

Estudio reológico del aglutinante de asfalto modificado por aceites de algodón y copaiba

Rheological study of asphalt binder modified by cotton and copaiba oils

Osires de Medeiros Melo Neto^{1,*}, Ana Maria Gonçalves Duarte Mendonça¹, John Kennedy Guedes Rodrigues¹, Robson Kel Batista de Lima¹, Carina Silvani¹, Ingridy Minervina Silva¹

¹ Department of Civil Engineering. Federal University of Campina Grande. Aprígio Veloso 882, 58428-830 Campina Grande, Brazil.

*Autor de correspondencia: osiresdemedeiros@servidor.uepb.edu.br

Este documento posee una [licencia Creative Commons Reconocimiento/No Comercial 4.0 Internacional](https://creativecommons.org/licenses/by-nc/4.0/)



Recibido: 12 octubre 2021 **Aceptado:** 27 octubre 2021 **Publicado:** 3 enero 2022

Resumen

Los aceites de copaiba y algodón tienen orígenes a gran escala en las regiones norte y noreste de Brasil, respectivamente. En el presente estudio se evaluaron los efectos de incorporar estos aceites a contenidos de 4 y 5% en Cemento Asfáltico de Petróleo con penetración 50/70. Los ligantes se analizaron mediante pruebas físicas y reológicas: penetración, punto de reblandecimiento, viscosidad rotacional, grado de rendimiento. Estas pruebas se realizaron antes y después del procedimiento de envejecimiento a corto plazo y la recuperación y el deslizamiento de estrés múltiple. Los resultados mostraron que la adición de los aceites permitió reducir las temperaturas de producción de las mezclas y redujo la viscosidad. Los ligantes asfálticos modificados con aceite de semilla de algodón fueron susceptibles al envejecimiento con valores de penetración retenidos por debajo del límite establecido en la norma. En general, los bioaceites que sustituyen parcialmente al aglutinante asfáltico provocan una pérdida de resistencia en la deformación permanente, pero también proporcionan una disminución de la temperatura de mezcla, lo que minimiza el consumo de energía en el proceso.

Palabras clave: Asfalto, bioaceites, aditivo verde, reología, viscosidad.

Abstract

Copaiba and cotton oils have large-scale origins in the northern and northeastern regions of Brazil, respectively. Thus, this study evaluated the effects of incorporating these oils at 4 and 5% contents in Petroleum Asphalt Cement with 50/70 penetration. Binders were analyzed by physical and rheological tests: penetration, softening point, rotational viscosity, and performance grade; these tests were performed before and after the short-term aging procedure and multiple stress creep and recovery. The results showed that the addition of the oils made it possible to reduce the production temperatures of the mixtures and reduced the viscosity. Asphalt binders modified with cottonseed oil were susceptible to aging with retained penetration values below the limit established in the standard. In general, bio-oils partially replacing the asphalt binder resulted in a loss of strength in permanent deformation, but it also provided a decrease in the mixing temperature, which minimizes the consumption energy in the process.

Keywords: Asphalt, bio-oils, green additive, rheology, viscosity.

1. Introduction

Conventional asphalt binders used to produce hot mixes asphalt (HMA) are derived from the petroleum refining process. However, the non-renewable resource and the increase in oil costs also reflect on the prices of asphalt paving and, thus, it becomes necessary to explore alternative asphalt binders [1-3].

With the rapid development of roads and pavement maintenance and rehabilitation, the demand for paving materials has grown since it was first introduced. At the same time, the source of crude oil used to produce asphalt binders has also been decreasing [4,5]. In addition, the growing environmental concerns have raised the interest of institutions, industry, and the whole community towards two crucial concepts: sustainability and circular economy [6].

Recent studies are being conducted to develop alternative asphalt binders from various biomass resources to construct flexible asphalt pavements [1,4]. Bio-oils are generally applied in the asphalt industry to asphalt binders as modifiers (content below 10% replacing the asphalt binder), extenders (25 to 75% replacing the asphalt binder), and substituents (100% content of bio-oils instead of the asphalt binder) [7].

Hot mixes asphalt (HMA) are used in flexible pavement covering and are produced at temperatures from 140 to 180°C, consume a large amount of energy, and also emit harmful gases that cause the greenhouse effect, contributing to global warming and pollution of the air [8]. Reducing the temperature reduces energy costs, less smoke, and greenhouse gas emissions [9]. To reduce these temperatures means emerge that make it possible to achieve this objective. Lucena, Silveira, and Costa [10] highlight the addition of organic or chemical additives, emulsions, and synthetic binders, which can considerably lower temperatures in the operation process. Portugal et al. [11] investigated the rheological effects of asphalt binder modified with soybean oil and determined that the ideal soybean oil content is in the range of 1 to 2%, regardless of whether the oil is virgin or residual. Wang et al. [1] also analyzed incorporating this same green additive and observed a reduction in resistance to permanent deformation and again in fatigue resistance, corroborating Portugal et al. [8]. Finally, Sun et al. [12] carried out a study evaluating the optimized asphalt bio-binder containing residual cooking oil. The bio-binder comprises residual cooking oil, virgin asphalt binder, hydrocarbon resin, low-density polyethylene, and SBS polymer. The results showed that the performance of the optimized bio-binder presented a version at a high temperature similar to the asphalt binder modified with SBS polymer.

Portugal et al. [8] analyzed the adding of virgin and residual corn oil to conventional asphalt binders (PAC 50/70) and modified them by SBS polymer. It was observed that the 1% content of corn oil, both virgin and residual, provided a reduction in manufacture and compaction temperatures around 6°C using the conventional asphalt binder and 4°C for the asphalt binder with SBS, without compromising the rheological properties. Zeng et al. [13] investigated the use of castor oil as a rejuvenator and aged asphalt binder. They verified that its addition leads to a reduction in temperatures, a drop in resistance to permanent deformation, and again in fatigue resistance. However, the gain in fatigue strength is more significant than the loss of resistance to permanent deformation.

Girimath and Singh [14] evaluated the adding of bio-oil derived from wood residue biomass in the physical and rheological properties of the asphalt binder. Contents of 2%, 4%, 6%, 8%, and 10% of bio-oil by total weight of binder were used. The addition of this modifier provided an increase in penetration, a decrease in softening point, and the viscosity of the asphalt binder. Therefore, 2% and 4% of bio-oil content satisfied the conditions established in the standard. Nogueira, Soares, and

Soares [15] investigated the use of cottonseed oil and fatty acid in an oxidized RAP asphalt binder. The study carried out by the authors concluded that the addition of these agents resulted in a reduction in stiffness, being beneficial for use in aged asphalt binders. However, depending on the cotton oil content to be added, it can also be helpful for conventional asphalt binders to reduce the compaction and manufacture temperature of the asphalt mixtures, encouraging the cultivation of this product in the Northeast region of Brazil. Furthermore, because it has a higher melting point (compared to other oils), cottonseed oil can withstand higher temperatures without losing its quality and significant changes in its properties.

Copaifera Langsdorffii, popularly called Copaiba, is a plant with a reddish trunk, found in the tropical region of Latin America, which produces an oil-resin extracted from its trunk. This tree occurs in greater incidence in Brazil. Through sustainable extraction, the plant can produce considerable amounts of oil, which, being of natural origin, do not harm the environment. Moreover, its use can improve the region's economic aspects and promote the preservation and planting of oil-producing species. Based on the above, the present study investigates the physical and rheological properties of asphalt binders modified with refined cotton oil and *Copaifera Langsdorffii* oil at 4% and 5% contents green additive.

2. Materials and Methods

The asphalt binder used in this study was Petroleum Asphalt Cement with 50/70 degree of penetration (PAC 50/70). Refined cotton and *Copaifera Langsdorffii* (copaiba) oils were obtained from local stores in Campina Grande-PB. Refined cottonseed oil was used due to the practicality of obtaining it on the market. Refined oil is free of free fatty acids and salts; volatile substances such as hydrocarbons, aldehydes, ketones, and low molecular weight esters; inorganic substances such as salts of calcium and other metals, silicates, phosphates; and moisture. These elements affect the stability of the product. However, studies that analyze the addition of pure cotton oil in asphalt binders are encouraged in order to possible analysis of performance and costs in the production of asphalt mixtures, which is not the focus of this research.

To carry out the research, contents of 4% and 5% of cottonseed oil and Copaiba oil were used as additives to the pure binder (PAC 50/70). The levels established for addition to the binder were based on studies carried out by Lucena, Silveira, and Costa [10], Sun et al. [12], Girimath and Singh [14], Nogueira, Soares, and Soares [15], Sun et al. [16], Pradham and Sahoo [17], which used contents in the range 1 to 8% of oils as modifier agents the asphalt binder. In the mixing process (binder/bio-oil), a FISATOM mechanical stirrer, Model 722D, was used.

The asphalt mixture was pre-heated in an oven at 120°C for about 90 minutes to ensure the necessary fluidity to allow homogenization. Then, the material was deposited in a beaker and inserted into the mechanical stirrer blanket, and subjected to a rotation 300 rpm to ensure homogeneity in the distribution of the mixture. Upon reaching the stabilization temperature (160°C), the oleaginous additives were added, separately, in proportion to the weight of the pure binder, and rotations were raised to 2000 rpm, keeping the mixture for 30 minutes for homogenization of the mixture, in contents of 4% and 5%. This technique was based on studies carried out by Souza [18] and Faxina [19]. Table 1 presents the description of the samples used in the research and their respective nomenclatures.

Table 1. Nomenclature of the samples used in this research

Samples	Nomenclature
Conventional pure binder	PAC 50/70
PAC 50/70 + 4% Refined Cotton Oil	4%RCO
PAC 50/70 + 4% Copaiba Oil	4%CO
PAC 50/70 + 5% Refined Cotton Oil	5%RCO
PAC 50/70 + 5% Copaiba Oil	5%CO

After obtaining the modified asphalt binders, the physical and rheological characterization of the binders was carried out, before and after the Rolling Thin Film Oven (RTFO) aging procedure ASTM D2872:2019, through the Penetration tests ASTM D5M:2020, Softening Point ASTM D36M-14:2020, Rotational Viscosity ASTM D4402:2015, Performance Grade (PG) ASTM D6373:2021 and Multiple Stress Creep Recovery (MSCR) ASTM D7405:2020.

3. Results and Discussion

In this section, the results obtained in the experimental phase of asphalt binders modified by Copaiba fine cotton oils are presented and discussed.

Physical characterization of pure and modified asphalt binders

Table 2 presents the results of physical characterizations for the study samples.

Table 2. Physical characterization of asphalt binders before and after RTFO

	Results					
	PAC 50/70	4%RCO	4%CO	5%RCO	5%CO	
0.1 mm penetration (100g, 5s at 25°C)	64.2	150.2	87.25	184.5	126.2	
Softening Point (°C)	49	40	44.25	40.5	42.25	
Rotational Viscosity (cP)	135 °C	430.6	300	282.5	282.5	287.5
	150°C	212	156	145	151	145
	177 °C	76.9	61	56	61	56
0.1 mm penetration (100g, 5s at 25°C)	46.5	81.4	59.2	100	69.5	
Softening Point (°C)	53.13	47	51	45	51.5	
Increase in Softening Point (°C)	4.13	7	6.75	4.5	9.25	
Retained Penetration (%)	72.49	54.19	67.9	54.20	55.1	
Rotational Viscosity (cP)	135 °C	603.75	420	438.5	370	441.25
	150°C	287	211	214	189	214.5
	177 °C	98.5	77.5	76	71.5	76.25

An increase in penetration can be observed with the increase in refined cotton oil and copaiba oil. The results corroborate the studies by Souza [18] and Portugal [20] in which the incorporation of oils to the asphalt binder increased penetration. The asphalt binders modified by refined cotton oil showed greater penetration among the evaluated binders before and after the RTFO aging process. According to the retained penetration, the sensitivity of the binder to aging can be verified: the higher the percentage of retained penetration, the lower the sensitivity to aging. National Agency for Petroleum, Natural Gas and Biofuels (ANP) resolution No. 19 defines the minimum of 55% for this parameter. It is observed that the samples with the addition of 4% and 5% of refined cotton oil do not meet the criteria.

By analyzing the softening point data with research by Souza [18] and Portugal [20], the fact that there is a decrease in the consistency of the asphalt binder with the addition of pure cotton and copaiba oils was already a result predicted. All samples met the criteria of resolution No. 19 of the ANP. The values obtained indicate a tendency to decrease the softening point for the PAC 50/70 when modified with pure cotton and copaiba oils, both the results before and after the RTFO. This fact reiterates the decrease in stiffness caused by the oil-modified binder verified by performing the penetration test. Before aging, the 4% cotton oil content before aging was the lowest softening point temperature, while values after RTFO the binder modified with 5% cotton oil had the lowest temperature. Therefore, the asphalt binders modified with cottonseed oil presented lower softening point temperature when compared to the pure binder and those altered with copaiba oil.

According to results in Table 2, it is noted that there was a decrease in viscosity of the binder by the increase in refined cotton oil contents, mainly at lower temperatures of the test, and there was a slight increase in viscosity at all temperatures of viscosity after RTFO when increasing the addition of copaiba oil from 4% to 5%. The asphalt binders modified with copaiba oil had low viscosity before and after RTFO; before RTFO, the binder with 4% addition of copaiba oil had lower viscosity, and after RTFO, the asphalt binder with the addition of 5% had lower viscosity. Thus, refined cotton oil and copaiba oil at the levels studied caused a decrease in viscosities to pure PAC, which is consequently reflected in the Compaction and Manufacture Temperatures (CMT), which is related to the workability of the binder. Bernucci et al. [21] point out that the ideal temperature of the PAC for carrying out the asphalt mixture should be situated at 0.17 ± 0.02 Pa·s when measured with a rotational viscometer. Table 3 shows the mixing temperatures found through interpolation to add refined cotton oil and copaiba oil.

Table 3. Ideal temperature for carrying out the Asphalt Mix after the addition of refined cotton oils and copaiba oil

Sample	The ideal temperature for asphalt mix
PAC 50/70	156°C
4%RCO	148°C
4%CO	147°C
5%RCO	147°C
5%CO	146.4°C

The results indicate that the addition of refined cotton oil and copaiba oil has a significant influence on reducing the PAC viscosity and, consequently, on the decrease of the ideal temperature for the asphalt mixture. This effect provided a decrease in the ideal temperature for the asphalt mixture at 9.6°C for 5% incorporation of copaiba oil, with the lowest temperature among the analyzed binders.

According to the Federal Highway Administration (FHWA), mixtures considered hot machined have temperatures above 150°C. By analyzing the results shown in Table 3, all modified asphalt binders had machining temperatures below 150°C.

Rheological analysis of pure and modified asphalt binders

The low PG temperature was not verified during the research because Brazil has a primarily tropical climate registering average temperatures of 25°C, discarding the need for low-temperature analysis. Nevertheless, Figure 1 shows the curves complex shear modulus ratio (G^*) and phase angle (δ) [$G^*/\sin\delta$] versus temperature in the range of 46°C to 64°C, for asphalt binders containing cotton and copaiba oils before and after the short-term aging procedure respectively. It can be seen that the $G^*/\sin\delta$ parameter decreased with increasing oil content and temperature before and after short-term aging for all samples evaluated. After RTFO, the mixtures became more rigid, with $G^*/\sin\delta$ parameters around twice as high as before the procedure for binders modified with refined cotton oil, a behavior also observed in the studies by Portugal [20]. Binders modified with copaiba oil showed values approximately three times higher after short-term aging. The decrease in stiffness with increasing temperature points to again in resistance to fatigue cracking [13]. The results obtained are consistent with the results of softening point and rotational viscosity found in the literature. Figure 2 presents the PG results before and after RTFO short-term aging.

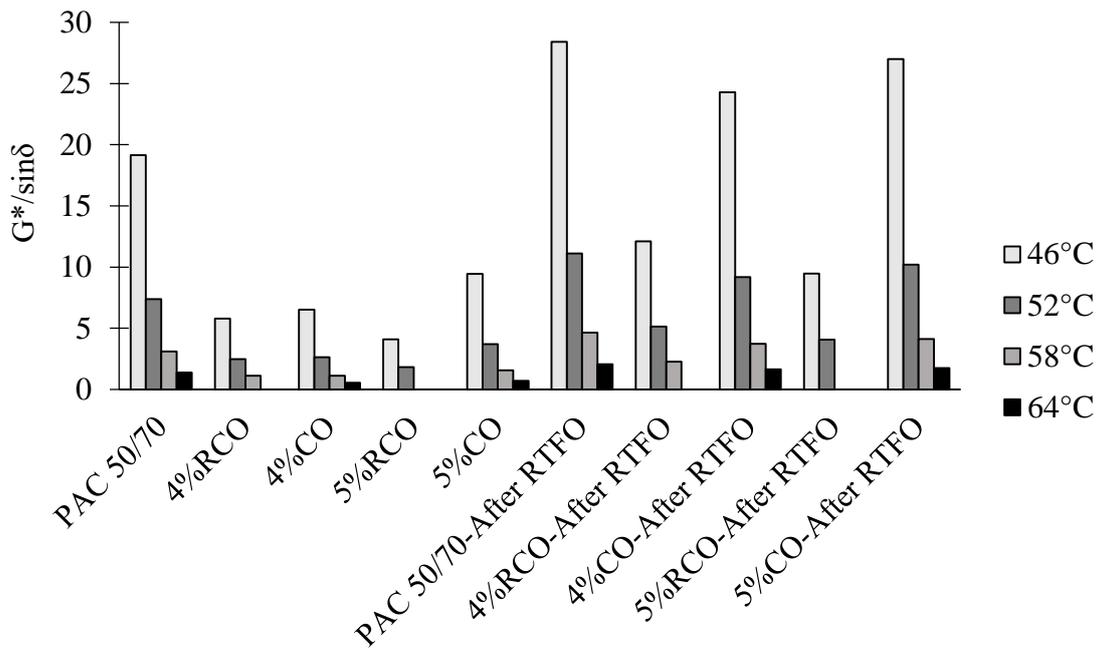


Fig.1 Parameter $G^*/\sin\delta$ versus temperature before and after short-term aging

Analyzing the results presented in Figure 2, it can be noticed that the PG obtained for PAC 50/70 after aging remained constant and equal in all modified asphalt binders, except for the binder with 5% incorporation of refined cotton oil that presented PG lower than the other modified ligands and pure PAC. The binder with 5% acceptable cotton oil content presented PG in a lower class than the others and was classified as 52°C. Therefore, the modified 5% RCO binder loses part of its strength and can only be used in places where the tread pavement temperature does not exceed 52°C.

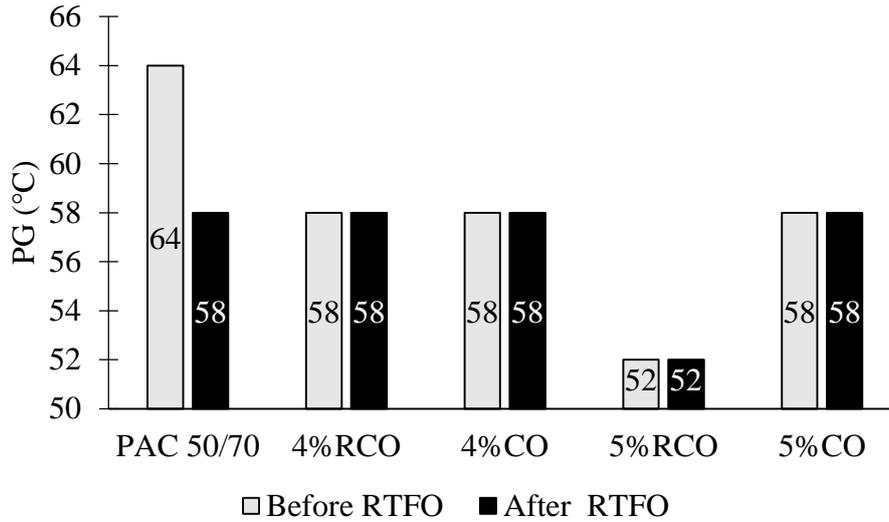


Fig.2 Degree of performance of pure and modified asphalt binders with refined cotton and copaiba oils before and after short-term aging RTFO

The execution of the MSCR test evaluates the recovery percentage (% R) when elasticity data are provided. It also evaluates the non-recoverable (Jnr) compilation, which in turn provides data on permanent deformation accumulation susceptibility and the percentage difference between non-recoverable (Jnr, diff) compilations, which provides data on sensitivity to an increasing level of tension. Regarding the results obtained for the Jnr at 3.2 kPa, it was also possible to classify the pure and modified asphalt binders' samples according to the Federal Highway Administration (FHWA) traffic criterion. The higher the value of Jnr, the material becomes more susceptible to permanent deformation. On the other hand, smaller values of Jnr indicate the binder's resistance to this effect. Figure 3 shows the non-recoverable (Jnr) compilation values at 0.1 kPa and 3.2 kPa.

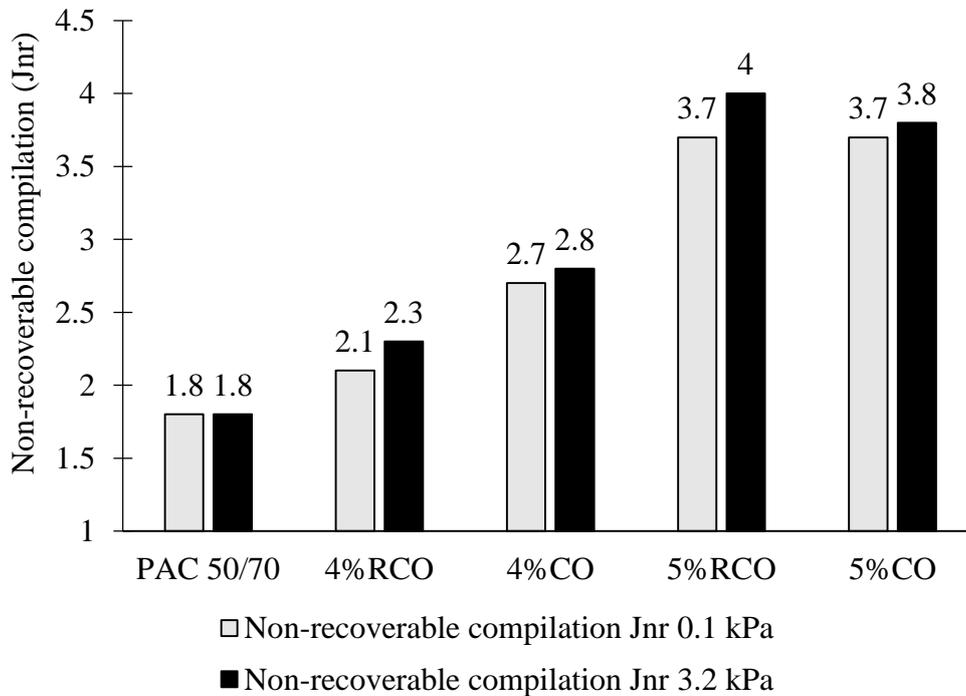


Fig.3 Non- recoverable (Jnr) compilation of pure and modified binders

From the analysis of the J_{nr} values in Figure 3, it can be noticed that the binders modified with refined cotton oil and copaiba oil with the application of tension of 0.1 kPa and 3.2 kPa presented higher values for non-recoverable compilation when compared to pure asphalt binders. The addition of refined cotton oil and copaiba oil increased the asphalt binder's susceptibility to permanent deformation. However, the binder modified with 4% fine cotton oil was the one with the closest values to the pure asphalt binder, being the least susceptible to permanent deformation among the modified asphalt binders.

According to AASHTO M320:2017, the relationship between values obtained for J_{nr} at 3.2 kPa and the traffic class in which the ligand is found can be made. Table 4 presents this classification.

Table 4. Classification of pavement loading level based on J_{nr} values

Property	J_{nr} (kPa ⁻¹)	Type of traffic	Number of passes on a standard axis
Jnr at 3.2 kPa at the maximum temperature of PG	2.0-4.0	Standard (S)	<10 millions
	1.0-2.0	Heavy (H)	>10 millions
	0.5-1.0	Very Heavy (V)	>30 millions
	0-0.5	Extremely Heavy (E)	>100 millions

Source: AASHTO M320:2017

The non-recoverable compilation of asphalt binders does not abruptly change between the tensions of 0.1 kPa and 3.2 kPa. Therefore, according to the classification of AASHTO M320:2017, the pure binder can be classified for heavy traffic, while binders added with 4% and 5% grades of refined cotton oil and copaiba oil are classified for standard traffic.

Among all the modified asphalt binders, the binder with the best performance included 4% copaiba oil. However, the second most significant reduction in machining temperature, as the binder with 5%CO, presented the most significant temperature reduction for the asphalt mixtures but greater susceptibility to permanent deformation. Given this, among the evaluated binders, the binder with 4%CO had the second most significant temperature reduction, 147°C, and presented results of susceptibility to permanent deformation close to the pure binder.

Another parameter analyzed in the MSCR test was an elastic recovery [22]. According to Federal Highway Administration, for binders with high J_{nr} , binders with a high non-recoverable (J_{nr}) compilation range, there is no specified minimum elastic recovery. The MSCR recovery percentage (%) can identify and quantify the effect of oil on the binder. The raising of the percentage values of this parameter results in the improvement of a binder modification to maintain elastic characteristics at high traffic levels. Figure 4 shows the elastic recovery values for binders modified with refined cotton oil and copaiba oil.

The addition of refined cotton oil and copaiba oil reduced the percentage of material recovery at the tension level of 3.2 kPa for all samples. However, given the analysis of the non-recoverable compliance parameters and the percentage of elastic recovery, the asphalt binders modified with oils tended to increase the percentage of recovery from 4% to 5% of addition for both oils. Therefore, the modified asphalt binder that showed the best results concerning susceptibility to deformation and elastic recovery was the mixture with the addition of 5% refined cotton oil, giving the ability to maintain its flexible characteristics at high traffic levels.

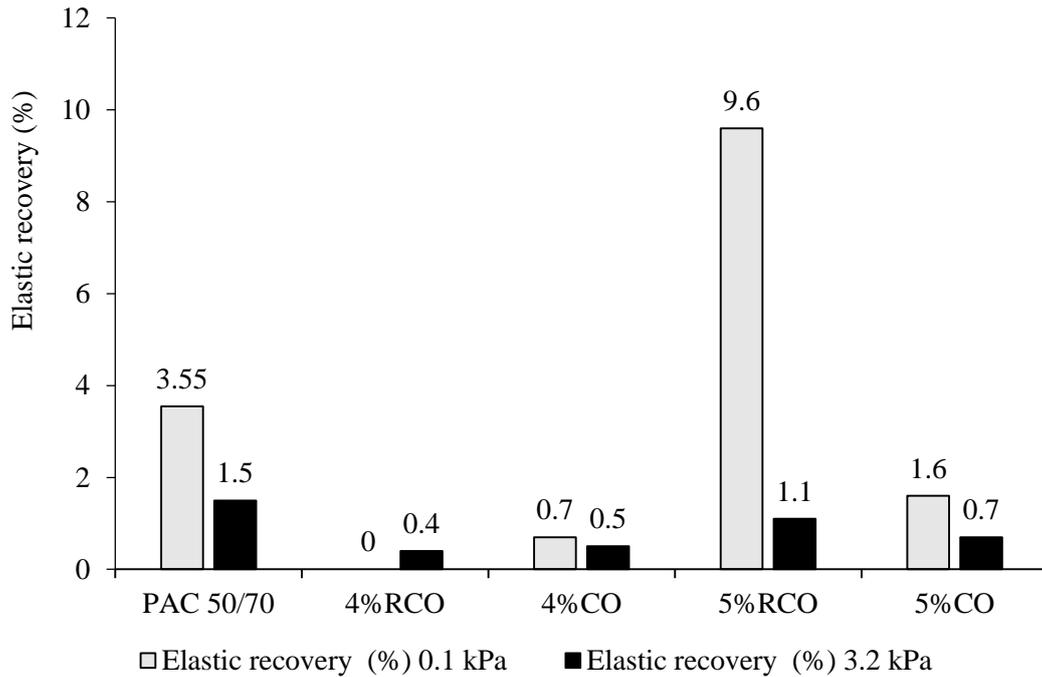


Fig.4 Elastic recovery at 0.1 kPa and 3.2 kPa for pure and modified binders

4. Conclusions

The findings in this research allowed us to conclude that the incorporation of cotton and copaiba oils reduced the viscosity and mixing temperature of the binders. Asphalt binders modified with 4% and 5% cottonseed oil were susceptible to aging with retained penetration values below the limit established in the standard. The mixture of a binder with 4% of copaiba oil showed the best results among the modified binders analyzed. The modified asphalt binders in this study showed a reduction in the classification of traffic level to standard. The addition of refined cotton oil acts more effectively in reducing viscosity, and the use of lower contents is indicated and that studies investigating the use of these oils in recycled asphalt mixtures are encouraged.

References

1. Wang, C., Xue, L., Xie, W., You, Z., Yang, X., *Laboratory investigation on chemical and rheological properties of bioasphalt binders incorporating waste cooking oil*. Construction and Building Materials, 2018. **167**: p. 348-358. DOI: <https://doi.org/10.1016/j.conbuildmat.2018.02.038>.
2. Yan, K., Zhang, M., You, L., Wu, S., Ji, H., *Performance and optimization of castor beans-based bio-asphalt and European rock-asphalt modified asphalt binder*. Construction and Building Materials, 2020. **240**. DOI: <https://doi.org/10.1016/j.conbuildmat.2019.117951>.
3. Shao, L., Wang, H., Zhang, R., Zheng, W., Hossiney, N., Wu, C., *Analysis of the chemical properties and high-temperature rheological properties of MDI modified bio-asphalt*. Construction and Building Materials, 2021. **267**. DOI: <https://doi.org/10.1016/j.conbuildmat.2020.121044>.
4. Gao, J., Wang, H., You, Z., Hasan, M.R.M., *Research on properties of bio-asphalt binders based on time and frequency sweep test*. Construction and Building Materials, 2018. **160**. DOI: <https://doi.org/10.1016/j.conbuildmat.2018.01.048>.

5. Cao, W., Wang, Y., Wang, C., *Fatigue characterization of bio-modified asphalt binders under various laboratory aging conditions*. Construction and Building Materials, 2019. **208**. DOI: <https://doi.org/10.1016/j.conbuildmat.2019.03.069>.
6. Ingrassia, L.P., Lu, X., Ferrotti, G., Canestrari, F., *Chemical, morphological and rheological characterization of bitumen partially replaced with wood bio-oil: Towards more sustainable materials in road pavements*. Journal of Traffic and Transportation Engineering, 2020. **7**: p. 192-204. DOI: <https://doi.org/10.1016/j.jtte.2019.04.003>.
7. He, M., Tu, C., Cao, D.W., Chen, Y.J., *Comparative analysis of bio-binder properties derived from different sources*. International Journal of Pavement Engineering, 2017. **20**: p. 792-800. DOI: <https://doi.org/10.1080/10298436.2017.1347434>.
8. Portugal, A.C.X., Lucena, L.C.F.L., Lucena, A.E.F.L., Costa, D.B., Lima, K.A., *Rheological properties of asphalt binders prepared with maize oil*. Construction and Building Materials, 2017. **152**: p. 1015-1026. DOI: <http://dx.doi.org/10.1016/j.conbuildmat.2017.07.077>.
9. Shu, X., Huang, B., Shrum, E.D., Jia, X., *Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP*. Construction and Building Materials, 2012. **35**: p. 125-130. DOI: <https://doi.org/10.1016/j.conbuildmat.2012.02.095>.
10. Lucena, L.C.F.L., Silveira, I.V., Costa, D.B., *Evaluation of asphalt binders modified with oil from Moringa Oleífera Lam for use in warm mixture*. Revista Matéria, 2016. **21**: p. 72-82.
11. Portugal, A.C.X., Lucena, L.C.F.L., Lucena, A.E.F.L., Costa, D.B., Patricio, J.D., *Evaluating the rheological effect of asphalt binder modification using soybean oil*. Petroleum Science and Technology, 2018. **36**: p. 1351-1360. DOI: <https://doi.org/10.1080/10916466.2017.1322980>.
12. Sun, D., Sun, G., Du, Y., Zhu, X., Lu, T., Pang, Q., Shi, S., Dai, Z., *Evaluation of optimized bio-asphalt containing high content waste cooking oil residues*. Fuel, 2017. **202**: p. 529-540. DOI: <http://dx.doi.org/10.1016/j.fuel.2017.04.069>.
13. Zeng, M., Li, J., Zhu, W., Xia, Y., *Laboratory evaluation on residue in castor oil production as rejuvenator for aged paving asphalt binder*. Construction and Building Materials, 2018. **193**: p. 276-285. DOI: <https://doi.org/10.1016/j.conbuildmat.2018.10.204>.
14. Girimath, S., Singh, D., *Effects of bio-oil on performance characteristics of base and recycled asphalt pavement binder's*. Construction and Building Materials, 2019. **227**. DOI: <https://doi.org/10.1016/j.conbuildmat.2019.116684>.
15. Nogueira, R.L., Soares, J.B.S., Soares, S.A., *Rheological evaluation of cotton seed oil fatty amides as a rejuvenating agent for RAP oxidized asphalts*. Construction and Building Materials, 2019. **223**: p. 1145-1153. DOI: <https://doi.org/10.1016/j.conbuildmat.2019.06.128>.
16. Sun, Z., Yi, J., Huang, Y., Feng, D., Guo, C., *Properties of asphalt binder modified by bio-oil derived from waste cooking oil*. Construction and Building Materials, 2016. **102**. DOI: <http://dx.doi.org/10.1016/j.conbuildmat.2015.10.173>.
17. Pradhan, S.K., Sahoo, U.C., *Performance assessment of aged binder rejuvenated with Polanga oil*. Journal of Traffic and Transportation Engineering, 2019. **6**: p. 608-620. DOI: <https://doi.org/10.1016/j.jtte.2018.06.004>.
18. Souza, J.L.S., *Study of the mechanical properties of asphalt mixtures with petroleum asphalt cement modified with castor oil*. Masters Dissertation. Department of Civil Engineering. Federal University of Campina Grande, 2012.
19. Faxina, A.L., *Study of the technical feasibility of using shale oil residue as an extender oil in asphalt-rubber binders*. Doctoral thesis. Department of Civil Engineering. University of Sao Paulo, 2006.
20. Portugal, A.C.X., *Rheological evaluation of petroleum asphalt cements modified with soybean and corn oil*. Doctoral thesis. Department of Civil Engineering. Federal University of Campina Grande, 2016.
21. Bernucci, L.B., Motta, L.M.G., Ceratti, J.A.P., Soares, J.B., *Asphalt Paving: Basic Training for Engineers* 2010, Rio de Janeiro: ABEDA.

22. Melo Neto, O.M., Ferreiro, A.A., Freire, T.S., Silva, G.C.B., Lucena, L.C.F.L., Sousa Neto, V.F., *Rheological Analysis of Asphalt Binders Modified with Hydrated Lime and Titanium Dioxide Nanoparticles*. International Journal for Innovation Education and Research, 2020. **8**: p. 579-598. DOI: <https://doi.org/10.31686/ijer.vol8.iss11.2787>.

Conflict of Interests

No potential competing interest is reported by the authors.

Author's Contribution

Osires de Medeiros Melo Neto. ORCID: <https://orcid.org/0000-0002-2535-0969>

Conceptualization, methodology, supervision, validation, draft, editing, and review of the manuscript.

Ana Maria Gonçalves Duarte Mendonça. ORCID: <https://orcid.org/0000-0002-4595-2959>

Conceptualization, methodology, supervision, validation, draft, editing, and review of the manuscript.

John Kennedy Guedes Rodrigues. ORCID: <https://orcid.org/0000-0003-0340-5567>

Conceptualization, methodology, supervision, validation, draft, editing, and review of the manuscript.

Robson Kel Batista de Lima. ORCID: <https://orcid.org/0000-0001-6917-9895>

Editing and review of the manuscript.

Carina Silvani. ORCID: <https://orcid.org/0000-0003-4472-7431>

Conceptualization, methodology, supervision, validation, draft, editing, and review of the manuscript.

Ingridy Minervina Silva. ORCID: <https://orcid.org/0000-0003-2538-9166>

Editing and review of the manuscript.