows particle size gradation. The aggregates were considered suitable for use in asphalt mixtures as their properties met technical requirement.

Table 2 - Physical properties of the aggregates

Test	Method	Requirement	Results		
			Crushed stone 19 mm	**Crushed stone 12.5 mm**	**Stone powder**
Bulk Specific Gravity, g/cm³		-	2.80	2.73	2.43
Apparent Specific Gravity, g/cm³		-	2.75	2.69	2.42
Absorption, %	ASTM C 127 and 128	≤2	0.61	0.51	0.74
Los Angeles Abrasion, %	ASTM C 131	≤55	26.05	25.40	-

2.4. Mixture design

A dense-graded asphalt mixture (C band from DNIT - ES 031/2006) with a maximum aggregate size of 19 mm was designed following the SUPERPAVE hot mix asphalt (HMA) mix design.

The inferior fuller curve (Figure 2) was chosen and the proportion of the aggregates were 35% of 19 mm crushed stone, 30% of 12.5mm crushed stone and 35% of stone powder. Test specimens were prepared in a SUPERPAVE Gyratory Compactor, with 100 gyrations. To obtain a volume of voids near 4%, the optimum asphalt content was 5.0%. The particle size distribution and design properties are shown in Table 3.

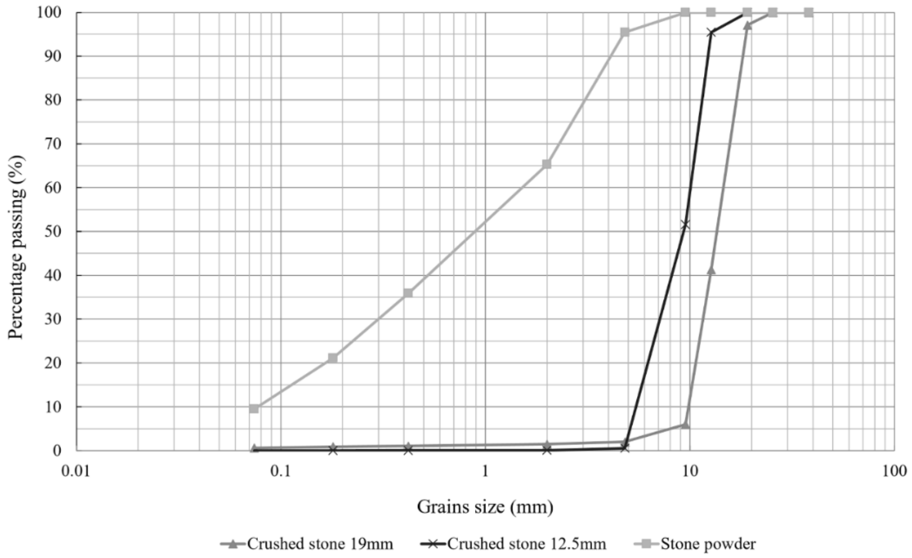

Figure 1. Particle size distribution of aggregates

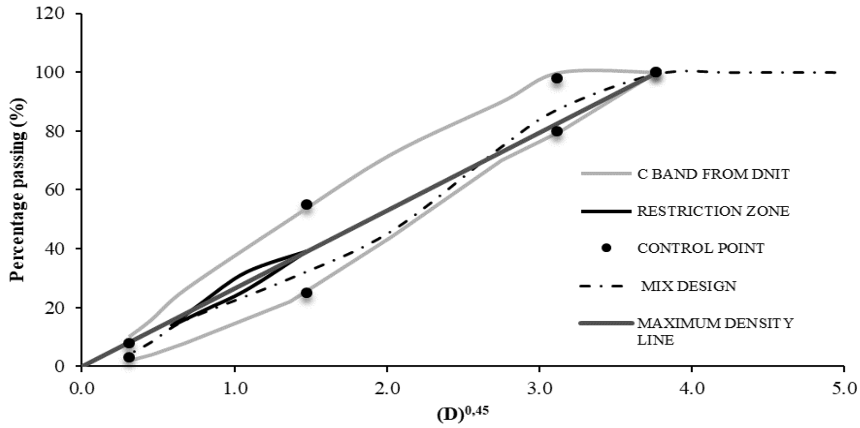

Figure 2. Curva granulométrica inferior

Table 3 - Particle size distribution and design properties of the asphalt mixture

Sieve size (mm)	Passing (%)
25.4	100.0
19.0	99.0
12.7	78.1
9.5	67.0
4.75	49.6
2.00	23.2
0.42	13.0
0.18	7.7
0.075	3.6
Property	**Result**
Binder content, %M	5.0
Bulk density, g/cm³	2.536
Air void content, %	3.9
Voids in mineral aggregate, %	14.5
Voids filled with bitumen, %	73.5

2.5. Mechanical tests

All mechanical tests results were obtained from the average of 3 to 6 samples of each mixture group.

To measure the indirect tensile strength (ITS), per DNIT 136/2018, a compressive load was applied diametrically to the samples by two metal strips at a speed of 0.8 mm/s, until reaching complete failure.

AASHTO T 283/14 was followed to measure the susceptibility to moisture damage of asphalt mixtures. This procedure consists in measuring the change of diametral tensile strength caused by water conditioning with a freeze-thaw cycle. Results are expressed as the indirect tensile strength ratio (ITSR), which is the percentage ratio between the ITS of samples subjected to accelerated water conditioning and the ITS of non-conditioned samples.

Standard NBR 16018/11 was followed to determine the resilient modulus of the cylindrical samples in diametral compression configuration. A compressive load of 10% of the indirect tensile strength was applied in pulsed waveform (Haversine), at 60 cycles per minute (1Hz), with an application time of 0.10s followed by 0.90s of rest.

To determine the dynamic modulus, per AASHTO TP-62 (2009) protocol, the Asphalt Mixture Performance Tester (AMPT) was used. Cylindrical samples with 100mm diameter and 150mm height were tested at 4.4, 21.1, 37.8°C and at loading frequencies of 25, 10, 5, 1, 0.5 and 0.1 Hz. From the results, master curves were constructed based on the time-temperature superposition principle at the reference temperature of 21°C.

The uniaxial repeated load test was performed to measure the rutting resistance of asphalt mixtures, per test method DNIT 184/2018. Samples with the same geometry as those used in dynamic modulus, presenting 7±0.5% of volume of voids, were oven heated at 60°C for five hours and then, using the AMPT, a compressive haversine pulse load was applied for 0.1 s every 0.9 s, producing axial stress of 204 kPa. The test is conducted to obtain the Flow Number. The test stopping criterion was either to reach 7200 loading cycles or a sample deformation of 50000 microstrains.

The fatigue life of the asphalt mixtures was measured by the fatigue life test in the diametral compression configuration, in controlled-stress mode, as per the DNIT 183/2018 test method. The fatigue life test was performed by subjecting cylindrical samples to diametric compression with repeated loading at a frequency of 1 Hz (0.10s of application followed by 0.90s of rest). The test was conducted at 25°C, at constant-stress mode of loading. Six load levels were used, ranging between 20 to 55% of the ITS. The test was stopped when 4mm of sample deformation was reached. Stresses difference at the sample centre (Δσ), in MPa, and the initial resilient deformation (ε_i) were calculated according to Equation 1 and Equation 2, respectively.

$$\Delta\sigma = 4\sigma t \quad (1)$$

$$\varepsilon i = \frac{\sigma t}{RM} \quad (2)$$

Where σ_t = vertical stress at the sample centre (MPa); RM = resilient modulus of asphalt mixture.

From these results, linear relationships were constructed between stress difference ($\Delta\sigma$) and number of cycles (N), as well as the curve of deformation (ε_i) x number of cycles (N). The regression lines follow Wöhler's fatigue prediction models (Equation 3 and Equation 4).

$$N = k_1 \left(\frac{1}{\Delta\sigma}\right)^{n_1} \quad (3)$$

$$N = k_2 \left(\frac{1}{\varepsilon_i}\right)^{n_2} \quad (4)$$

Where: N = load cycles until failure; k_1, k_2, k_3 and k_4= regression coefficients determined in the test.

Cantabro test was conducted following standard DNIT-ME 383/99, using Los Angeles Abrasion drum for 300 revolutions at 30–33 rpm without the steel spheres, at 25°C. The cantabro mass loss corresponds to the percentual difference between the mass of asphalt mixture samples before and after the test. This is a simple and efficient procedure to determine the durability of asphalt mixtures; even though it is already used widely to assess open-graded friction course or porous friction course mixes, the test is also useful for dense-graded asphalt mixtures (Cox et al., 2017).

3. RESULTS

3.1. Indirect Tensile Strength (ITS)

Figure 3 displays the average ITS results with respective standard deviation bars.

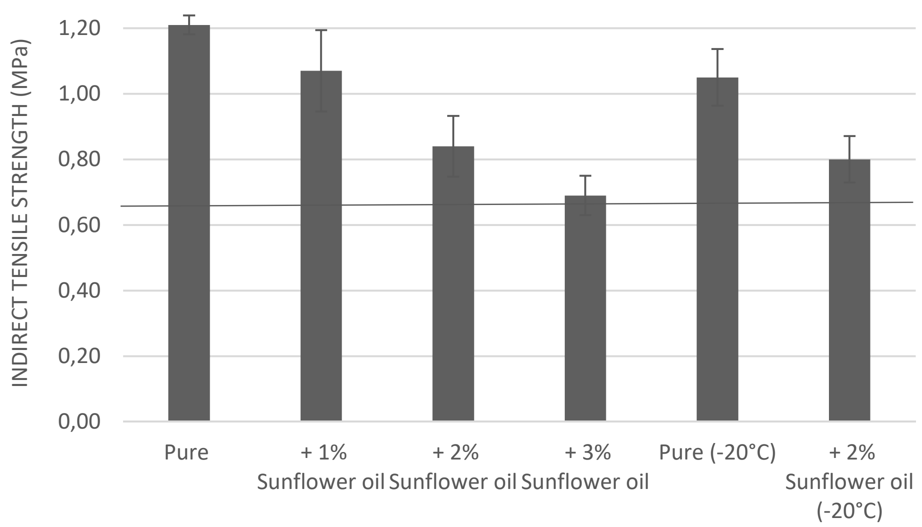

Figure 3. Average indirect tensile strength results.

A tendency of decreasing ITS is observed with the increase in oil content added to the asphalt binder of the mixtures. These decreases were 11.6%, 30.6%, and 43.3% for the average results of 1%, 2%, and 3% sunflower oil, respectively, compared to those of neat binder. In these results, no significant variations were observed between the ITS values for the mixtures with a 20°C reduction of mixing and compaction temperatures.

Heteroscedastic t-tests with 5% level of significance (n) were conducted between the values for neat binder and the modified samples, pair by pair. The values of 1% sunflower oil mixture presented no statistical differences to the values of neat binder, as a p-value of 0.186 was obtained.

Despite that, all results are above the minimum requirement of 0.65MPa per DNIT ES 031/2006 for asphalt concrete. One possible reason for the observed trend is the decrease in temperature production of the mixtures with larger contents of sunflower oil.

Pilati (2008) produced dense asphalt mixtures with shale oil residue-modified asphalt binder. The ITS of the mixture with 14% oil to the asphalt binder experienced a 57% decrease of ITS compared to an asphalt mixture with neat binder. Merighi and Suzuki (2017) also observed that a WMA presented ITS lower than the reference hot asphalt mixture. According to these authors, the reductions in ITS are associated with an increase in the volume of voids in the WMA. Otherwise, the smaller the volume of voids, the greater the ITS, since both parameters are intrinsically related.

3.2. Resilient modulus

Figure 4 shows the average results and standard deviation bars of resilient modulus for the mixtures with neat binder and with oil-modified binders.

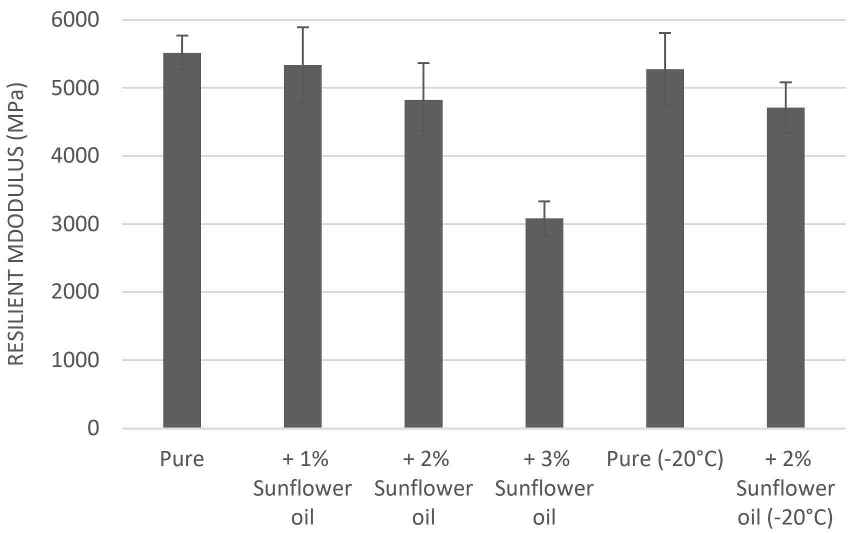

Figure 4. Average resilient modulus results

The mixtures with oil-modified binders presented a decrease in the resilient modulus compared to the mixture with neat binder, with the mixture modified by 3% oil presenting the most pronounced decrease.

T-tests with n = 5% carried out between the values for neat binder and the modified samples, pair by pair, showed that the resilient modulus of 1% sunflower oil samples are not statistically different to the values of neat binder, as a p-value of 0.503 was obtained; whereas p-values for 2% and 3% sunflower oil were below 0.05, which means that the differences for these samples are statically different from the neat binder mixtures. Samples with a reduction of 20°C are not statistically different from samples compacted at the temperature obtained through the viscosity test, as a p-value of 0.11 was obtained for the neat binder and 0.37 for samples with 2% of sunflower oil.

Pilati (2008) also observed that the mixtures composed of shale oil-modified binder had lower stiffness than the mixture with neat binder. Also, the increase in the oil content from 7% to 14% resulted in considerable decreases in stiffness.

Yu et al. (2018) studied asphalt rubber mixtures modified with various warm mix asphalt additives. The mixtures modified with WMA additives were produced at 16°C lower than that composed of pure asphalt rubber (AR). Compared to the stiffness of the samples with AR, the asphalt mixture with Sasobit® presented an increase in resilient modulus, whereas the other WMA additives (wax paraffin, two chemical additives, and one foaming additive) reduced this parameter. As all additives increases the viscosity of the base binder, it can be argued that the rheology of asphalt binder influences the stiffness modulus but it is also important to take into account mixing temperature for changes in this parameter.

Rodrigues et al. (2017) added Moringa oil at 0.5% and 1% of the asphalt binder weight and produced samples of dense-graded asphalt mixtures. The authors observed an increase in resilient modulus for the oil-modified samples compared to the samples with neat binder. They affirm that, with WMA additives, it is possible to produce asphalt mixtures using lower temperatures than that established by the viscosity test without compromising the mechanical performance of asphalt mixtures.

3.3 Water damage susceptibility

Figure 5 displays the average results and deviation bars of indirect tensile strength ratio (ITSR) for the mixtures with neat binder and with oil-modified binder.

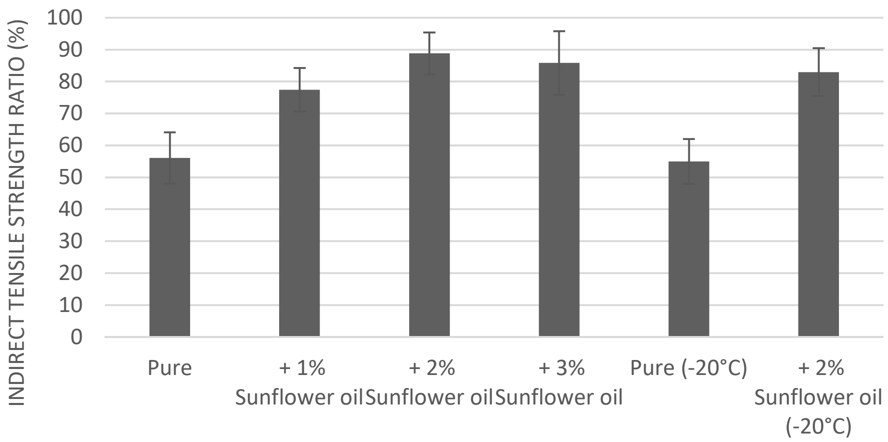

Figure 5. Average results of the indirect tensile strength ratio

Protocol AASHTO T238 suggests that asphalt mixtures designed by SUPERPAVE criteria have a minimum 80% of ITSR. Figure 4 shows that mixtures with 2% and 3% sunflower oil have ITSR above the minimum. However, the mixtures composed of neat binder and binder with 1% sunflower oil did not achieve the requirement. Although these values are below the standard requirement, the mixture with 1% sunflower oil presented a 21.3% ITSR increase compared to the mixture with neat binder.

ITSR tended to increase with the increment in sunflower oil content, even though this parameter slightly decreased for the mixture with 3% sunflower oil with regard to that of mixture with 2%. The asphalt mixture with 2% sunflower oil had the highest resistance to moisture damage, with an ITSR value of 88.8%.

Such tendency of rising ITSR with increment in sunflower oil addition is unexpected as lower production temperatures might decrease the resistance to moisture of asphalt mixtures. However, other researchers also verified a similar trend when adding WMA additives to the asphalt binder: Sales et al. (2016) studied asphalt mixtures with binders modified with CCBit and obtained a similar behavior: an increasing trend of ITSR with the increase in CCBit content, but from 2.5% to 3.0% CCBit in the asphalt binder, ITSR of the asphalt mixture showed a reduction of 34%.

Ribeiro (2011) studied the application of asphalt binder modified with 2% cashew nut shell liquid in asphalt mixtures and evaluated the moisture susceptibility of asphalt mixtures. The average ITSR value for the oil-modified mixture was 42% higher than that of the asphalt mixture with the non-modified binder. Similarly to the results of this work, the enhancement in adhesion and cohesion is related to surfactant properties of the cashew nut shell liquid, which provides greater compatibility to binder and aggregates.

3.4 Dynamic modulus

Master curves are used to describe viscoelastic characteristics of asphalt binders and asphalt mixtures in a large range of test temperatures and frequencies (Weldegiorgis and Tarefder, 2014). Andrei et al. (1999) affirm that the dynamic modulus of asphalt mixtures at high service temperature (54.4°C) can be excellently correlated to field rutting resistance, while the dynamic modulus at intermediate test temperature has a great correlation with the fatigue cracking resistance of asphalt mixtures.

Figure 6 shows the complex modulus master curves of all groups of samples studied, at a reference temperature of 21°C.

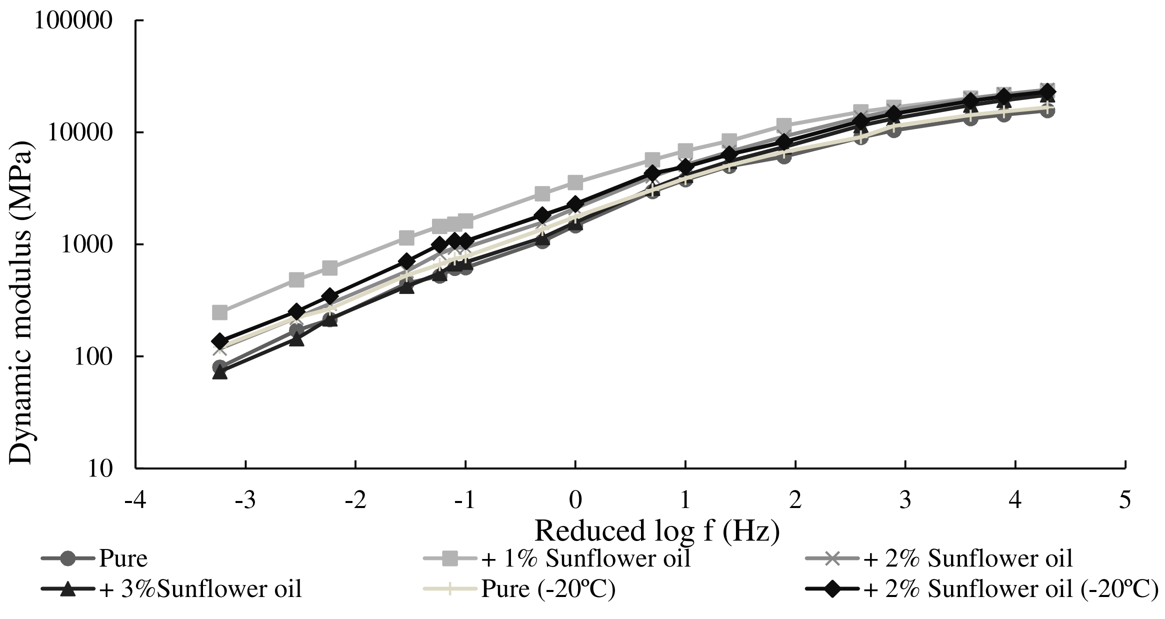

Figure 6. Master curves of the asphalt mixtures

Figure 6 shows that the oil addition is translated into higher dynamic moduli than the mixture with neat binder. The mixture with 1% sunflower oil presents the higher dynamic moduli in all test frequencies and temperatures. According to Goh and You (2008), this behavior indicates that mixtures modified with sunflower oil would have better performance in terms of rutting compared to the control mixture.

Yu et al. (2018) observed that dynamic modulus values increased with the increment in test frequency at each temperature. Compared to the asphalt mixture composed of pure asphalt rubber, mixtures with chemical WMA additives had lower modulus at all frequencies, implying their worse rutting resistance but better low-temperature performance. Whereas the master curves of the mixture with Sasobit®, which is an organic additive, nearly coincide with that of the samples with pure asphalt rubber.

3.5. Flow Number

Figure 7 displays the average cycles number at which each group of mixtures reached the Flow Number (FN).

The mixture with neat binder presented the highest number of loading cycles before flowing by shear deformation under constant volume, which is translated into greater rutting resistance. The addition of 1%, 2%, and 3% sunflower oil reduced the average FN of the control mix. Mixtures with a temperature reduction of 20°C also maintained this trend. It was expected that these values would constantly decrease with the increment of oil content. However, the result for 2% diverged from this trend. T-tests with n = 5% showed that the values for the pure binder mixture are not statistically different from those of the mixture with 2% sunflower oil, as a p-value of 0.206 was obtained.

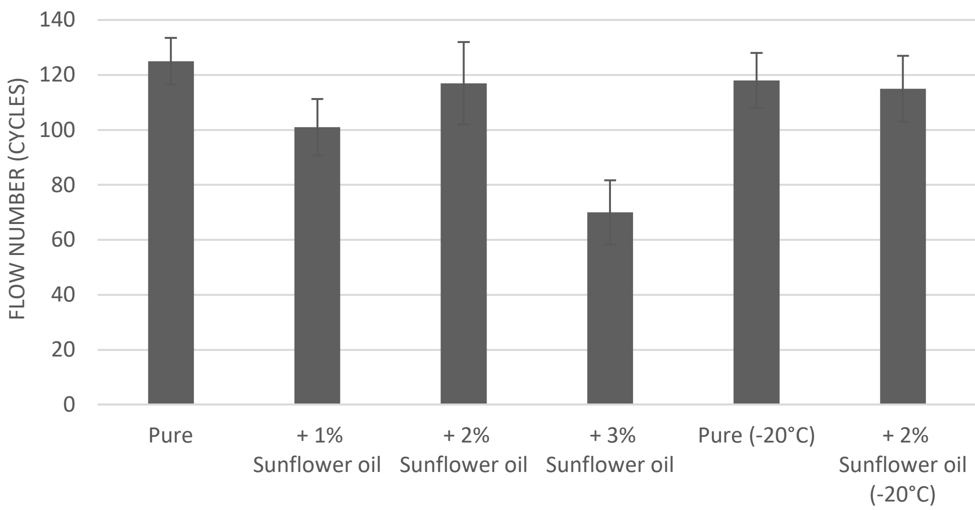

Figure 7. Average Flow Number results

According to Zhao et al. (2012) the production temperatures are a significant factor in the rutting performance of asphalt mixtures; the decreasing temperatures are associated with WMA technologies that present increasing rut depth, as less aging occurs to the binder during mixing.

Bundy (2012) added 2% CCBit113AD to a 30/45 pen asphalt binder. The samples with the WMA additive were compacted at different temperatures ranging from 110°C to 155°C, while the control mixtures were composed of neat 30/45 pen asphalt binder compacted at 155°C. The author observed that both the additive addition and the decrease in compaction temperature decreased the flow number of the mixtures.

On the other hand, Rodrigues et al. (2017) found that the flow number of the control asphalt mix was increased with the addition of Moringa oil to the asphalt binder. these authors analyzed the mechanical properties of asphalt mixtures using binders modified by the addition of Moringa oil at levels of 0.5 and 1.0%. The asphalt mixture was designed according to the Marshall Mix design method.

3.6. Fatigue life

The number of cycles until reaching fatigue of the asphalt samples was plotted versus stress difference (Figure 8) and initial resilient deformation (Figure 9). From both graphs, fatigue equations were determined and their parameters k_1, k_2, n_1, and n_2 and coefficient of determination (R^2) are presented in Table 4.

All fatigue models had great values of coefficient of determination. The equation models for the mixture with neat binder best fitted the data, while the lowest R^2 was observed for the mixture with +3% sunflower oil. Figure 8 suggests that the mixture with neat binder has greater fatigue life than the mixtures with oil-modified binder.

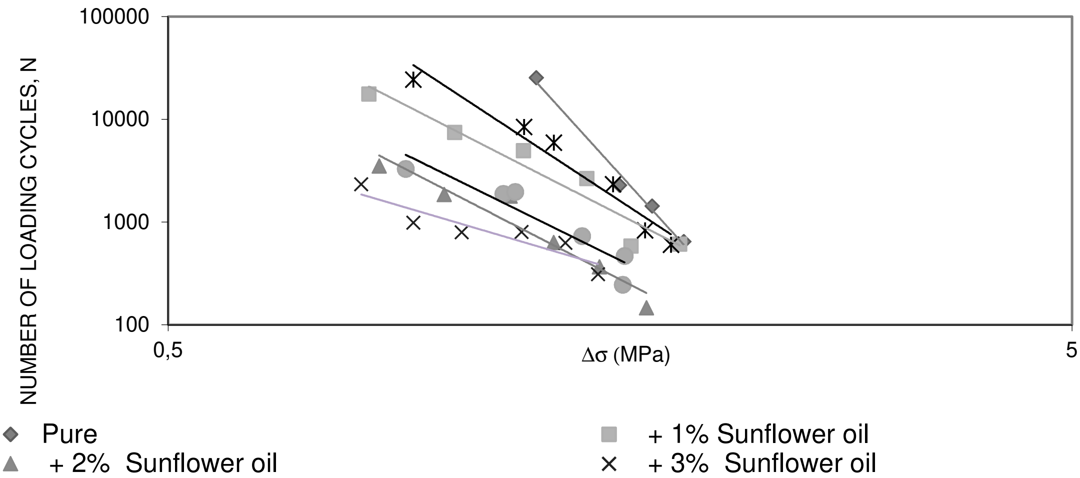

Figure 8. Fatigue life x Stress difference

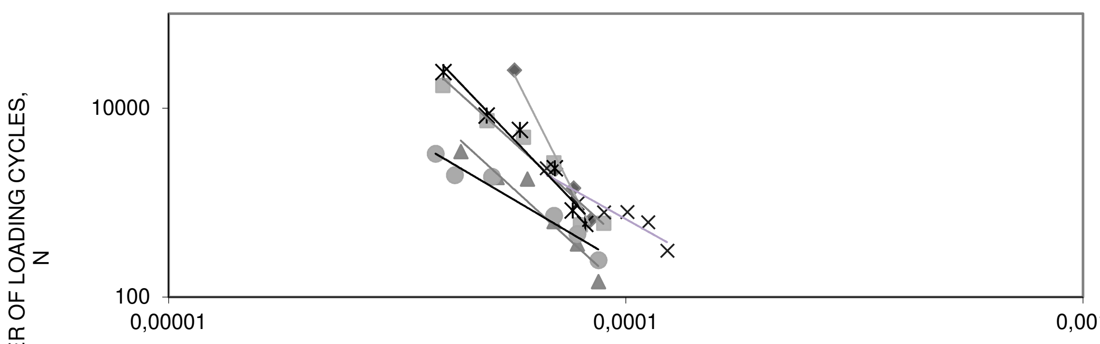

Figure 9. Fatigue life x initial resilient deformation

Bundy (2012) found coefficients n1 ranging between 1 to 8 to mixes produced with neat pen 50/70 asphalt binder and modified with WMA additives such as AD-Warm and CCBit 113AD. In this research, these values varied between 2.58 and 9.72, which reveals that the mixtures studied have different slopes for Δσ x N curves. As n1 of the mixture with neat binder was the highest among them, this mixture is the most sensible to variation in stress differences. Therefore, even though the mixture with neat binder had the greatest fatigue life at low stresses, at high stresses this value decreases considerably, and the mixtures with oil-modified binder outperform it, especially the mixture with 1% sunflower oil.

Table 4 - Parameters obtained from fatigue prediction equations

	Δσ x N			εi x N		
	R^2	K_1	n_1	R^2	K_2	n_2
Pure	0.988	247740	9.702	0.984	4×10^{-37}	9.603
+1% Sunflower oil	0.930	9221.6	4.496	0.938	1×10^{-15}	4.392
+2% Sunflower oil	0.923	2199.2	4.526	0.924	2×10^{-16}	4.416
+3% Sunflower oil	0.844	1104.1	2.589	0.880	1×10^{-8}	2.710
Pure (-20°C)	0.952	22679	5.779	0.959	1×10^{-18}	5.069
+2% Sunflower oil (-20°C)	0.882	3093.8	4.332	0.952	9×10^{-10}	2.489

Rodrigues et al. (2017), who also conducted the fatigue test by diametral compression under controlled stress, observed that the mixtures composed by moringa oil-modified binders presented better performance to fatigue than the standard mixture for all stress levels. The mixture 0.5% oil was the most resistant to fatigue at low stresses, while the mixture 1.0% oil was more resistant at high stresses.

Through coefficient n_2, Figure 9 shows a similar behaviour as Figure 8. Fatigue life, in terms of resilient deformations, was analyzed at three levels: 3.10^{-5} cm/cm (low level; 6.10^{-5} cm/cm (medium level) and 1.10^{-4} cm/cm (high level). At the medium level, the best fatigue behavior was for the mixture with neat binder and the mixtures with 1% and 2% sunflower oil. However, for high level of deformation, the mixture with 3% sunflower oil performed the best.

Rodríguez-Alloza and Gallego (2017) analysed the performance of AR-WMA mixtures containing Sasobit® and Licomont BS 100®. In the four-point bending test (EN 12697-24), the AR-WMA mixtures had the same or higher fatigue resistance than the mixture with pure AR.

3.7. Cantabro loss

Figure 10 shows the average cantabro loss and deviation bars for the asphalt mixtures studied.

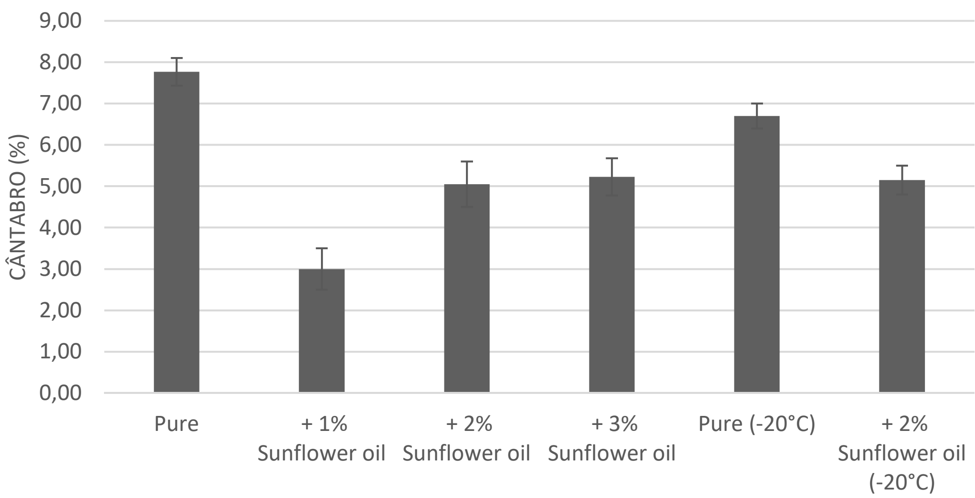

Figure 10. Average cantabro test results

The asphalt mixture composed of pure binder has the greater loss. The addition of sunflower oil reduced the cantabro loss of the control mixture by up to 67%. According to Rodrigues et al. (2017), this behavior may be related to an increased adhesion between the modified binder and the aggregates. This is also verified in the moisture susceptibility test results. Criteria of 15–30% mass loss are found depending on test temperature and conditioning, which vary worldwide (COX et al., 2017). Even taking the strictest criteria, all asphalt mixtures studied attend the requirement.

4. CONCLUSIONS

Mixing and compaction temperatures decreased proportionally to the content of sunflower added to the base binder, even though the reductions provided by those additions were not significant. The greatest reduction in temperature due the sunflower addition was 6°C for addition content of 3%. As this reduction does not allow the classification of the modified binder in a typical WMA, a new mixture was produced with 2% sunflower oil, the optimum content found in this work, at a temperature different from the temperature determined by the viscosity chart with the reduction of 20°C. This reduction provides energy savings during the heating of asphalt binder and aggregates at the asphalt plant.

Overall, the mechanical performance of asphalt mixtures composed of oil-modified asphalt binder decreased compared to that of the mixture with neat asphalt binder, even though all of them are suitable for application in surface courses according to the current technical requirements for asphalt concrete. An exception to these results was observed for water sensitivity: asphalt mixtures with sunflower oil-modified binders presented less susceptibility to moisture than their non-modified equivalent, resulting in enhanced adhesion. Besides, the fatigue life of the modified mixtures was less susceptible to stress variation.

In these results, no significant variations were observed between the values for the mixtures with a 20°C reduction of mixing and compaction temperatures. Furthermore, there are indications that it can be used as an adhesion promoter of asphalt mixtures. Therefore, sunflower oil may be a feasible alternative to reduce production temperatures of asphalt binders and bring environmental and economic benefits.

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