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Analysis of temperature variation during mixing and compaction and the impact of beeswax on the stiffness of asphalt mixtures

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ABSTRACT: This study explores the potential of beeswax as a modifier for asphalt mixtures, focusing on its impact on pavement performance. The physical properties of the asphalt binder modified with 1 and 5% beeswax by weight of the binder were evaluated through penetration, softening point, and rotational viscosity tests. The modified binders were used to produce asphalt mixtures, where stiffness was assessed through indirect tensile strength and resilient modulus tests. The results indicated that beeswax reduced the binder's consistency, with a 9 and 12°C decrease in mixing and compaction temperatures when using 5% beeswax, demonstrating the potential for reducing greenhouse gas emissions in production and energy consumption. Statistical analyses revealed significant changes in mechanical properties, highlighting the impact of beeswax as a modifier. Warm mixtures with 1 and 5% beeswax showed 10.85 and 16.87% reductions in indirect tensile strength and 32.05 and 10.03% in resilient modulus, respectively, compared to conventional hot asphalt mixtures. Despite slightly lower performance at temperatures 10°C lower, the variations remained within acceptable limits. These findings underscore beeswax as a sustainable additive for asphalt pavements, offering viscosity reduction, lower working temperatures, and environmental benefits comparable to conventional modifiers.
Keywords: alternative material; asphalt binder; physical and mechanical properties; t-test.

Análise da variação de temperatura durante a mistura e compactação e o impacto da cera de abelha na rigidez de misturas asfálticas

RESUMO: Este estudo explora o potencial da cera de abelha como modificador de misturas asfálticas, focando no impacto no desempenho do pavimento. Avaliou-se as propriedades físicas do ligante asfáltico modificado com 1 e 5% de cera de abelha por peso do ligante por meio de ensaios de penetração, ponto de amolecimento e viscosidade rotacional. Os ligantes modificados foram utilizados na produção de misturas asfálticas, onde a rigidez foi avaliada por meio dos ensaios de resistência à tração indireta e módulo de resiliência. Os resultados indicaram que a cera de abelha reduziu a consistência do ligante, com uma diminuição de 9 e 12°C nas temperaturas de mistura e compactação ao usar 5% de cera, mostrando potencial para reduzir as emissões de gases de efeito estufa na produção e consumo de energia. Análises estatísticas revelaram alterações significativas nas propriedades mecânicas, destacando o impacto da cera de abelha como modificador. As misturas mornas com 1 e 5% de cera de abelha apresentaram reduções de 10,85 e 16,87% na resistência à tração indireta, e de 32,05 e 10,03% no módulo de resiliência, respectivamente, em comparação com misturas asfálticas convencionais a quente. Apesar de um desempenho ligeiramente inferior das misturas a temperaturas 10°C mais baixas, as variações permaneceram dentro dos limites aceitáveis. Essas descobertas destacam a cera de abelha como um aditivo sustentável para pavimentos asfálticos, oferecendo redução de viscosidade, temperaturas de trabalho mais baixas e benefícios ambientais comparáveis aos modificadores convencionais.
Palavras-chave: material alternativo; ligante asfáltico; propriedades físicas e mecânicas; teste-t.

1. INTRODUCTION

In Brazil, due to limited investments in railways and waterways and the high cost of air transport, most cargo transfers and passenger transportation occur through road networks. There are two primary types of road pavements: flexible, which consists of asphalt material, and rigid, composed of concrete slabs. Brazil produces the most commonly used asphalt mixtures. The utilization of hot mixtures provides the advantage of increased resistance to the stresses induced by vehicular traffic (COSTA et al., 2023; MELO NETO et al., 2023a; DE MORAES et al., 2023; QUEIROZ et al., 2023). However, the widespread use of hot asphalt mixtures on Brazilian roads has led to detrimental effects due to the high production temperatures, typically ranging from 150°C to 180°C. These elevated temperatures necessitate significant fuel combustion during the mixing process, resulting in excessive energy consumption and the emission of environmentally harmful gases, exacerbating the greenhouse effect and leading to adverse financial and environmental consequences. Moreover, the high temperatures release asphalt fumes, posing a health risk to exposed workers and causing damage to the working environment (MENDONÇA et al., 2022; MELO NETO et al., 2023b).

The quality of asphalt binder diminishes over time, starting from its production at the refinery to its eventual end in highway applications. This aging process leads to the deterioration of the mechanical properties of the asphalt mixture (SILVA et al., 2022; TORRES et al., 2024). Alternative practices have been developed to mitigate this challenge, such as utilizing warm mixture asphalt (WMAs). These mixtures are produced at intermediate temperatures, typically from 100°C to 145°C, resulting in reduced fuel consumption, lower energy expenditure, and environmental benefits. Moreover, the adoption of WMAs provides improved working conditions. Lowering the temperatures used during mixing and compaction minimizes the aging process caused by oxidation (Silva et al., 2021; Moraes et al., 2022). To produce Warm Mixtures Asphalt (WMAs), modifications can be made to the mix production process, and a modifying additive such as foamed asphalt, surfactant additives, and organic additives can be incorporated. These modifiers decrease the viscosity of the asphalt binder, resulting in lower temperatures required during the mixing and compaction processes.

Beeswax is a potential material for producing warm asphalt mixtures in this context. Beeswax is a material with high thermal capacity, impervious to water, composed of various substances, with a melting point between 61 and 65°C, a solidification point between 61.5 and 63°C, and evaporation at 250°C. At low temperatures, it can become hard and brittle. Additionally, it is insoluble in water and cold alcohol, partially soluble in hot alcohol and ether, and soluble in hot fats, essential oils, hot benzene, chloroform, and turpentine (NUNES et al., 2012). To produce one kilogram of wax, bees require about six to seven kilograms of honey, and the average wax production corresponds to 2% of the normal honey production. Nunes et al. (2012) also emphasize that beeswax has a wide range of applications, as no other material has been found to possess such emollient, softening, molding, and waterproofing properties. Major consumers of beeswax include the cosmetics industry, candle industry, and beekeeping industry, where it is considered a by-product. It is also used in waterproofing materials, the armament and pharmaceutical industries, the manufacture of greases, and encaustic (a painting technique that uses wax), in the composition of adhesive tape, paints, and varnishes, and it is an excellent electrical insulator.

Beeswax aligns with the principles of the bioeconomy, an industrial production model that uses biological resources for sustainable solutions, replacing fossil and non-renewable resources, such as petroleum-derived asphalt binder (LOPES, 2015). Thus, this study investigated the effects of beeswax on the physical properties of asphalt binder, with contents of 1% and 3% by weight, and its influence on the stiffness of asphalt mixtures. The mixtures were produced at the mixing temperatures obtained in the rotational viscosity test for each binder (pure, modified with 1% wax, and modified with 3% wax) and at temperatures 10°C lower to evaluate the influence of temperature on stiffness.

2. MATERIAL AND METHODS

2.1. Materials

The asphalt binder used in this study was characterized by a penetration grade of 50/70 and a Performance Grade (PG) of 64°C (maximum temperature), obtained from a company in Campina Grande, Paraíba. This specific binder is commonly used to produce asphalt mixtures in Brazil. The aggregates used with the binder were granite aggregates with 19 and 9.5mm dimensions. Fine aggregate consisted of sand and stone dust, while hydrated lime was the filler material. The coarse and fine aggregates were supplied by a quarry located in Campina Grande, and the hydrated lime was sourced from the local market. Figure 1 showcases the block form of the wax supplied by the company Apiário Nutrimel in Brazil. The wax was solid, with granules passing through a 2.36 mm sieve, the smallest mesh suitable for handling the wax.

Figure 1. Beeswax before and after sieving.
Figura 1. Cera de abelha antes e depois da peneiração.

2.2. Methods

2.2.1. Modification of the asphalt binder

The incorporation contents of beeswax were determined at 1 and 5% based on previous studies involving other types of waxes (GONÇALVES DA SILVA et al., 2021; DE MORAES et al., 2022). The mixing process involved incorporating the beeswax into the binder using a mechanical stirrer (FISATOM, Model 722) under controlled temperature and rotation conditions. The methodology employed in the research by Melo Neto et al. (2022) was followed, utilizing a temperature of 130°C for 40 minutes at a speed of 1000 rpm. The beeswax was gradually and incrementally added during the initial 20 minutes of mixing. To evaluate the effects of aging, both the pure binder and the modified binder underwent the Rolling Thin Film Oven (RTFO) process, enabling a comparison of the physical parameters before and after the aging process.

2.2.2. Asphalt mixture dosage

The initial step involved establishing the granulometric composition, which adhered to the C range specifications of DNIT (National Department of Infrastructure and Transportation), considering the concepts of Control Points and Restriction Zones. Three granulometric compositions, known as Fuller curves, were defined for testing purposes: one lower, one intermediate, and one upper curve. Table 1 provides the aggregate proportions for each tested curve. Using the established granulometric curves, 18 specimens were molded with a binder content of 5%. Among these specimens, six were allocated to each granulometric curve, with two specimens for $N_{initial}$, two for $N_{project}$, and two for $N_{maximum}$. The specimens' compaction was conducted per the American Society for Testing and Materials (ASTM D6925, 2015) standard, specifying different compaction gyrations based on the considered traffic volume. For this research, Medium to High traffic conditions were considered, resulting in $N_{initial}$ = 8 turns, $N_{project}$ = 100 turns, and $N_{maximum}$ = 160 turns. $N_{initial}$ and $N_{maximum}$ serve as parameters for evaluating the compatibility of the mixture. At the same time, $N_{project}$ is utilized to achieve a void volume of 4%, which is crucial for determining the binder content of the mix. The maximum measured density (Gmm) was also analyzed using the Rice Test, following the ASTM D2041 (2010) standard. Void volumes, voids in the mineral aggregate, and maximum specific mass (Gmm) were calculated. Based on these parameters, the lower granulometric curve was chosen for further analysis, as its void volume was equivalent to 4%. Therefore, the design binder content was established at 5%.

Table 1. Asphalt mixture proportioning data.
Tabela 1. Dados de dosagem de mistura asfáltica.

Sieve opening (mm)	Specification DNIT – Ranger C		Curves		
	% Min.	% Max.	Upper (%)	Intermediate (%)	Lower (%)
25.40	100.00	100.00	100.00	100.00	100.00
19.10	100.00	100.00	99.51	99.10	98.98
12.70	80.00	100.00	91.12	83.71	81.49
9.50	70.00	90.00	87.18	77.61	74.27
4.80	44.00	72.00	67.80	57.36	45.43
2.00	22.00	50.00	49.30	40.76	26.14
0.420	8.00	26.00	23.99	20.11	14.03
0.180	4.00	16.00	12.30	10.45	8.81
0.074	2.00	10.00	5.79	5.53	4.98

Aggregate percentage of design mixtures

Curves	Gravel 19mm	Gravel 9.5mm	Sand	Stone dust	Filler
Upper (%)	12.00	30.00	15.00	42.00	1.00
Intermediate (%)	22.00	31.00	15.00	30.00	2.00
Lower (%)	25.00	45.00	3.00	25.00	2.00

Volumetric parameters of mixture

Curves	% Asphalt binder	Maximum specific mass (Gmm)			Void volume in aggregates	Void volume
		$N_{initial}$	$N_{project}$	$N_{maximum}$		
Upper (%)	5.0	87.69	94.51	95.32	12.15	5.49
Intermediate (%)	5.0	90.80	96.48	97.13	11.52	3.52
Lower (%)	5.0	93.07	95.95	97.18	12.85	4.05
Limits		< 89	96	< 98	13 (min)	4.00

2.2.3. Experimental Tests

The pure and modified asphalt binder samples underwent physical characterization tests, including Penetration (ASTM D5/D5M, 2020), Softening Point (ASTM D36, 2020), Rotational Viscosity (ASTM D 4402, 2023), and the Rolling Thin Film Oven (RTFO) (ASTM D2872, 2019). Additionally, the asphalt mixtures produced using the modified binders were subjected to two mechanical tests: Indirect Tensile strength (DNIT 136, 2018) and resilient modulus (DNIT 135, 2018). The data obtained from these physical and mechanical characterization tests will be discussed in topic 3. However, during the rotational viscosity test, it was observed that adding 1% beeswax did not significantly reduce working temperatures (mixing and compaction). Only with a 5% beeswax content were temperatures characteristic of warm asphalt mixtures achieved. Therefore, to also assess the influence of working temperatures on the mechanical performance of the mixtures, the tensile strength and resilient modulus of the control mixtures (0% beeswax) and mixtures containing 1% beeswax were analyzed. These mixtures were compacted and mixed at 10°C lower than the initial temperatures. All assays were performed in triplicate.

The nomenclature of the samples was defined according to the amount of wax added to the binder: 0, 1, and 5%. Since the mixtures were produced at the obtained working temperatures (hot mix asphalt – HMA) and at temperatures 10°C lower (warm mix asphalt – WMA), it is appropriate to categorize them accordingly. The produced mixtures were designated as 0% HMA (0% beeswax in hot mix asphalt), 0% WMA (0% beeswax in warm mix asphalt), 1% HMA (1% beeswax in hot mix asphalt), 1% WMA (1% beeswax in warm mix asphalt), and 5% WMA (5% beeswax in warm mix asphalt).

2.2.4. Statistical analysis

In this research, the Student's t-test was employed to verify if there is a statistically significant difference between the means of the asphalt binder groups in the penetration, softening point, and rotational viscosity tests (before RTFO) and of the asphalt mixtures in the indirect tensile strength and resilient modulus tests. This test is used when concluding a small collected sample is necessary to make inferences about the entire population. A significance level of 5% (0.05) was chosen for the hypothesis test. If the calculated p-value is lower than 0.05, it indicates a significant difference between the means of the two evaluated groups. On the other hand, if the p-value is greater than or equal to 0.05, the means between the groups are considered equivalent.

3. RESULTS

3.1. Characterization of asphalt mixture constituents

Table 2 presents the results of characterizing these constituent materials used in the asphalt mixtures. The results obtained from the characterization tests fall within the limits set by international standards. These findings align with previous studies that have employed the same type of binder and aggregates in both hot and warm asphalt mixtures (CARVALHO et al., 2021; CRUZ et al., 2022; PORTO et al., 2023).

Table 2. Characterization of the constituents of asphalt mixtures.
Tabela 2. Caracterização dos constituintes das misturas asfálticas.

Asphalt binder				
Tests		Results	Limits	Standards
Penetration 0.1 mm (100g, 5s at 25ºC)		57.3	50 at 70	(ASTM D5/D5M, 2020)
Softening Point (ºC)		48.5	NA	(ASTM D36, 2020)
Rotational Viscosity(cP)	135 °C	371.3	≥274	(ASTM D 4402, 2023)
	150°C	185.0	≥112	
	177 °C	69.25	57 at 285	

Aggregates						
Tests	Standards	Limits	Results			
			Gravel 19 mm	Gravel 9.5 mm	Stone dust	Sand
Actual specific mass (g/cm³)	(ASTM C127, 2024)	NA	2.775	2.722	2.576	2.540
Apparent specific mass (g/cm³)		NA	2.799	2.757	2.555	2.426
Absorption (%)		≤2	0.47	0.47	0.32	0.48
Shape Index	(ASTM D 4791, 2019)	≥0.5	0.87	0.71	NA	NA
Sand Equivalent (%)	(ASTM D2419, 2014)	≥55	NA	NA	72.32	55.20

Particle size distribution of grains (ASTM D 6913, 2009)				
Sieve opening (mm)	Percentage (%) of material passing through the sieve (accumulated)			
	Gravel 19 mm	Gravel 9.5 mm	Stone dust	BAM
25.40	100.00	100.00	100.00	100.00
19.10	95.90	100.00	100.00	100.00
12.70	26.03	95.82	100.00	100.00
9.50	4.78	33.35	99.13	100.00
4.80	2.25	1.44	97.30	99.85
2.00	2.04	0.82	90.23	81.18
0.420	1.93	0.77	34.58	41.52
0.180	1.93	0.52	4.57	24.48
0.074	1.92	0.52	0.85	10.69

Note: NA: Not Applicable.

3.2. Physical analysis

Table 3 presents the results of the tests conducted on the asphalt binder samples. As expected, wax increased penetration, as warm mixtures typically exhibit reduced binder viscosity. According to the DNIT 095 (2006) standard, the minimum retained penetration should be 55%. It is evident from Table 3 that all binder samples met this specification, indicating satisfactory results. The minimum softening point requirement for the asphalt binder, classified with penetration 50/70, is 46°C according to the DNIT 095 (2006) standard. It is observed that all samples fulfilled this specification as well. Furthermore, the same standard states that the variation in softening point after aging should not exceed 8°C. It can be observed that all samples satisfied this specification, with the smallest variation obtained in the sample containing 5% beeswax, suggesting the additive's resistance to the aging process.

3.3. Mechanical evaluation of mixtures

Table 4 presents the results obtained from the mechanical tests and the parameters of the statistical tests performed to compare the different asphalt mixtures evaluated in this study. It can be seen from Table 4 that the warm asphalt mixtures with 1 and 5% beeswax showed a reduction in stiffness compared to the reference asphalt mixture (0% HMA) by 10.85 and 16.87%, respectively. This reduction in stiffness was also confirmed in the resilient modulus test with reductions of 32.05 and 10.04% compared to the 0% HMA asphalt mixture. These data corroborate the results obtained for the asphalt binders, which demonstrate a reduction in viscosity and increased penetration by adding beeswax at both contents (1 and 5%), indicating a decrease in the binder's consistency.

4. DISCUSSIONS

4.1. Physical analysis

The results of Table 3 differ from those obtained with carnauba wax, where previous studies (DE MORAES et al., 2022; GONÇALVES DA SILVA et al., 2021) demonstrated an increase in binder consistency after adding wax. In other words, beeswax exhibited a greater potential for softening than carnauba wax, which was previously recommended as an additive for asphalt mixtures. Additionally, the DNIT 095 (2006) standard sets a limit of up to 0.5% mass loss, and it was observed that all samples were within the acceptable range for aging tolerance, indicating that they do not compromise the quality of the pavement. Thus, using beeswax as an additive has proven viable and does not negatively impact the pavement quality.

The addition of beeswax to the binder resulted in a decrease in viscosity, both before and after the Rolling Thin Film Oven (RTFO) test. This observation aligns with findings from previous studies (DE MORAES et al., 2022; GONÇALVES DA SILVA et al., 2021) that investigated the addition of carnauba wax to the asphalt binder using similar amounts as in this research. One of the objectives of determining viscosity is identifying the mixing and compaction temperatures of the asphalt binder. The traditional method specified by ASTM D2493 (2017) was employed for this purpose. This method defines the mixing temperature as the temperature at which the binder has a rotational viscosity of 0.17 ± 0.02 Pa.s. In comparison, the compaction temperature is defined as the temperature at which the binder has a viscosity of 0.28 ± 0.03 Pa.s. Based on these criteria, the temperatures were determined through interpolation and are presented in Table 3. It was observed that adding 1 and 5% beeswax decreased the mixing and compaction temperatures compared to the pure binder. All the values obtained for the mixing and compaction temperatures were below 180°C, satisfying the requirements of the DNER-ES 385 (1999) standard. However, despite the reduction in temperatures, the mixture with 1% beeswax did not meet the criteria for a warm mix asphalt (WMA). Therefore, it was decided to work with mixing and compaction temperatures 10°C lower than those obtained in this study for the mixtures with 0% and 1% beeswax. This adjustment aimed to classify the mixture as a WMA and allowed for the analysis of the mechanical properties of the mixture.

Table 3. Asphalt binders properties.
Tabela 3. Propriedades dos ligantes asfálticos.

Tests		Beeswax content		
		0%	1%	5%
Penetration 0.1 mm (100g, 5s to 25ºC)		57.30	87.10	103.00
Penetration Retained (%)		76.21	57.63	74.70
Softening Point (ºC)		48.50	46.25	49.30
Softening Point Variation (ºC) - RTFO		4.00	5.00	1.70
Rotational Viscosity (cP)	135 °C	380	320	250
	150°C	190	170	140
	177 °C	90	80	60
Rotational Viscosity (cP) - RTFO	135 °C	505	470	340
	150°C	350	240	180
	177 °C	100	90	80
Mixing temperature (°C)		154	152	145
Subtracting 10°C from the mixing temperature (°C)		144	142	NA
Compaction temperature (°C)		142	141	130
Subtracting 10°C from the compacting temperature (°C)		132	131	NA
Mass Variation (%)		0.0947	0.0346	0.0517

Statistical analysis - Penetration 0.1 mm (100g, 5s at 25ºC)

Binders evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0% x 1%	3	4	$1.25x10^{-6}$	0.610
0% x 5%	3	4	$3.06x10^{-6}$	2.245
1% x 5%	3	4	$2.3x10^{-4}$	2.365

Statistical analysis - Softening Point (ºC)

Binders evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0% x 1%	3	4	0.0584	1.101
0% x 5%	3	4	0.3410	0.823
1% x 5%	3	4	0.0177	0.925

Statistical analysis - Rotational Viscosity (cP) – 135°C

Binders evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0% x 1%	3	4	0.0033	137.5
0% x 5%	3	4	$8.7x10^{-5}$	98.0
1% x 5%	3	4	0.0003	60.5

Statistical analysis - Rotational Viscosity (cP) – 150°C

Binders evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0% x 1%	3	4	0.0136	34.0
0% x 5%	3	4	0.0002	25.0
1% x 5%	3	4	0.0043	40.0

Statistical analysis - Rotational Viscosity (cP) – 170°C

Binders evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0% x 1%	3	4	0.1143	37.0
0% x 5%	3	4	0.0022	28.0
1% x 5%	3	4	0.0179	40.0

Note: NA: Not Applicable.

Table 4. Mechanical properties of mixtures.
Tabela 4. Propriedades mecânicas das misturas.

	0% HMA	0% WMA	1% HMA	1% WMA	5% WMA
Indirect Tensile strength (MPa)	0.83	0.83	0.93	0.74	0.69
Resilient Modulus (MPa)	6685	5145	4627	4542.5	6014.5

Statistical analysis - Indirect Tensile Strenght

Mixtures evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0%HMA x 0%WMA	3	4	1.00000	0.0003625
0%HMA x 1%HMA	3	4	0.00360	0.0004
0%HMA x 1%WMA	3	4	0.00930	0.00055
0%HMA x 5%WMA	3	4	0.00101	0.0004
0%WMA x 1%HMA	3	4	0.00300	0.0003625
0%WMA x 1%WMA	3	4	0.00822	0.0005125
0%WMA x 5%WMA	3	4	0.00084	0.0003625
1%HMA x 1%WMA	3	4	0.00057	0.00055
1%HMA x 5%WMA	3	4	0.00012	0.0004
1%WMA x 5%WMA	3	4	0.05934	0.00055

Statistical analysis - Resilient Modulus

Mixtures evaluated pair by pair	Obs.	Degree of freedom	p-value	Pooled variance
0%HMA x 0%WMA	3	4	$4.740x10^{-9}$	100.000
0%HMA x 1%HMA	3	4	$1.16x10^{-10}$	28.000
0%HMA x 1%WMA	3	4	$2.34x10^{-11}$	13.625
0%HMA x 5%WMA	3	4	$7.673x10^{-9}$	24.125
0%WMA x 1%HMA	3	4	$3.922x10^{-7}$	103.000
0%WMA x 1%WMA	3	2	0.0001627	NA
0%WMA x 5%WMA	3	4	$4.581x10^{-8}$	99.125
1%HMA x 1%WMA	3	4	$1.430x10^{-5}$	16.625
1%HMA x 5%WMA	3	4	$5.29x10^{-10}$	27.125
1%WMA x 5%WMA	3	4	$9.2x10^{-11}$	12.750

Note: HMA: Hot Mix Asphalt, NA: Not Applicable, Obs.: Observations, WMA: Warm Mix Asphalt.

Regarding the statistical tests, it was found that the addition of beeswax caused a significant increase in penetration compared to the pure binder for both tested contents (1 and 5%). As for the softening point, an important difference was only observed between the binder samples with 1% and 5%, where the p-value was below the significance level of 5% (0.05). The reduction in rotational viscosity was more evident at the lower test temperatures (135 and 150°C), where all binder samples showed statistically significant differences with p-values below 0.05. At the temperature of 170°C, the only samples that did not show a significant difference were 0% and 1%, with a p-value above the significance level (>5%). In other words, the 5% beeswax content had more potential to reduce the asphalt binder's viscosity and, consequently, the mixing and compaction temperatures.

4.2. Mechanical evaluation of mixtures

According to Motta (2011), changes in the mixing temperature can result in significant variations in the void volume of the mixtures, thereby influencing the indirect tensile strength values. The results presented in Table 4 show that the mixture containing 1% beeswax reduced indirect tensile strength due to the 10°C temperature reduction during production and compaction. On the other hand, the control mix (0% beeswax) maintained similar indirect tensile strength values even after being produced and compacted at temperatures 10°C lower. The mixture with 5% beeswax showed the lowest indirect tensile strength value among the analyzed mixtures. However, it is important to note that despite the decrease, all the obtained indirect tensile strength values remain within the minimum limit (0.65 MPa) established by the DNIT 031 (2006) standard for asphalt mixtures used in roadways. Therefore, it can be inferred that the addition of beeswax resulted in a reduction in the indirect tensile strength of the mixtures, which is consistent with the findings of De Moraes et al. (2022), who observed a similar decrease in indirect tensile strength when adding carnauba wax at contents of 1%, 2%, and 3%.

According to Bernucci et al. (2022), typical values of the resilient modulus range from 2,000 MPa to 8,000 MPa at a temperature of 25°C. It can be observed that all the results obtained in this study fall within this range. The reduction in working temperatures influenced the stiffness of the asphalt mixtures. Lower working temperatures result in less rigidity of the mixtures, indicating that the aging process during the production stage of the mixtures was less aggressive towards the binder and aggregates. Costa et al. (2024) state that the analysis of the resilient modulus should not be considered in isolation or interpreted directly, as acceptable values can vary depending on the pavement structure. Similar behavior was observed by De Moraes et al. (2022) when adding 1% and 3% carnauba wax to the asphalt binder. The use of 1% wax reduced the resilient modulus compared to the control mixture (0% wax), while the use of 3% wax did not significantly affect the resilient modulus of the mixture. This research observed a similar tendency when using 1 and 5% beeswax. Overall, the results indicate that adding beeswax at different contents influenced the resilient modulus of the asphalt mixtures, but the values obtained were still within an acceptable range.

Through statistical analysis, it has been determined that beeswax significantly influences the performance of asphalt mixtures, particularly when considering lower mixing and compaction temperatures. In the indirect tensile strength test, it was observed that only certain mixtures did not exhibit significant differences between them, namely 0%HMA with 0%WMA and 1%WMA with 5%WMA, as their p-values were greater than 0.05. However, statistically significant differences were observed between all evaluated mixtures and under all production conditions in the resilient modulus test. The obtained p-values were below the significance level of 5% (0.05), thus rejecting the null hypothesis that there is no statistically significant difference between the means of the evaluated groups. These findings align with the observed physical effects on the asphalt binder, such as reduced consistency and stiffness after adding beeswax.

5. CONCLUSIONS

The preliminary study on the use of beeswax as an asphalt binder modifier has yielded several important conclusions:

The addition of beeswax at contents of 1 and 5% maintained the asphalt binder's physical properties within regulatory specifications, indicating improved stability and reduced mass loss during aging.

The incorporation of beeswax reduced mixing and compaction temperatures by 2 and 1°C for the 1% beeswax content and 9 and 12 °C for the 5% beeswax content, respectively.

Asphalt mixtures produced at 10°C lower than the obtained mixing and compaction temperatures showed slightly inferior performance. However, the differences remained within the expected performance range.

The statistical analysis proved to be an effective tool in evaluating the significance of the data, demonstrating significant changes in the properties of the mixtures with the addition of beeswax.

Beeswax, particularly at a content of 5%, exhibited great potential as an additive for reducing the viscosity of the asphalt binder. This would thereby lower the working temperatures required and contribute to reducing greenhouse gas emissions during the production process of the mixtures.

These findings indicate that beeswax can be a promising alternative as an asphalt binder modifier, offering potential environmental and performance benefits. Further research and experimentation are recommended to explore its full potential and optimize its use in asphalt mixtures.

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