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Effects of Waste Lubricant Oil on Rheological Properties of Asphalt Binders: Implications for Sustainable Asphalt Mixture Production

Efectos del Aceite Lubricante Residual en las Propiedades Reológicas de los Ligantes Asfálticos: Implicaciones para la Producción Sostenible de Mezclas Asfálticas

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Abstract

Reusing waste lubricant oil as an environmentally-friendly alternative for disposal and transforming it into a value-added product is a promising solution. This study aimed to evaluate the rheological properties of asphalt binder (PG 64-XX) modified with waste hydraulic oil. Two levels of oil content, 3% and 5% by weight of the base binder, were added. Physical and rheological tests, including penetration, softening point, rotational viscosity, and performance grade (PG) tests, were conducted before and after subjecting the samples to the Rolling Thin Film Oven (RTFO), multiple stress creep and recovery (MSCR), linear amplitude sweep (LAS), and master curve procedures. Results showed that the addition of oil decreased the stiffness of the base binder, making it more susceptible to premature cracking and instability. However, the mixture and compaction temperatures decreased with the oil addition. Overall, considering the investigated oil contents, the asphalt binders modified with waste hydraulic oil did not exhibit satisfactory performance. It is hypothesized that incorporating residual hydraulic oil in recovered asphalt binders may yield more favorable results.

Keywords: Asphalt binder; Compaction temperature; Environmental sustainability; Instability; Mixture temperature; Modified binder; Premature cracking; Rheological properties; Value-added product; Waste lubricant oil.

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Resumen

Reutilizar el aceite lubricante residual como una alternativa respetuosa con el medio ambiente y transformarlo en un producto de valor agregado es prometedor. Este estudio evaluó las propiedades reológicas de los ligantes asfálticos (PG 64-XX) modificados con aceite hidráulico residual. Se añadieron dos niveles de contenido de aceite, 3% y 5% en peso del ligante base. Se realizaron pruebas físicas y reológicas, incluyendo penetración, punto de reblandecimiento, viscosidad rotacional y pruebas de grado de rendimiento (PG), antes y después de someter las muestras a procedimientos como el horno de película delgada en movimiento (RTFO), deformación y recuperación bajo múltiples tensiones (MSCR), barrido de amplitud lineal (LAS) y curva maestra. Los resultados mostraron que la adición de aceite redujo la rigidez del ligante, aumentando su susceptibilidad a la formación prematura de grietas e inestabilidad. Sin embargo, las temperaturas de mezcla y compactación disminuyeron con la adición de aceite. En general, considerando los contenidos de aceite investigados, los ligantes asfálticos modificados con aceite hidráulico residual no demostraron un rendimiento satisfactorio. Se plantea la hipótesis de que incorporar aceite hidráulico residual en ligantes asfálticos recuperados podría generar resultados más favorables.

Palabras clave: Ligante asfáltico; Temperatura de compactación; Sostenibilidad ambiental; Inestabilidad; Temperatura de mezcla; Ligante modificado; Formación prematura de grietas; Propiedades reológicas; Producto de valor agregado; Aceite lubricante residual.

1. Introduction

Hot Mix Asphalt (HMA) is widely used as the surface course in flexible pavements [1]. The production of HMA involves heating aggregates and asphalt binder at temperatures ranging from 140ºC to 180ºC. Unfortunately, this process contributes to greenhouse gas emissions and consumes a significant amount of energy [2]. The demand for raw materials in the paving industry has increased, leading to a depletion of crude oil reserves used in asphalt binder production [3], [4]. In light of this, there has been a growing interest in exploring sustainable and renewable materials as alternatives [5].

The rising cost of oil, which has a direct impact on the production expenses of asphalt binders, has become a significant concern for the asphalt industry. As a result, there is an increasing focus on exploring sustainable alternative oils within the paving sector [6], [7], [8]. The incorporation of bio-oils into asphalt binders offers benefits such as reduced mixing and compaction temperatures of asphalt mixtures and decreased greenhouse gas emissions during production [9]. To address these objectives, Warm Mix Asphalt (WMA) technologies have been developed, enabling the reduction of mixing and compaction temperatures without compromising the performance and workability of asphalt mixtures [10].

The initial development of additives for Warm Mix Asphalt (WMA) took place in Europe starting from 1997, as a response to align the practices of the asphalt industry with the requirements of the Kyoto Protocol. In addition to the environmental benefits, the use of WMA offers advantages such as reduced worker exposure to asphalt fumes, decreased asphalt aging, and the potential for an extended paving season [11], [12]. WMA technology encompasses a diverse range of processes and products, which can be broadly classified into three types: foaming technologies, organic or wax additives technologies, and chemical additives technologies. Each of these technologies improves the workability of the asphalt mixture in different ways [13], [14]. Organic additives contain long-chain hydrocarbons that lower the viscosity of the asphalt binder at high temperatures when incorporated. Chemical additives enhance aggregate wetting and modify the internal friction of the mixture, resulting in improved workability [15]. Another process, known as foaming, involves the addition of water to the hot asphalt binder, generating small bubbles that reduce the viscosity of the binder [16].

Among the various organic additives, the use of oils has garnered significant attention. Lucena et al. [11] conducted a study utilizing moringa oil for the production of Warm Mix Asphalt (WMA). The incorporation of this oil resulted in a notable reduction of 5ºC in both mixing and compaction temperatures, while maintaining the performance of the original asphalt binder. In a similar vein, Portugal et al. [2] investigated the effects of incorporating 1% corn oil by weight into a 50/70 pen grade base binder. The authors observed a significant reduction of 6ºC in production temperatures while preserving the favorable rheological performance of the modified binder. Additionally, Portugal et al. [17] examined the behavior of an asphalt mixture with an asphalt binder modified using waste and new soybean oil. The results demonstrated that the addition of 1% of both oils to the base binder led to improvements in its physical and rheological properties, along with a reduction of 2.7ºC in production temperatures. In a separate study, Girimath and Singh [18] utilized wood residue biomass as a raw material source for the production of bio-oils. The authors investigated the physical and rheological properties of the asphalt binder modified with varying levels of this bio-oil, ranging from 2% to 10% with alternating increments of 2%. The characterization results of the modified binder for the 2% and 4% contents aligned with the specifications outlined in the standard. The incorporation of this additive resulted in a decrease in viscosity and softening point, while increasing the degree of penetration, thus acting as a viscosity-reducing modifier.

The production of lubricant oils in Brazil reached approximately 1,542,585 m³ in 2018, as reported by the Brazilian National Agency of Petroleum, Natural Gas, and Biofuels [19]. While around 40% of this volume is collected and properly disposed of in compliance with Brazilian environmental legislation, there remains a significant amount of oil that is not correctly managed, potentially leading to environmental impacts. Waste lubricating oil contains hydrocarbons, heavy metals, PCBs (Polychlorinated Biphenyls), and other halogen compounds, which can contribute to air pollution when burned as low-grade fuel. Moreover, if these substances come into contact with soil and water sources, they can enter the food chain through natural cycles, posing risks to human health [20]. In light of these concerns, the exploration of reuse alternatives for waste lubricant oil presents an environmentally friendly solution for its disposal while also transforming it into a value-added product. This study focuses on evaluating the impact of incorporating lubricating oil, derived from the maintenance of hydraulic machines, on the rheological properties of asphalt binder.

2. Materials and Methods

The asphalt binder utilized in this study was a PG 64-XX grade binder with a penetration grade of 50/70. The waste lubricant oil employed originated from Lubrax Hydra®, and its expiration date was undetermined. The oil was collected from the maintenance of hydraulic machines at the Laboratory of Pavement Engineering, Federal University of Campina Grande. To conduct the research, two different contents of waste hydraulic oil, namely 3% and 5%, were added as modifiers to the pure binder (PG 64-XX). The selection of these additive levels was based on previous studies by Lucena et al. [11], Girimath and Singh [18], Sun et al. [21], Sun et al. [22], and Pradham and Sahoo [23], which investigated oil contents ranging from 1% to 8% as modifiers for asphalt binders. The modification of the base binder with waste lubricant oil was performed using a low shear mechanical mixer (FISATOM, Model 72) at a temperature of 135ºC. The mixture was subjected to mixing for 20 minutes at a speed of 410 rpm. The addition contents of 3% and 5% were determined based on studies conducted by Souza [24] and Faxina [25]. Table 1 provides a description of the samples utilized in the research and their respective nomenclatures.

Table 1. Nomenclature of the samples used in this research

Samples	Nomenclature
Asphalt Binder PG 64-XX	0% oil
PG 64-XX + 3% Waste Hydraulic Oil	3% oil
PG 64-XX + 5% Waste Hydraulic Oil	5% oil

The physical and rheological characterization of the modified asphalt binders was conducted through a series of tests. The tests performed included: (i) Penetration tests according to ASTM D5M [26]; (ii) Softening Point tests according to ASTM D36M-14 [27]; (iii) Rotational Viscosity tests according to ASTM D4402 [28]; (iv) Performance Grade (PG) tests according to ASTM D6373 [29]. These tests were carried out both before and after subjecting the binders to Rolling Thin Film Oven (RTFO) testing, as per ASTM D2872 [30]. Additionally, Multiple Stress Creep Recovery (MSCR) tests were performed according to ASTM D7405 [31], and Linear Amplitude Sweep (LAS) tests were conducted following AASHTO TP 101-12 [32] guidelines. Master curve analysis was also performed. The rheological tests were performed using a hybrid Oscillatory Rheometer Discovery HR-1 rheometer at the Pavement Engineering Laboratory (LEP) located at the Federal University of Campina Grande (UFCG) in Brazil. These tests were carried out in accordance with the Superpave methodology for the analysis of both pure and modified asphalt performance. Based on the results obtained, an optimal content among the tested modifiers was identified, which exhibited the best performance characteristics.

The maximum performance of the binder was determined based on the temperature at which the parameter $G^*/\sin\delta$ exceeded 1.0 kPa (prior to short-term aging) and 2.2 kPa (after the aging process in the Rolling Thin Film Oven - RTFO). The ASTM specification D6373 [29] provides standard maximum temperature ranges for PG analysis of binders, ranging from 46°C to 82°C. Tests were conducted on samples both before and after undergoing the RTFO process. The continuous PG determination was carried out in 1°C increments within a temperature range of 46°C to 82°C. The MSCR test, based on ASTM D7405 [31], was performed using the respective PG temperatures. This test involved applying 10 cycles, each at two load levels (0.1 kPa and 3.2 kPa). Each cycle consisted of a 1-second creep load period followed by a 9-second relaxation period. The Jnr and R's parameters (% recovery) were obtained from this test. These procedures allowed for the evaluation of the rheological properties and performance characteristics of the asphalt binder before and after aging, providing valuable insights into its suitability for specific applications.

The LAS test was conducted in accordance with ASHTO TP 101-12 [32], which specifies that samples should be aged in both the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV). However, due to limitations in the laboratory, the LAS test was only performed on samples aged in the RTFO.During the LAS test, it was necessary to heat the rheometer's geometry to 56°C to ensure proper sample adhesion. Consequently, the samples in the Dynamic Shear Rheometer (DSR) needed to be cooled to 25°C for the LAS test. The LAS test consisted of two steps: (1) Frequency scanning: The sample was subjected to shear load at a temperature of 25°C, with frequencies ranging from 0.1 to 30 Hz and an amplitude level of 0.1%. This step aimed to obtain the rheological properties of the asphalt binders. (2) Amplitude sweep: Small torques were applied to the same sample at a constant frequency of 10 Hz, while the amplitude level was varied from 0.1 to 30%. This step measured the damage experienced by the binder.

The master curve was constructed based on observations of the material's response to applied stresses in relation to variations in the complex modulus (G*) measured in kilopascals, frequency in hertz (Hz), phase angle (δ) in degrees (º), and temperature in degrees Celsius (ºC). The test was performed with temperature steps of 6ºC, starting from 46ºC up to a maximum temperature of 82ºC. For each temperature step, the values of G* and δ were plotted on log-log scales, resulting in master curves. The master curve analysis allowed for a comprehensive understanding of the material's viscoelastic behavior and its performance across a range of temperatures and frequencies.

3. Results and Discussion

In this section, we present and discuss the results obtained from the experimental phase of asphalt binders modified with waste hydraulic oil. The results obtained in this experimental phase provided important insights into the effects of waste hydraulic oil on the rheological properties of asphalt binders. These findings will be further discussed and analyzed in the following sections, considering their implications for the performance and suitability of the modified binders for paving applications. The results presented are the average of three samples, without repetition.

3.1. Physical Characterization of Pure and Modified Asphalt Binders

Table 2 displays the results of the physical characterizations conducted on the study samples. The observed behavior aligns with findings from the literature [24], [33], [34], [35], which indicate a similar trend of increased penetration when vegetable oil is added to asphalt binders. The asphalt binder samples modified with waste hydraulic oil exhibited comparable penetration values. According to ANP No. 19 [36], a minimum retained penetration value of 55% is required. However, based on the data presented in Table 2, the modified samples did not meet this specification, indicating susceptibility to aging. The thermal susceptibility index (TSI) provides insights into the sensitivity of the binder to temperature variations. TSI values can range between -1.5 and 0.7, with higher values indicating lower thermal susceptibility, meaning the binder is less affected by temperature changes. The results indicate that the incorporation of 3% oil reduced the susceptibility of the asphalt binder to temperature variations. The sample with 3% oil exhibited the least susceptibility among all the samples analyzed in this study.

Table 2. Physical characterization of asphalt binders

Characteristic	Limits	Results			Standard
		0% oil	3% oil	5% oil	
Softening point, ºC	≥46.0	51	44	42	ASTM D36M-14 [27]
Penetration (100g, 5s, 25°C), dmm	50 to 70	51	123	124	ASTM D5M [26]
Thermal susceptibility index (TSI), ºC	-1.7 to +0.5	-0.90	-0.27	-1.11	ASTM D36M-14 [27] / ASTM D5M [26]
Mass variation after short-term ageing, %	≤0.5	0.123	0.18	0.863	ASTM D2872 [30]
Retained penetration, %	≥55.0	59.87	37.8	46.62	ASTM D5M [26]
Softening point variation, °C	≤8	4	8	7	ASTM D36M-14 [27]

Nevertheless, all tested samples remained within the specified limit. These findings suggest that the addition of waste hydraulic oil influenced the physical properties of the asphalt binder, particularly in terms of penetration and thermal susceptibility. The deviations from the specified limits indicate the need for further investigation and optimization to achieve binder compositions that meet the required standards and exhibit improved performance characteristics.

$$\text{TSI} = \frac{(500)(\log\text{PEN}) + (20)(\text{T°C}) - 1951}{120 - (50)(\log\text{PEN}) + (\text{T°C})} \qquad (1)$$

- T°C = Softening point
- PEN = Penetration 0.1 mm (100 g, 5 s at 25°C)

The decrease in the softening point of the asphalt binder after the addition of waste hydraulic oil aligns with the expected results based on previous studies [24], [33], [34], [35]. All tested samples exhibited values within the established criteria [36]. This reduction in softening point confirms the observed decrease in stiffness observed in the penetration test conducted on the modified asphalt binder samples. The loss of mass due to short-term aging gradually increased with the increase in oil content, with a more pronounced effect observed for the 5% oil addition. This behavior can be attributed to the higher susceptibility of the oil components to volatilization compared to the binder components. Consequently, the retained penetration of the neat binder was reduced by approximately 37% and 23% with the addition of 3% and 5% oil, respectively. These findings indicate that the incorporation of waste hydraulic oil influenced the rheological properties of the asphalt binder, leading to a decrease in stiffness and an increase in the susceptibility to volatilization. The extent of these effects varied with the oil content, suggesting the need for careful consideration of the desired performance characteristics when determining the optimal oil content for asphalt binder modification.

3.2. Rheological Analysis of Pure and Modified Asphalt Binders

3.2.1. Rotational Viscosity

Figure 1 illustrates the exponential trend lines obtained from the viscosity-temperature relationship at temperatures of 135ºC, 155ºC, and 177ºC for both the modified and pure asphalt binders, before and after short-term aging. The upper and lower limits of viscosity are also depicted, representing the range of mixing and compacting temperatures for the studied binders. The modification of the binder resulted in lower viscosity values, indicating improved workability compared to the pure binder. This viscosity reduction subsequently leads to a decrease in the required mixing and compaction temperatures.

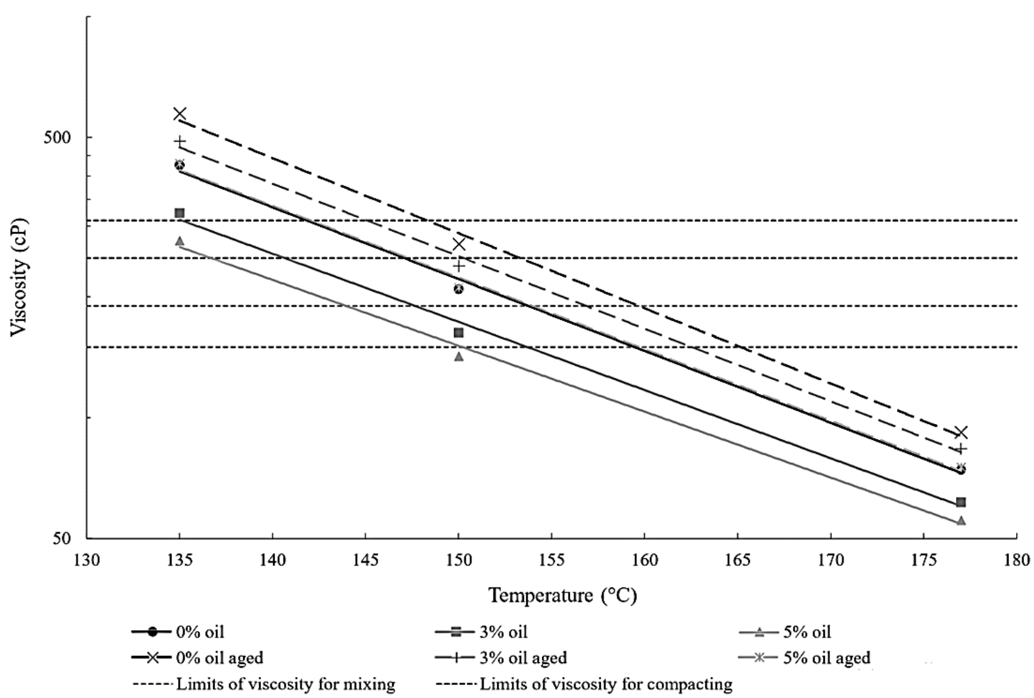


Figure 1. Trend lines of viscosity versus temperature.

The reduction in viscosity has the added benefit of reducing energy consumption during the heating process of the asphalt binder for asphalt mixture production. However, it is important to carefully evaluate the extent of viscosity reduction to avoid potential issues such as the formation of cracks in the pavement. Table 3 provides an overview of the range of mixing and compacting temperatures for the binders, as well as the effect of aging on binder viscosity, which is analyzed through the aging viscosity index. The aging viscosity index quantifies the change in viscosity before and after short-term aging, providing insights into the binder's performance characteristics.

The results obtained indicate that the incorporation of waste hydraulic oil has a significant impact on reducing the viscosity of the asphalt binder, thereby lowering the ideal temperature for the asphalt mixture. The average mixing temperature for the unmodified binder was reduced by 7ºC and 10ºC with the addition of 3% and 5% oil content, respectively. Similarly, the compaction temperatures were reduced by 6.5ºC and 9.5ºC. These findings highlight the effectiveness of waste hydraulic oil in reducing the required temperatures for asphalt production. The viscosity aging index, which reflects the change in viscosity before and after short-term aging, increased as the oil content increased. This can be attributed to the decreased stiffness observed in the modified samples. Moreover, the modified binder becomes more susceptible to aging as the oil content increases, suggesting that the oil used may have already undergone oxidation, making it more prone to aging. According to the Federal Highway Administration guidelines, mixtures classified as "hot mix" typically have temperatures above 150°C. Upon analyzing the results presented in Table 3, it is evident that all modified asphalt binders exhibited temperatures below 150°C, indicating that they fall within the range of "hot mix" asphalt temperatures.

3.2.2. Performance Grade (PG)

Due to the primarily tropical climate in Brazil, where average temperatures are around 25°C, the evaluation of low-temperature performance (PG temperature) was not conducted in this research. Therefore, Table 4 presents the PG temperature and failure temperature of the asphalt binder, as well as the aging index calculated based on the G*/sinδ parameter before and after short-term aging at different test temperatures. The PG temperature represents the maximum allowable temperature for the asphalt binder to maintain its desired performance characteristics. The failure temperature indicates the temperature at which the binder loses its ability to resist deformation under load. These parameters are important for assessing the suitability of the binder for specific applications and climate conditions. The aging index, determined by comparing the G*/sinδ values before and after short-term aging, provides insight into the effect of aging on the binder's rheological properties. It indicates the extent to which the binder's performance is affected by aging and can help assess its long-term durability. Table 4 presents these important parameters and provides valuable information regarding the performance and aging characteristics of the asphalt binder under study.

The modification of the asphalt binder with both 3% and 5% waste hydraulic oil resulted in a decrease of one step (6°C) in the PG temperature, classifying them as PG 58-XX. This reduction in PG temperature indicates improved workability and reduced stiffness of the binder, as expected based on previous studies [37], [38], [39], [40]. Interestingly, the increase in oil content did not significantly alter the rigidity of the binder.

Table 3. Mixing and compaction temperatures and viscosity aging index

Sample	Range of mixing Temperature (°C)	Range of compaction Temperature (°C)	Viscosity aging index (%)		
			135 °C	150 °C	177 °C
0% oil	154 - 159	143 - 147	34.31	29.67	23.91
3% oil	147 - 152	136 - 141	50.97	46.63	36.18
5% oil	144 - 149	134 - 137	55.66	48.42	35.59

Table 4. PG test summary

Samples	PG Temperature	Failure Temperature	Aging index			
			46 °C	52 °C	58 °C	64 °C
Oil 0%	64	67.1	2.07	2.04	1.97	1.87
Oil 3%	58	63.5	2.30	2.24	2.14	2.08
Oil 5%	58	61.0	2.64	2.56	2.49	2.42

The failure temperature, which represents the temperature at which the binder loses its ability to resist deformation under load, decreased with the increase in oil content. This suggests that the addition of waste hydraulic oil reduces the high-temperature performance of the binder. The aging index of the pure binder decreased with the oil modification, indicating a higher susceptibility to oxidation. This finding is consistent with the mass loss and viscosity aging index results discussed earlier, further confirming the influence of the oil on the aging properties of the binder. Figure 2 illustrates the variations in the complex shear modulus (G*) of the modified and unmodified asphalt binder samples with temperature. As expected, the complex shear modulus decreases as the temperature increases for all samples. This change in rheological behavior from elastic to viscous with increasing temperature is a well-known phenomenon in asphalt binders [41]. Overall, the results demonstrate that the addition of waste hydraulic oil affects various rheological properties of the asphalt binder, including PG temperature, failure temperature, aging index, and complex shear modulus. These findings provide valuable insights into the performance characteristics of the modified binder under different temperature conditions.

At the measurement temperatures, the complex shear modulus values were higher for the pure binder sample compared to the modified samples. This difference in complex modulus values was most pronounced at low temperatures. This result is expected since the addition of oil reduces the viscosity of the asphalt binder, making it less rigid. However, the decrease in complex modulus values is not beneficial as it indicates a reduction in the binder's resistance to damage. The variations of the phase angle (δ) with temperature are presented in Figure 3.

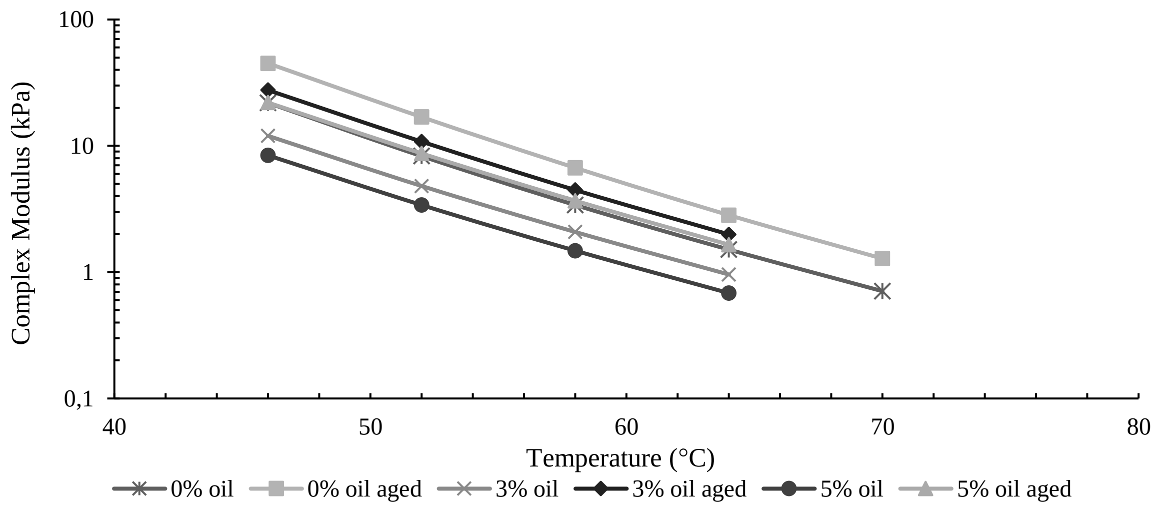


Figure 2. Changes of complex shear modulus with the temperature for the asphalt binder modified with 0, 3 and 5% waste hydraulic oil.

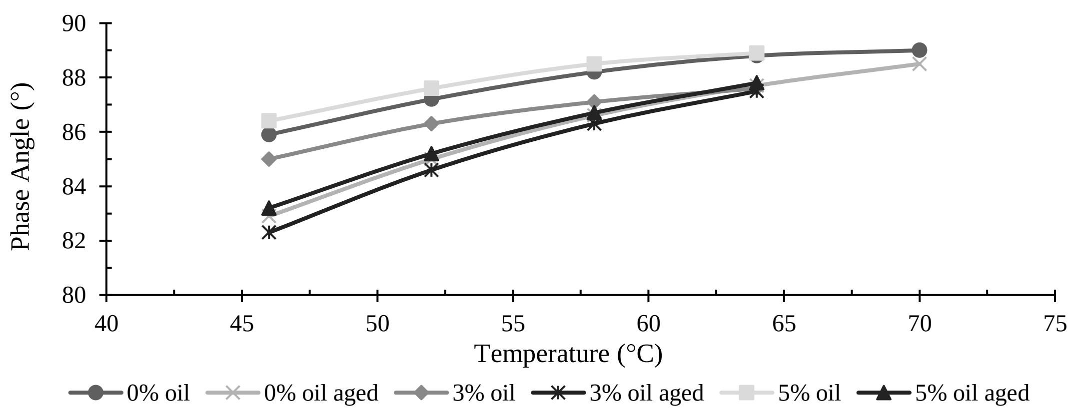


Figure 3. Changes of phase angle (δ) with the temperature for the asphalt binder modified with 0%, 3% and 5% oil.

The phase angle exhibited a rheological behavior opposite to that described for the complex modulus. The phase angle values increased with increasing temperature. The phase angle is a measure of the asphalt binder's elasticity. Lower phase angle values indicate more elastic materials with a greater capacity to respond to damage. The increase in phase angle with temperature suggests that the modified asphalt binder becomes more elastic as the temperature rises. This could be attributed to the lower stiffness and increased workability resulting from the addition of waste hydraulic oil. However, it is important to note that excessively high phase angle values can also indicate a decrease in binder stability and a potential for rutting or deformation under traffic loads. The observed differences in complex shear modulus and phase angle between the pure and modified asphalt binders highlight the impact of waste hydraulic oil on the rheological properties of the binder. These results provide valuable insights into the binder's behavior under varying temperature conditions and its potential performance in road construction and pavement applications.

3.2.3. Multiple Stress Creep Recovery (MSCR)

Table 5 presents the results obtained from the MSCR test, including the non-recoverable compliance (Jnr) and percentage of elastic recovery (%Rec) for the applied loads of 0.1 kPa and 3.2 kPa. Additionally, the differences in Jnr (Jnrdiff) and %Rec (%Rdiff) between the two applied loads are calculated and presented in the table. The MSCR test provides valuable information about the rutting and recovery properties of asphalt binders. The Jnr parameter represents the permanent deformation or non-recoverable strain experienced by the asphalt binder, while %Rec indicates the ability of the binder to recover its original shape after deformation. By analyzing the differences between the two applied loads, insights into the binder's ability to resist permanent deformation under different stress levels can be obtained. The MSCR test was conducted at the PG temperature of the asphalt binders as well as the PG temperature of the modified binders for comparison with the pure binder. This allows for a comprehensive evaluation of the performance and rut resistance of the modified binders compared to the unmodified binder.

The results obtained from the MSCR test indicate that the addition of waste hydraulic oil to the asphalt binder increases the non-recoverable compliance (Jnr) parameter, suggesting a higher susceptibility to permanent deformation. This effect becomes more pronounced with an increase in the oil content, indicating that a higher percentage of oil magnifies the binder's vulnerability to deformation. Based on the classification proposed by AASHTO M320 [42], the modified asphalt binders, as well as the pure binder, can be classified as "Standard" in terms of their resistance to permanent deformation. This classification is determined by correlating the Jnr value at 3.2 kPa with the traffic volumes that the binders can withstand. The percentage difference values between the 0.1 kPa and 3.2 kPa non-recoverable compliance (Jnrdiff) are also provided in Table 5. According to ASTM D7405, the Jnrdiff parameter reflects the binder's sensitivity to stress differences at high temperatures. It is recommended that the Jnrdiff values should not exceed 75%. The modified binders in this study show increased Jnrdiff values, indicating a higher sensitivity to stress variations under elevated temperatures. However, all samples tested remain below the specified limit. The binders, including both the modified and pure binders, exhibit low values of elastic recovery (%Rec), indicating low elasticity. As a result, these binders are not recommended for use in field applications where high elasticity and resistance to deformation are desired [43].

3.2.4. Master Curve

Figure 4 illustrates the master curve of the complex modulus for both the pure and modified asphalt binders. The construction of this master curve follows the superposition principle, which allows for the representation of the modulus's dependence on time or temperature in shorter tests. The performance of the binders is evaluated across different frequency bands,

Table 5. MSCR test summary

Parameter	0% oil		3% oil	5% oil
PG temperature, ºC	58	64	58	58
Jnr at 0.1 kPa, kPa^{-1}	1.48	3.80	2.24	2.9
Jnr at 3.2 kPa, kPa^{-1}	1.53	3.90	2.37	2.95
Jnr_{diff}, %	3.55	2.57	5.67	1.67
%Rec at 0.1 kPa, %	2.12	0.56	2.58	-1.38
%Rec at 3.2 kPa, %	1.04	0.13	0.81	0.44
$\%R_{diff}$, %	51.08	76.37	68.53	132.16

which correspond to different temperature levels. After undergoing short-term aging, both the pure and modified binders exhibited an increase in the parameter |G*|, indicating an increase in material stiffness, as expected. However, the oil-modified samples displayed reduced stiffness at high frequencies, corresponding to lower temperatures. This behavior aligns with expectations, as the addition of oil enhances the fluidity of the asphalt binder, resulting in reduced rigidity. This characteristic can be desirable to a certain extent, as long as the binder can still withstand the applied stresses.

3.2.5. Linear Amplitude Sweep (LAS)

Figure 5 (a) displays parameters A and B, which represent the resistance to accumulated damage for the asphalt binders studied. Parameter A shows an increase with the addition of oil to the pure binder. A higher value of parameter A indicates that the sample maintained its initial integrity, implying improved resistance to accumulated damage. Thus, the samples with 5% oil exhibited the highest integrity. Parameter B, on the other hand, increased by approximately 2% and 12% with the addition of 3% and 5% oil, respectively. These increases suggest a higher susceptibility to deformation levels for the oil-modified asphalt binders. A higher value of parameter B indicates increased susceptibility to fatigue damage. In Figure 5 (b), the derivatives of the fatigue models for each asphalt binder are shown. These models were determined using the viscoelastic damage principle (VECD) and were obtained from the LAS test conducted at 25°C. The fatigue life estimated for the samples at strain levels of 2.5%, 5%, and 10% indicates that the oil-modified samples exhibited higher values, implying better fatigue tolerance compared to the pure asphalt binder.

Figure 6 displays the results of damage intensity for samples with 0%, 3%, and 5% oil. Parameter C represents the ratio between the values of G·sinδinitial and G·sinδ for each amplitude of deformation. This parameter allows the estimation of material integrity and the assessment of damage caused to the samples. Table 6 presents the VECD coefficients obtained from the curves shown in Figure 6. C0 represents the initial state of the asphalt binder, where damage is zero and integrity is 100%. Therefore, it has a value of 1. For optimal performance of the modified asphalt binder, it is desirable to have lower reductions in G·sinδ, indicating greater resistance to damage. This behavior is indicated by higher values of C1 and lower values of C2, as C1 represents small reductions in G·sinδ during the test. From Table 6, it can be observed that the values of parameter C1 remained constant, while the values of C2 increased. This suggests high variations in the value of G*·sinδ, indicating that the modification makes the binder less resistant to damage. The pure binder sample (0% oil) exhibited the lowest value of C2, indicating better resistance to damage compared to the modified samples. In summary, the results indicate that the addition of oil to the asphalt binder leads to increased susceptibility to damage, as reflected by higher values of C2. The pure binder sample, without oil modification, showed better resistance to damage with lower C2 values.

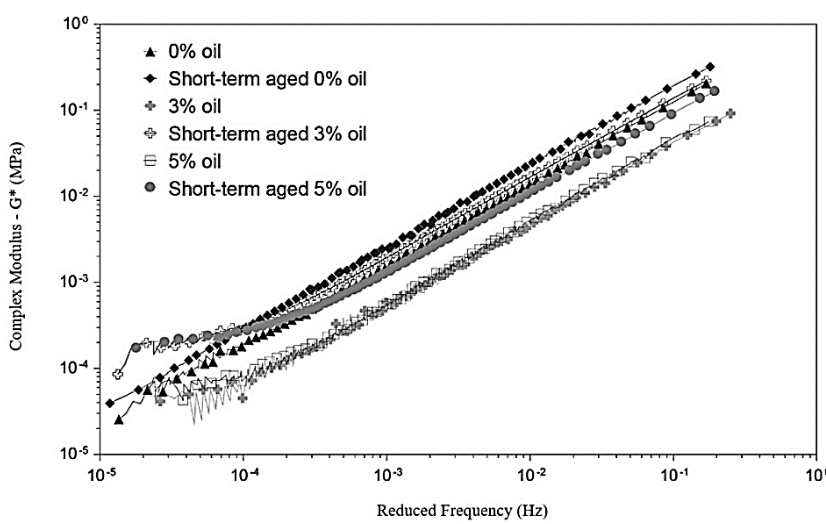
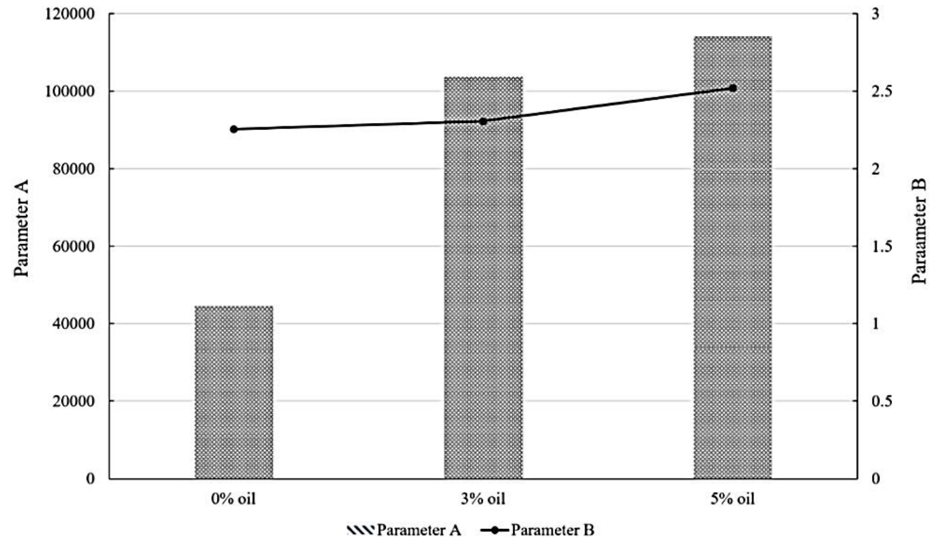
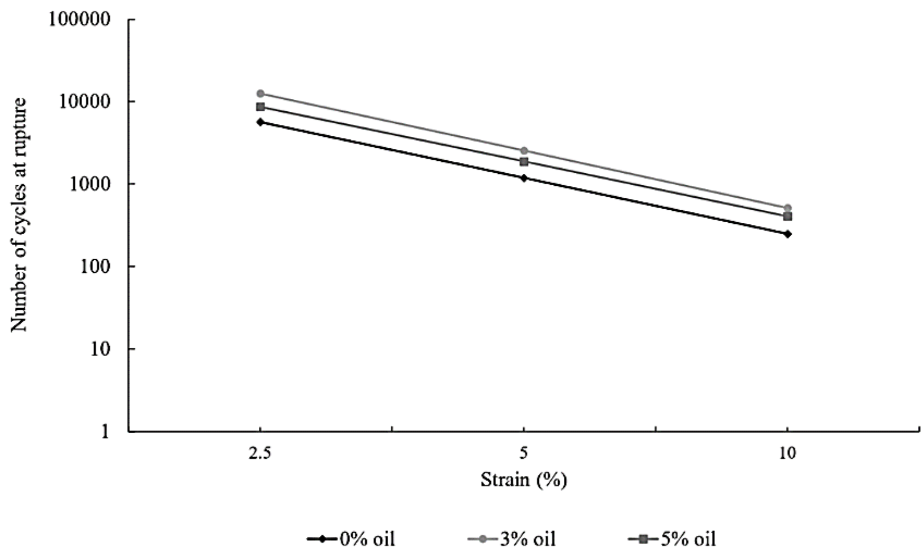


Figure 4. Master curves of the asphalt binders.



(a)



(b)

Figure 5. (a) Parameters A and B obtained through LAS, (b) fatigue life estimation of the asphalt binders.

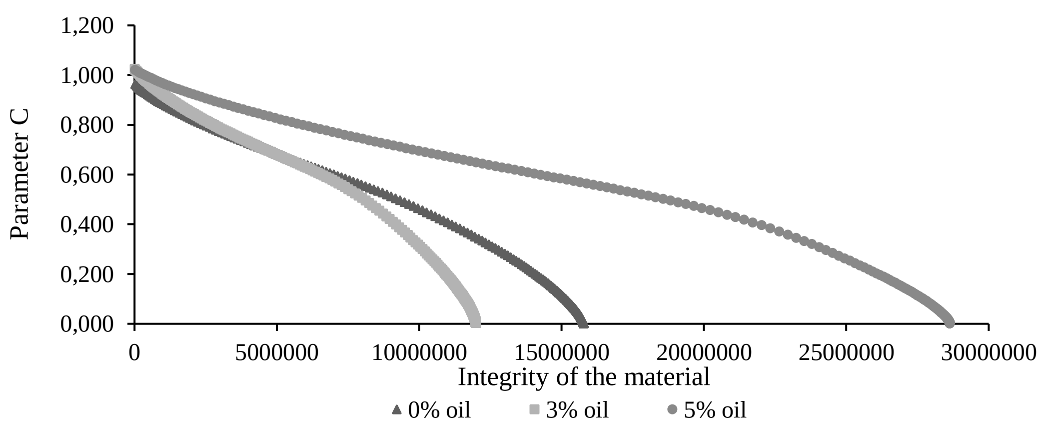


Figure 6. Integrity of the material (Parameter C).

Table 6. Parameters C obtained from the damage intensity curve

Sample	C_0	C_1	C_2
0% oil	1.000	0.000	0.619
3% oil	1.000	0.000	1.139
5% oil	1.000	0.000	1.036

4. Results

Based on the findings of this study, several conclusions can be drawn:

(1) The modified binder did not meet the minimum criteria in terms of stiffness values and resistance to permanent deformation during the characterization phase. This indicates that the addition of waste lubricant oil negatively affected the rheological properties of the asphalt binder.

(2) Although the modified binders exhibited reduced mixture and compaction temperatures, which could potentially lead to lower energy consumption during production, it is not recommended to use these binders due to their poor performance in terms of stiffness and resistance to deformation.

(3) Further studies should focus on exploring the use of waste lubricant oils from different sources as additives for asphalt binders. This research suggests that the environmental impacts of asphalt mixture production could be reduced by incorporating these materials. However, additional investigations are required to assess the suitability of different sources of waste lubricant oil.

(4) Future studies are encouraged to investigate the use of residual hydraulic oil at lower contents. This could help determine the optimal dosage that provides desirable rheological properties without compromising the performance of the asphalt binder.

(5) The incorporation of residual hydraulic oil into reclaimed asphalt binders may yield satisfactory results. Reclaimed asphalt binders are derived from recycled materials and have already undergone aging and oxidation. The addition of residual hydraulic oil could potentially enhance their properties and improve their performance.

Overall, this study highlights the importance of considering the effects of waste lubricant oil on the rheological properties of asphalt binders. Further research is needed to optimize the dosage and source of waste oil to achieve improved binder performance while reducing environmental impacts.

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Autor Contributions

I. M. Silva: Conceptualization, Methodology, Investigation, Data Curation. O. M. Melo Neto: Data Curation, Writing - Original Draft, Writing - Review & Editing. A. G. de Barros: Data Curation, Writing - Original Draft, Writing - Review & Editing. L. C. F. L. Lucena: Conceptualization, Supervision, Project administration. A. F. F. Monteiro: Writing - Original Draft.

Conflicts of Interest

The authors declare no conflict of interest.

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