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Influence of Organic Wax on SBS-Modified Asphalt Mixtures: Stability, Flow, and Mechanical Properties

Víctor Peña Dueñas[1], Janet Yéssica Andía Arias[2], Rosali Ramos Rojas[1], Nelfa Estrella Ayuque Almidon[3], Fernando Anacleto Boza Ccora[3], Aron Jhonatan Aliaga Contreras[3], Carlos Javier Huamán Albino[1,*], Juan Gabriel Benito Zuñiga[4], Luis Gerardo Becerra Infantas[5]

[1]Faculty of Engineering, Academic School of Civil Engineering, Universidad Continental, Peru
[2]Department of Civil Engineering, Universidad Rey Juan Carlos, Spain
[3]Faculty of Engineering, Universidad Nacional del Centro del Perú, Peru
[4]Faculty of Engineering, Universitat Politècnica de València, Spain
[5]School of Civil Engineering, The University of Sydney, Australia

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Abstract Extreme temperature fluctuations in the central highlands of Peru cause significant deterioration of conventional asphalt pavements, particularly in high-altitude regions like the Mantaro Valley, impacting transportation safety and economy. This study evaluates the influence of beeswax (Organic Wax, OW) on the performance of Hot Mix Asphalt 85/100 for cold climates. The methodology involved testing conventional and SBS-modified asphalt mixtures with OW concentrations of 0.5%, 1%, 2%, and 4% at production temperatures of 100 ℃, 120 ℃, and 130 ℃. Performance was assessed using the Marshall, Lottman (indirect tensile strength), and Cantabro (abrasion) tests. The results showed that the optimal performance was achieved with the SBS-modified mixture containing 2% OW and produced at 120 ℃, which yielded a stability of 18.51 kN, a flow of 3.10 mm, air voids of 5.31%, and an adhesion loss of 8.55%. Furthermore, an OW dosage of at least 1% was found to be necessary to ensure adequate resistance to moisture damage, achieving a Tensile Strength Ratio (TSR) of approximately 80%. These findings confirm that modifying asphalt with beeswax enhances the durability and performance of pavements, making them more resilient to the extreme climatic conditions of the Mantaro Valley.

Keywords Asphalt Mixes, Sustainable Pavement, Asphalt Binder Formulations, Hot Mix Asphalt, Wax, Waste Honeycombs

1. Introduction

In Peru, temperatures exhibit a marked variation, reaching 31 ℃ during the summer in West Lima and other districts, according to SENAMHI data [1], while in the southern highlands they drop to -14 ℃ during the winter [2]. These thermal fluctuations significantly impact road infrastructure, where freeze-thaw cycles deteriorate conventional asphalt pavements. The damage is particularly accentuated in cold regions with greater thermal amplitude [3]. In Indonesia [4], population growth has led to an increase in vehicular traffic. In response to this issue, the effect of low-density polyethylene (LDPE) plastic waste on PEN 60/70 asphalt was investigated, evaluating its performance regarding cracking, durability, and resistance using the Marshall method. Experiments were conducted with LDPE additions of 2%, 4%, 6%, 8%, and 10%, maintaining a 5% asphalt content. The results demonstrated that a 4% LDPE addition is optimal, meeting the established standards with a 5% void in the mixture, a 15.2% void in the mineral aggregate, a 67.1% void filled with asphalt, a stability of 1036.6 kg, a flow of 3 mm, and a Marshall Quotient of 345.5 kg/mm. This addition significantly reduced the asphalt's susceptibility to cracking. Other research on recycled plastics has shown similar positive results. One study [5] demonstrated that a 9% addition of polyethylene terephthalate (PET) from water bottles improved Marshall stability to 13.8 kN, while another [6] reported maximum stability with 15% high-density polyethylene (HDPE), both maintaining flow values within permissible limits. Beyond plastics, industrial by-products have also been explored. Kim et al. [7] explored the use of thermal power plant bottom ash as a replacement for lime filler in polymer-modified asphalt concrete mixtures. Different replacement levels (0%, 25%, 50%, and 75%) were evaluated, identifying that 25% was optimal in terms of indirect tensile strength (ITS). This mixture, with a 25% ash replacement, demonstrated improvements in density, adhesion, and durability, attributed to the particle size and chemical composition of the ash. Likewise, the study by Cetin et al. [8] demonstrated improvements in the resistance of the mixtures to water effects, including freeze-thaw cycles, using filler additives such as fly ash. Furthermore, the use of specific polymers like styrene-butadiene-styrene (SBS) has been analyzed, proving effective at 5% to enhance mechanical and deformation properties [9], and at 2% to increase tensile strength (TSR) and cracking resistance compared to pure asphalt binder [10].

This study compares the physical and mechanical behavior of conventional asphalt mixtures and SBS-modified asphalt mixtures, both with the addition of beeswax. This research aims to address the recurring problems on the roads of the Junín region, where pavements exhibit severe functional and structural failures (cracks, fissures, peeling, alligator cracking, and rutting) in less than five years. These deteriorations increase transportation costs and affect the safety, comfort, and economy of the pavement.

The main objective is to analyze the influence of beeswax on the stability and flow of hot mix asphalt (HMA) 85/100 in the frigid climates of the Mantaro Valley. The methodology employed is experimental. Initially, the aggregate was characterized, and subsequently, briquettes were prepared using PEN 85/100 asphalt and PEN 85/100 asphalt modified with SBS. These briquettes were subjected to Marshall tests (ASTM D6927 [11]), ITS (ASTM D6931 [11]), and the Cantabro test (UNE-EN 12697-17 [12]). Using the Marshall volumetric method (ASTM D6926 [13]), the optimal asphalt content and the best properties for the asphalt mixture were determined. With this information, both the conventional PEN 85/100 asphalt and the SBS-modified asphalt were modified, totaling 361 briquettes each, by adding percentages of beeswax. The production temperatures (100 ℃, 120 ℃, and 130 ℃) and the percentages of wax (0.5%, 1%, 2%, and 4%) were varied, and then the Marshall, Lottman, and Cantabro tests were performed.

2. Materials and Methods

In this study, an experimental design was employed, using local materials from the Junín region. The process began with the characterization of the aggregate, followed by the fabrication of asphalt briquettes that included organic wax (OW). These briquettes were subjected to a volumetric analysis using the Marshall method to determine the optimal asphalt content and properties of the modified asphalt mixture. The evaluation was carried out following ASTM standards and included Marshall tests, the Cantabro test, and the Lottman test (ASTM D6927 [14], AASHTO M320 [15], ASTM D1559 [16], ASTM D5581 [17], UNE-EN 12697-17 [12]). The detailed methodology is illustrated in the flowchart in Figure 1.

2.1. Aggregate

2.1.1. Coarse Aggregate

For the sampling of coarse and fine aggregates, the materials were extracted from a quarry located in the Puente la Breña sector (Pilcomayo), Pilcomayo district, with UTM coordinates of 473405.00 m E and 8668114.00 m S. The particle size distribution curve of the coarse aggregate was determined according to standard NTP 339.128 [18], and the results are presented in Figure 2.

Similarly, the particle size distribution curve of the fine aggregate was determined according to standard NTP 339.128 [18]. The results are presented in Figure 3.

For the coarse aggregate, the magnesium sulfate soundness test revealed a mass loss of 3.86%, indicating high resistance and its suitability for environments with sulfates [19]. On the other hand, the Los Angeles Abrasion test showed a mass loss of 18.47% due to abrasion and impact. These results suggest that the material has good wear resistance, an important characteristic for applications in road surfaces [20], as shown in Figure 4.

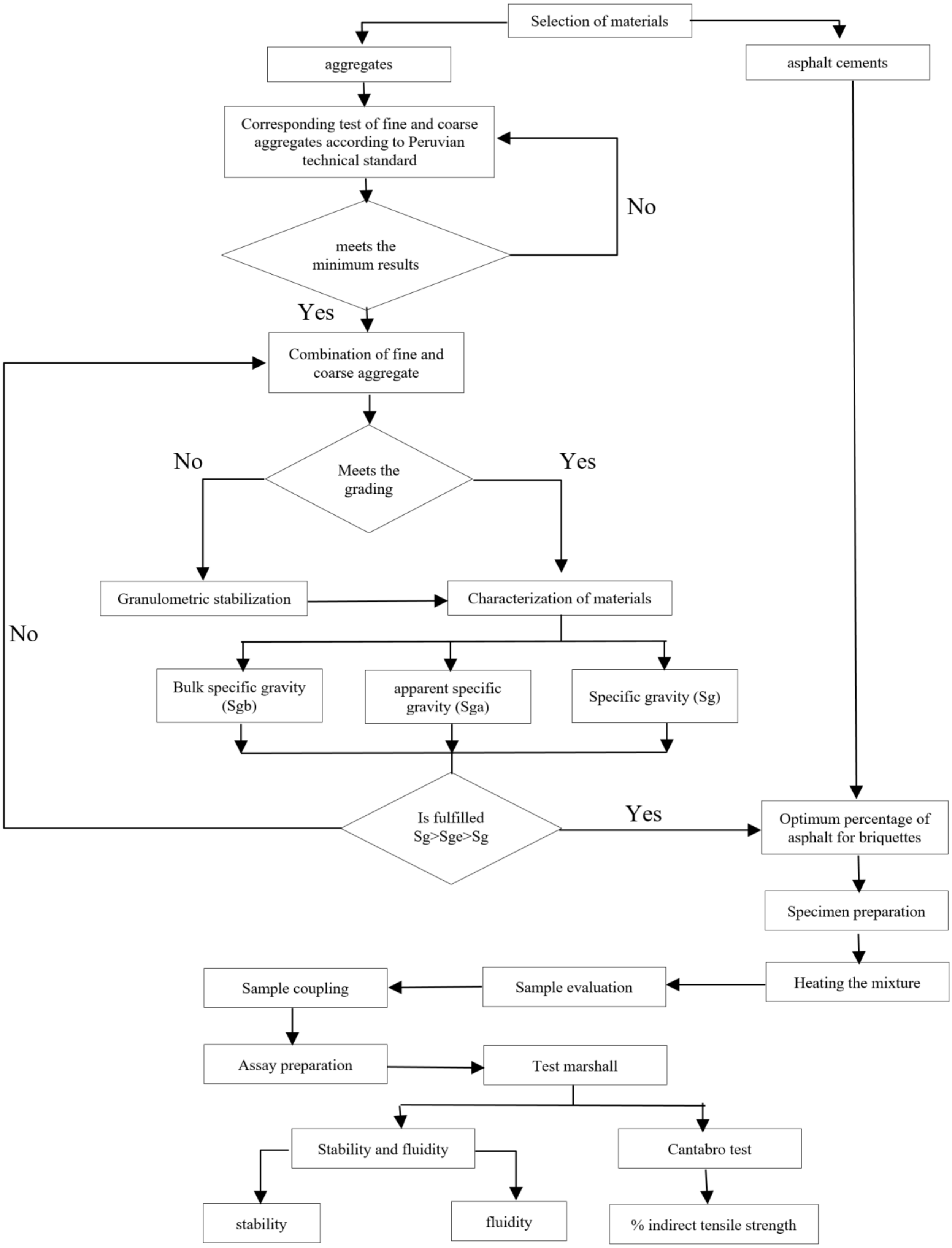

Figure 1. Marshall Mix Design Methodology Flowchart

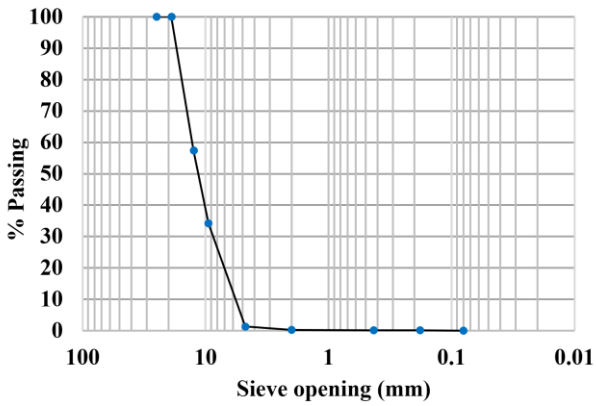

Figure 2. Particle size distribution curve of coarse aggregate

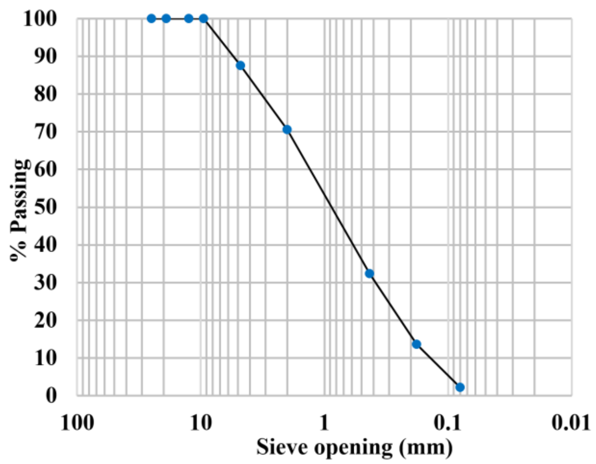

Figure 3. Particle size distribution curve of fine aggregate

Figure 4. Los Angeles abrasion test

The flat particle test yielded a percentage of 28.11%, indicating a significant proportion of particles with this shape, which could negatively affect the workability of concrete and the stability of asphalt mixtures. These results suggest the need for improvements through additional crushing processes [21]. Regarding elongated particles, a percentage of 19.95% was obtained, which indicates a moderate quality according to the same test [21], as shown in Figure 5.

Figure 5. Flat and elongated particle test

The fractured faces test yielded a result of 85%, which indicates good aggregate quality and ensures adequate adhesion and cohesion in mixtures [22], as shown in Figure 6.

Figure 6. Percent Fractured Face Test

The total soluble salts test yielded a result of 360 ppm, which indicates the presence of soluble salts without causing significant damage [23]. The absorption, evaluated at 1.11%, reflects a good quality aggregate with moderate porosity and a reasonable water absorption capacity [24].

2.1.2. Fine Aggregate

The results of the fine aggregate tests showed that the sand equivalent test yielded 71%, which suggests good quality with a moderate presence of fine and clayey particles [25]. The plasticity index test indicated that the sample does not exhibit plasticity [26]. The total soluble salts test revealed 360 ppm, which represents a low level of reaction and suggests that the fine aggregates have a low concentration of components susceptible to reaction with magnesium sulfate [23]. The loose unit weight showed a density of 1619 kg/m^3, and the compacted unit weight presented a density of 1735 kg/m^3[27]. The Riedel-Weber test indicated a value of 10, which represents that the molar solution of sodium carbonate does not cause displacement of the bituminous binder, indicating strong and durable adhesion to the fine aggregates [28]. Finally, the absorption presented a value of 1.65%, which suggests a moderate percentage of absorption, indicating a moderate porosity and water absorption capacity in the fine aggregate [29].

2.2. Organic Wax

OW is mainly composed of carbohydrates and water. Among its minor constituents are minerals, nitrogenous matter, and organic acids [30]. The physicochemical properties of OW are detailed in Table 1.

Table 1. OW physical and chemical properties.

Properties	Approximate Values
Moisture Content (%)	15.68 ±0.03
pH	4.58 ±0.01
Specific Gravity (g/ml)	1.46 ±0.01
Viscosity (cP)	13.6 ±0.25 and 16.5 ±0.25
Free Acidity (meq/ kg)	8.75 - 62.71
Total Solids (%)	72.2 ±0.22 and 76.5 ±0.52
Reducing Sugars (%)	53.0 - 70.7
Ash Content (%)	0.73 ±0.01
Electrical Conductivity (mS/cm)	0.82 ±0.01
Mineral Content (%)	0.01 - 1.68

The high moisture content of OW could negatively influence the adhesion of aggregates to the asphalt mixture, favoring the creation of unstable emulsions and reducing the durability of the mixture. OW has an acidic pH, which could affect its reactivity with the asphalt and other components of the mixture. Its specific gravity, between 1.36 and 1.46 g/ml, indicates that OW is relatively dense. Electrical conductivity can indicate the presence of mineral salts, which could influence the rheological properties of asphalt. Likewise, the viscosity of OW could impact the workability of the asphalt mixture, either facilitating or complicating its application. OW, as extracted from the honeycomb, was an aqueous dispersion. It was handled carefully to avoid altering its physicochemical characteristics [31], as shown in Figure 7.

Figure 7. Beeswax

The consistency of OW can vary between fluid, viscous, partially or fully crystallized (solid). This property is mainly influenced by the water content and, to a lesser extent, by the fructose/glucose ratio; a higher amount of fructose tends to decrease the viscosity of OW. A higher content of higher sugars also increases its consistency. Viscosity, which is a key texture attribute in liquids, depends significantly on temperature, decreasing as temperature increases. Additionally, viscosity varies depending on the water content; the higher the water content, the lower the viscosity [31].

2.3. Filler

Hydrated lime was used as a filler, a material employed as an asphalt thickener and an aggregate-asphalt adhesion improver. This filler must comply with the specifications of AASHTO M-303 [32] or ASTM D-242 [33] standards. The chemical composition of the hydrated lime is presented in Table 2.

Table 2. Calcium hydroxide composition

Element	Percentage
Calcium Hydroxide (Ca $(OH)_2$)	85% min.
Magnesium Oxide (MgO)	0.7% max.
Silica (SiO_2)	1% max.
Insoluble in HCl	1.5% max.
Moisture (H_2O)	1% max.

2.4. Asphalt

Asphalt is a mixture of solid or semi-solid hydrocarbons that can be found naturally or produced through petroleum refining. The main components of asphalt are detailed in Table 3. In this study, PEN 85/100 asphalt and SBS 85/100 modified asphalt were used.

Table 3. Asphalt composition

Element	Percentage
Carbon	82% - 88%
Hydrogen	8% - 11%
Sulfur	0% - 6%
Oxygen	0% - 1.5%
Nitrogen	0% - 1%

2.5. Hot Mix Asphalt (HMA)

Hot Mix Asphalt (HMA) is produced at elevated temperatures, typically between 100 ℃ and 140 ℃, as illustrated in Figure 8. This category of asphalt involves advanced technologies and products that enhance its properties, allowing for longer transport distances and improved workability and compaction. However, care must be taken during preparation, as the addition of certain modifiers can have adverse effects [34].

The Marshall design for HMA increases the durability and resistance of pavements. This method uses lower temperatures than traditional mixtures, which reduces emissions and energy consumption. The Marshall design includes material selection (ASTM D6927 [14]), combination and dosage adjusted to AASHTO M320 [15], and compaction (ASTM D1559 [16]), evaluating stability, flow, and density (ASTM D5581 [17]). Initially, two asphalt cement bases were established: PEN 85/100 and SBS 85/100, the latter modified with SBS at a proportion of 3%. From these bases, the asphalt mixtures were prepared in two main groups:

- PEN 85/100 asphalt mixture sample (NAM)
- SBS 85/100 modified asphalt mixture sample (AMS)

The HMA mixtures using NAM and AMS were modified with OW at proportions of 0.5%, 1%, 2%, and 4%. For a more detailed description of the samples, the nomenclatures presented in Table 4 were employed.

For the tests, 722 briquettes were prepared. In the stability and flow test, the Marshall Press was used, applying a constant load to the asphalt mixture specimens at a speed of 50.8 mm per minute. During the stability test, the total deformation of the specimen in millimeters was recorded at the point of failure. The Cantabro abrasion test was performed to assess the durability and cohesion of the mixtures. For this test, HMA specimens, as shown in Figure 9, were prepared according to the specified design. After compaction, the briquettes were cured for 24 hours at room temperature. Each specimen was then placed in the Cantabro abrasion drum and rotated for 300 revolutions at a constant speed of 30-33 rpm. After the test, the specimen was removed, any loose material was brushed off, and the mass loss was calculated as a percentage of the initial weight.

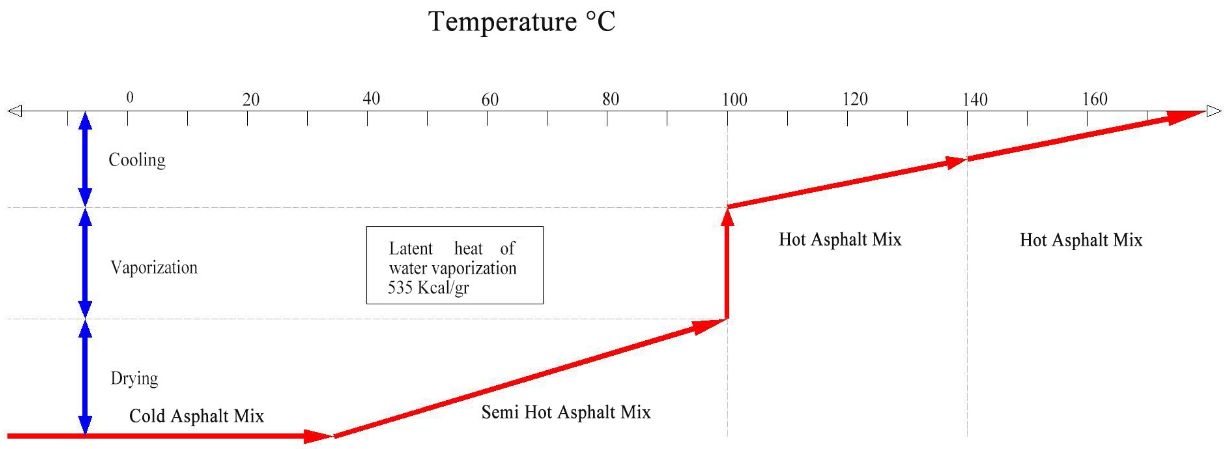

Figure 8. Classification of asphalt mixtures by temperature [35]

Table 4. Sample Nomenclature and Experimental Design

Temperature	PEN 85/100 Asphalt Mixture Sample (NAM)				SBS 85/100 Modified Asphalt Mixture Sample (AMS)			
100 ℃ 120 ℃ 130 ℃	NAM100 ℃	NAM100 ℃	NAM100 ℃	NAM100 ℃	AMS100 ℃	AMS100 ℃	AMS100 ℃	AMS100 ℃
	NAM120 ℃	NAM120 ℃	NAM120 ℃	NAM120 ℃	AMS120 ℃	AMS120 ℃	AMS120 ℃	AMS120 ℃
	NAM130 ℃	NAM130 ℃	NAM130 ℃	NAM130 ℃	AMS130 ℃	AMS130 ℃	AMS130 ℃	AMS130 ℃
	0.5	1	2	4	0.5	1	2	4
		Organic Wax (OW) Dosage Percentage						

Figure 9. Asphalt Mixture Specimens before the Cantabro Abrasion Test

3. Results and Discussions

3.1. Marshall Stability and Flow Results for NAM and AMS Specimens

As shown in Figure 10, the NAM130 ℃ samples with 4% OW and AMS120 ℃ samples with 4% OW achieved maximum stability values of 22.50 kN and 22.17 kN, respectively. These values represent significant increases of 150% and 146.33% compared to the minimum allowable stability of 9 kN. Conversely, the NAM100 ℃ samples with 1% OW and AMS100 ℃ samples with 4% OW presented minimum stability values of 10.66 kN and 10.61 kN, respectively, slightly exceeding the established minimum limit.

Regarding the void percentage, the NAM130 ℃ samples with 4% OW showed a void percentage of 2.53%, and the AMS120 ℃ samples with 4% OW showed a void percentage of 2.68%, neither of which meets the allowable range of 4% to 6%. In contrast, the NAM100 ℃ samples with 1% OW, with a 4.72% void percentage, are within the acceptable range. However, the AMS100 ℃ samples with 4% OW presented a void percentage of 2.44%, also outside the allowable range. These results highlight the variability in properties based on the temperatures and OW contents evaluated.

As shown in Figure 11, the NAM and AMS samples with different percentages of OW exhibited varied flow results. Specifically, the NAM100 ℃ samples with 4% OW, NAM130 ℃ samples with 4% OW, NAM130 ℃ samples with 2% OW, AMS100 ℃ samples with 0.5% OW, AMS120 ℃ samples with 0.5% OW, AMS120 ℃ samples with 1% OW, AMS100 ℃ samples with 2% OW, AMS120 ℃ samples with 2% OW, AMS120 ℃ samples with 4% OW, and AMS130 ℃ samples with 4% OW, showed flow values between 2 mm and 3.5 mm, which comply with the allowable range. However, other values exceeded this limit.

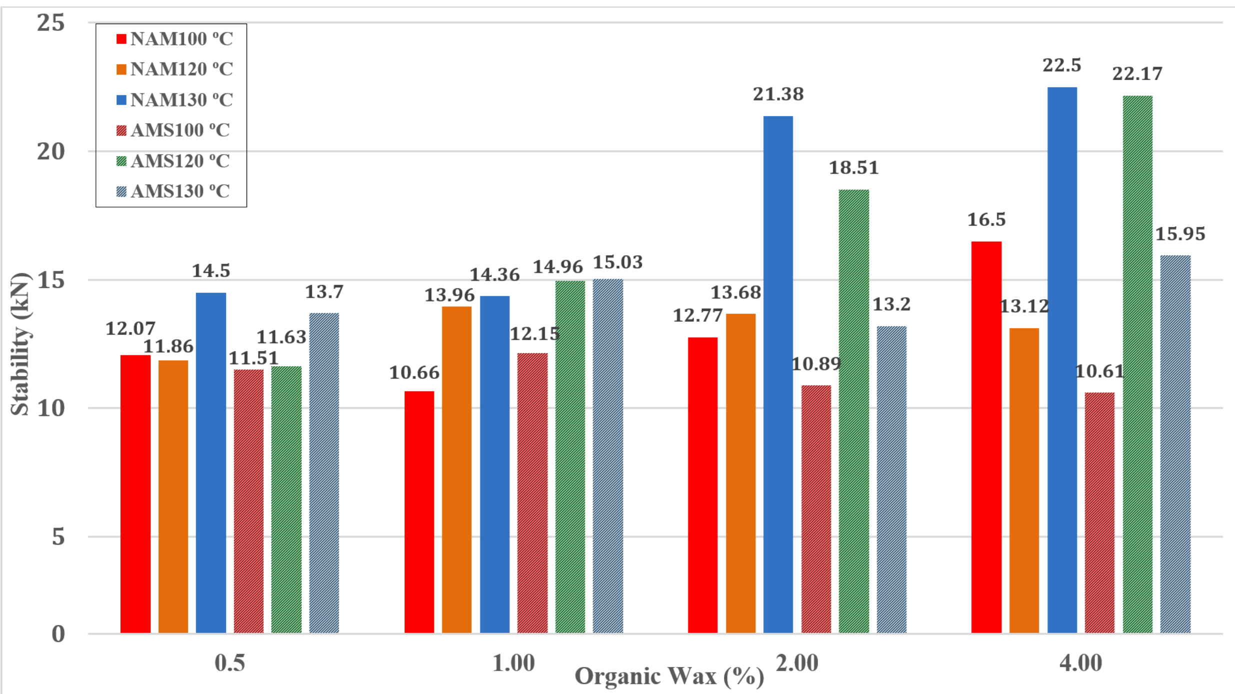

Figure 10. Stability values for the NAM and AMS specimens

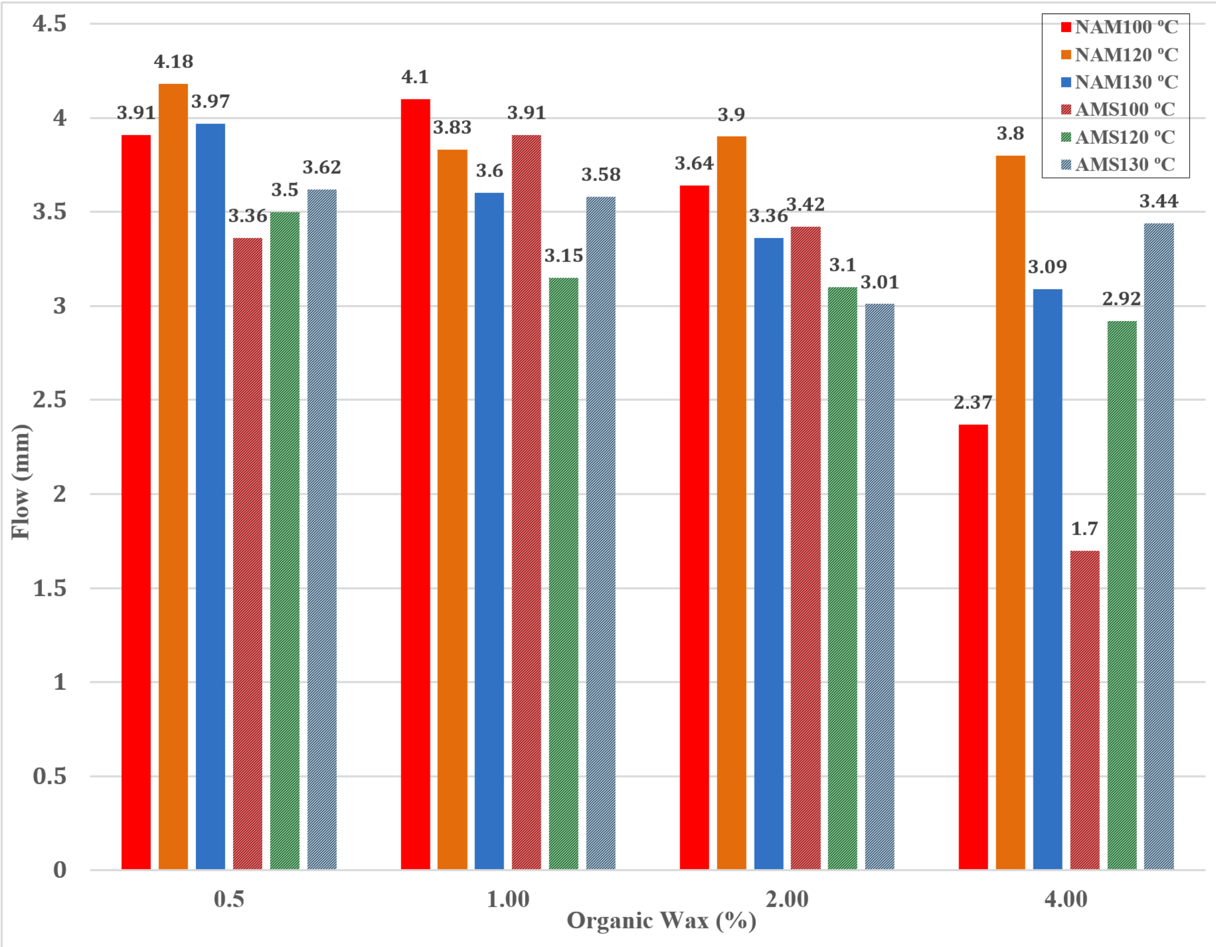

Figure 11. Flow values for the NAM and AMS specimens

Regarding the void percentage, as shown in Figure 12, the NAM130 ℃ samples with 4% OW, which showed 2.53%, and the NAM100 ℃ samples with 4% OW, which showed 2.56%, do not meet the acceptable range of 4% to 6%. The NAM130 ℃ samples with 2% OW, which showed 3.33%, approach the allowable range. Conversely, among the AMS samples, only AMS120 ℃ samples with 0.5% OW, which showed 5.84%, and AMS120 ℃ samples with 1% OW, which showed 4.63%, meet the range. The AMS120 ℃ samples with 4% OW, which showed 2.68%, and AMS130 ℃ samples with 4% OW, which showed 2.72%, do not reach the acceptable range. These results demonstrate significant differences in properties depending on the temperatures and OW percentages.

The NAM120 ℃ sample with 0.5% OW exhibits favorable values that meet the stability and void percentage criteria; however, the flow slightly exceeds the allowable range, with a value of 4.18 mm. Similarly, the AMS120 ℃ samples with 0.5% OW, AMS120 ℃ samples with 1% OW, and AMS120 ℃ samples with 2% OW favorably meet the stability, flow, and void percentage criteria. The overall results are presented in Table 5.

The NAM130 ℃ sample with 4% OW exhibited a 150% increase in stability compared to the required minimum, reaching a value of 22.5 kN with a flow of 3.09 mm. In contrast, a previous study [4] examined the addition of 4% LDPE plastic waste mixed with asphalt, reporting a Marshall stability of 10.17 kN—a 13% increase over the minimum requirement—with a flow of 3 mm. Similarly, another study [5] investigated PET in varying percentages (3%–12%), achieving a maximum stability of 11.82 kN with 9% HDPE, which was 31.33% higher than the minimum required shear strength, with a flow of 2.38 mm. This result suggests a rigid mixture capable of resisting deformations within the allowable range. Additionally, another study [6] evaluated the effect of HDPE and LDPE variations on asphalt mechanical properties, reporting that the addition of 15% HDPE resulted in a stability of 8.7 kN and a flow of 3.09 mm.

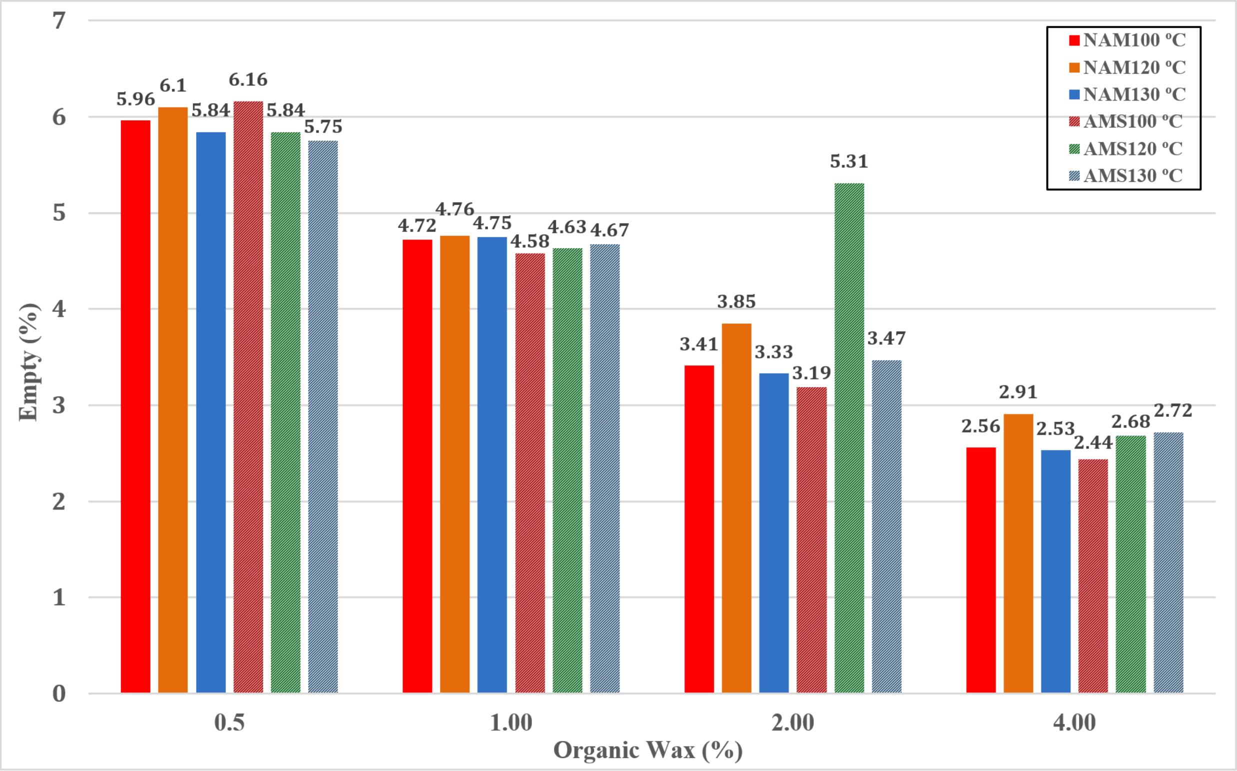

Figure 12. Void Percentage as a Function of Organic Wax in NAM and AMS Mixtures

Table 5. Obtained results

Specimen	Organic Wax (%)	Stability (kN) > 9	Flow (mm) Range: 2 – 3.5	Void Percentage (%) Range: 4 - 6
NAM100 ℃	0.5	X		
NAM100 ℃	1	X		X
NAM100 ℃	2	X		
NAM100 ℃	4	X	X	
NAM120 ℃	0.5	X		X
NAM120 ℃	1	X		
NAM120 ℃	2	X		
NAM120 ℃	4	X		
NAM130 ℃	0.5	X		
NAM130 ℃	1	X		
NAM130 ℃	2	X	X	
NAM130 ℃	4	X	X	
AMS100 ℃	0.5	X	X	
AMS100 ℃	1	X		X
AMS100 ℃	2	X	X	
AMS100 ℃	4	X		
AMS120 ℃	0.5	X	X	X
AMS120 ℃	1	X	X	X
AMS120 ℃	2	X	X	X
AMS120 ℃	4	X	X	
AMS130 ℃	0.5	X		X
AMS130 ℃	1	X		X
AMS130 ℃	2	X		
AMS130 ℃	4	X	X	

When comparing the studies, it is observed that the addition of various materials effectively improves the mechanical properties of asphalt while maintaining the workability of the mixtures. Furthermore, organic wax presents an advantage over other sustainable additives, such as PET, LDPE, and HDPE, by providing a superior increase in stability, reaching 22.5 kN, with a flow of 3.09 mm—well within the allowable range. This balance reflects both good rigidity and flexibility of the mixture. The AMS120℃ sample with 4% OW exhibited a 146.33% increase in stability compared to the minimum requirement, with a flow of 3.10 mm. Likewise, the stability results suggest that organic wax outperforms PET and LDPE in enhancing asphalt properties [5], [7,] [36]. In contrast, another study [37] demonstrated that an asphalt mixture incorporating fiberglass and Asbuton B-5/20 achieved Marshall stability values ranging from 248.9% to 395.6%, with a flow between 5 and 7 mm. While these results indicate superior strength, the flow values exceeded the allowable range, whereas the M2+4C+120T sample remained within acceptable limits.

Concerning the effects of AMS, the Marshall stability test results showed that the sample without AMS had a slight advantage in terms of maximum stability. Specifically, the NAM130℃ sample with 4% OW achieved the highest stability increase of 150%, while the modified AMS120℃ sample with 4% OW showed a maximum increase of 146.33%. In both cases, the highest stability was obtained with 4% OW. Additionally, all samples, whether modified with AMS or not, exhibited flow values within the allowable range.

3.2. Cantabro Test Results for NAM and AMS Specimens

As shown in Figure 13, the NAM and AMS samples exhibited varying percentages of asphalt adhesion loss. Among the NAM samples, NAM100℃ with 0.5% OW showed a 12.95% adhesion loss, which represents a 48.49% increase compared to the NAM130℃ sample with 1% OW, which had a 6.67% adhesion loss. Similarly, within the AMS samples, AMS120℃ with 1% OW reached an 11.50% adhesion loss, reflecting a 41.74% increase compared to the AMS130℃ sample with 4% OW, which recorded a 6.70% adhesion loss. These results demonstrate significant variations in asphalt adhesion depending on the temperature and OW content.

The NAM130℃ sample with 1% OW exhibited an adhesion loss of 6.67%. In a separate study [7], the incorporation of 25% crushed bottom ash as a filler in polymer-modified asphalt concrete mixtures improved performance and reduced weight loss. These findings indicate increased resistance to abrasion and lower adhesion loss between the binder and aggregate, suggesting a significant enhancement in the durability and stability of asphalt mixtures.

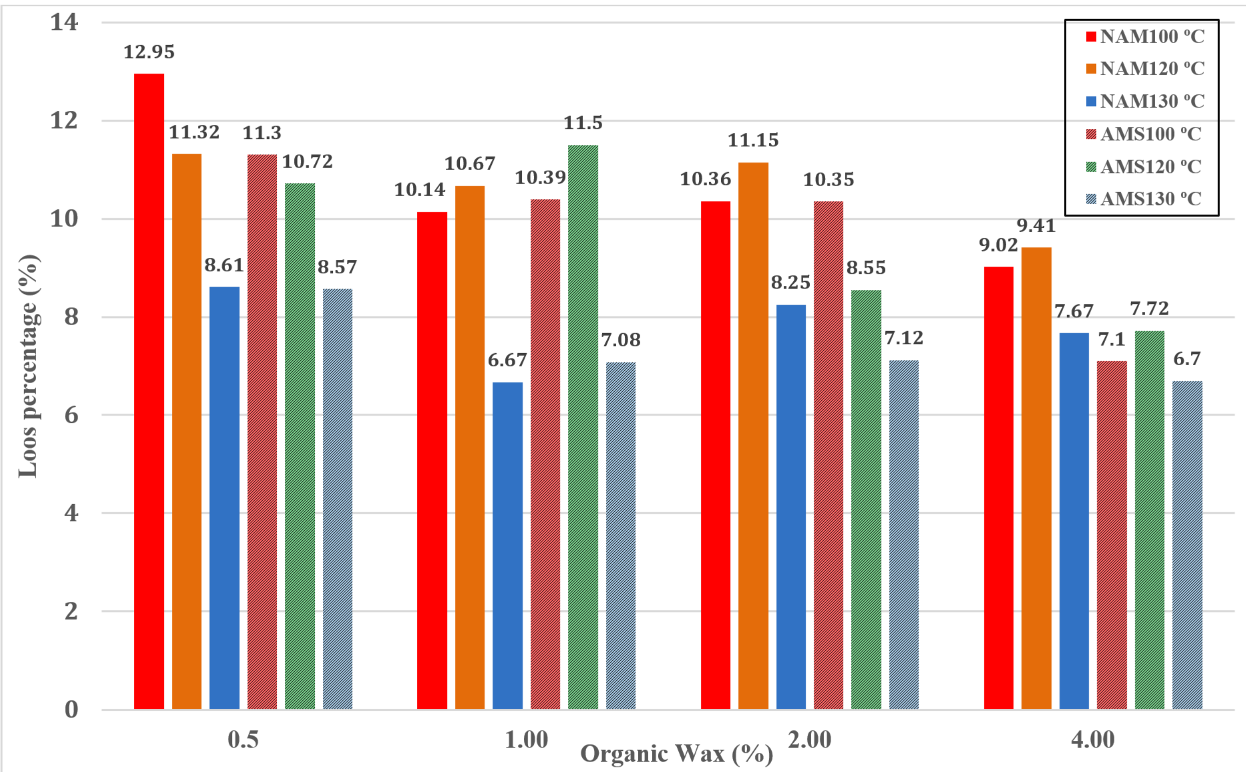

Figure 13. Influence of Organic Wax on Asphalt Adhesion Loss

3.3. Lottman Test Results for NAM and AMS Specimens

Figure 14 presents the results of the NAM100 ℃, NAM120 ℃, and NAM130 ℃ combinations across three cycles of the Lottman test. The averages of the evaluated cycles are shown in Table 6, indicating that all values exceed 80%, thus complying with the INV 450-20 standard.

Figure 15 shows the relationship between the percentage of organic wax and flow (mm) at temperatures of 100 ℃, 120 ℃, and 130 ℃ across three cycles. The flow decreases with an increase in the organic wax percentage, reaching a minimum near 2%, and then increases slightly. The mixtures at 130 ℃ exhibit the lowest flow values, indicating higher stability, while those at 100 ℃ show greater deformations. Moreover, the flow progressively decreases with each cycle, highlighting 130 ℃ as the most favorable temperature.

Figure 16 presents the Lottman test results for the AMS100 ℃, AMS120 ℃, and AMS130 ℃ combinations across three cycles. The averages of the evaluated cycles are shown in the Table 7, indicating that all values surpass 80% and comply with the INV 450-20 standard, except for the third cycle in AMS100 ℃.

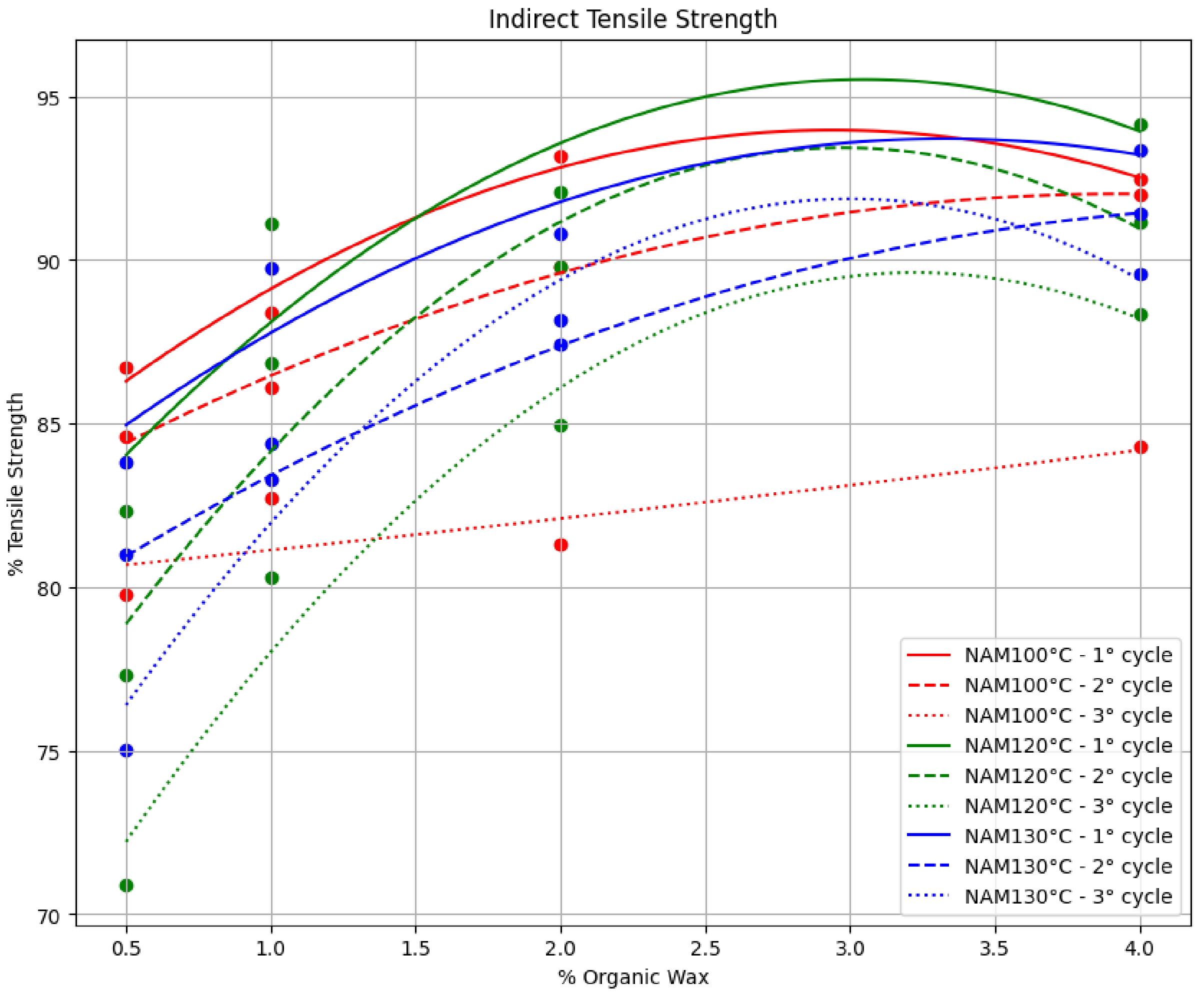

Figure 14. Tensile strength values for the NAM100 ℃, NAM120 ℃, and NAM130 ℃ specimens

Table 6. Average Lottman test results for the NAM samples across three cycles

Specimens	1st Cycle (%)	2nd Cycle (%)	3rd Cycle (%)
NAM100 ℃	90.20	88.13	82.03
NAM120 ℃	89.91	86.29	81.14
NAM130 ℃	89.43	85.80	84.30

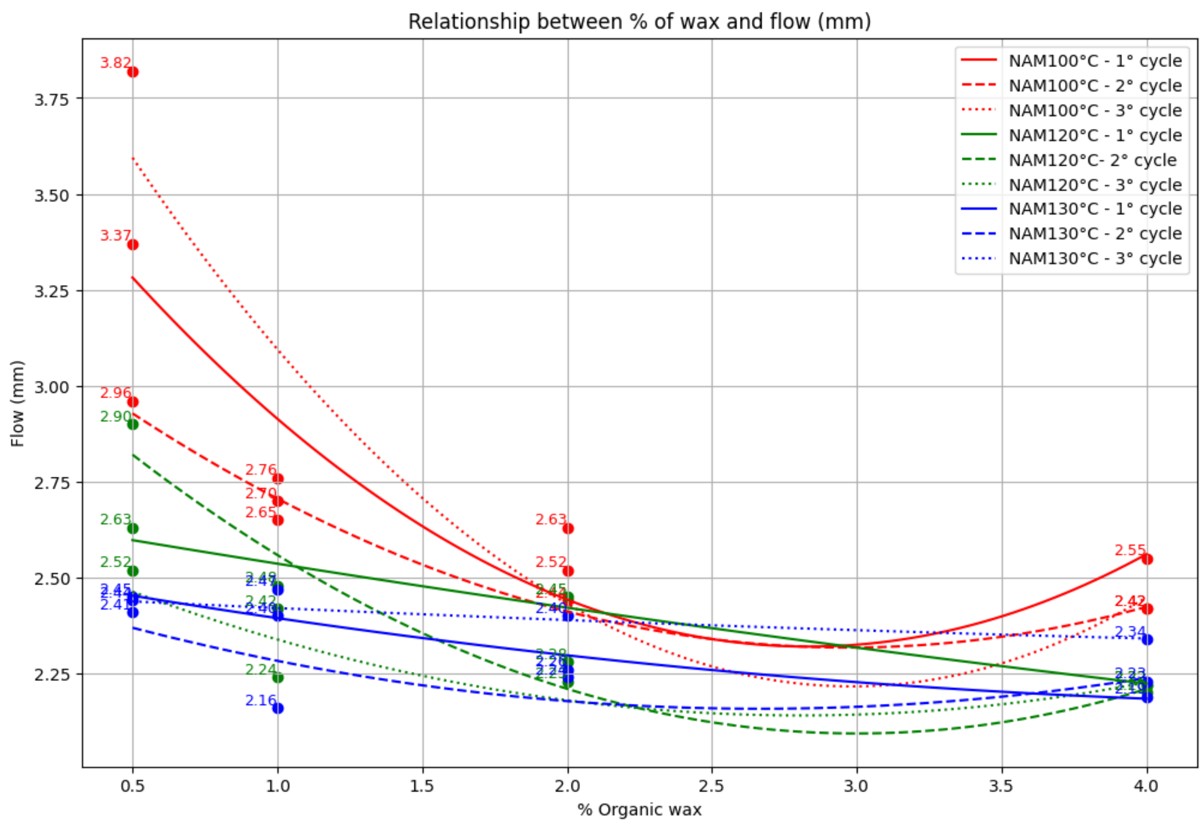

Figure 15. Flow values for the NAM100 ℃, NAM120 ℃ and NAM130 ℃ specimens

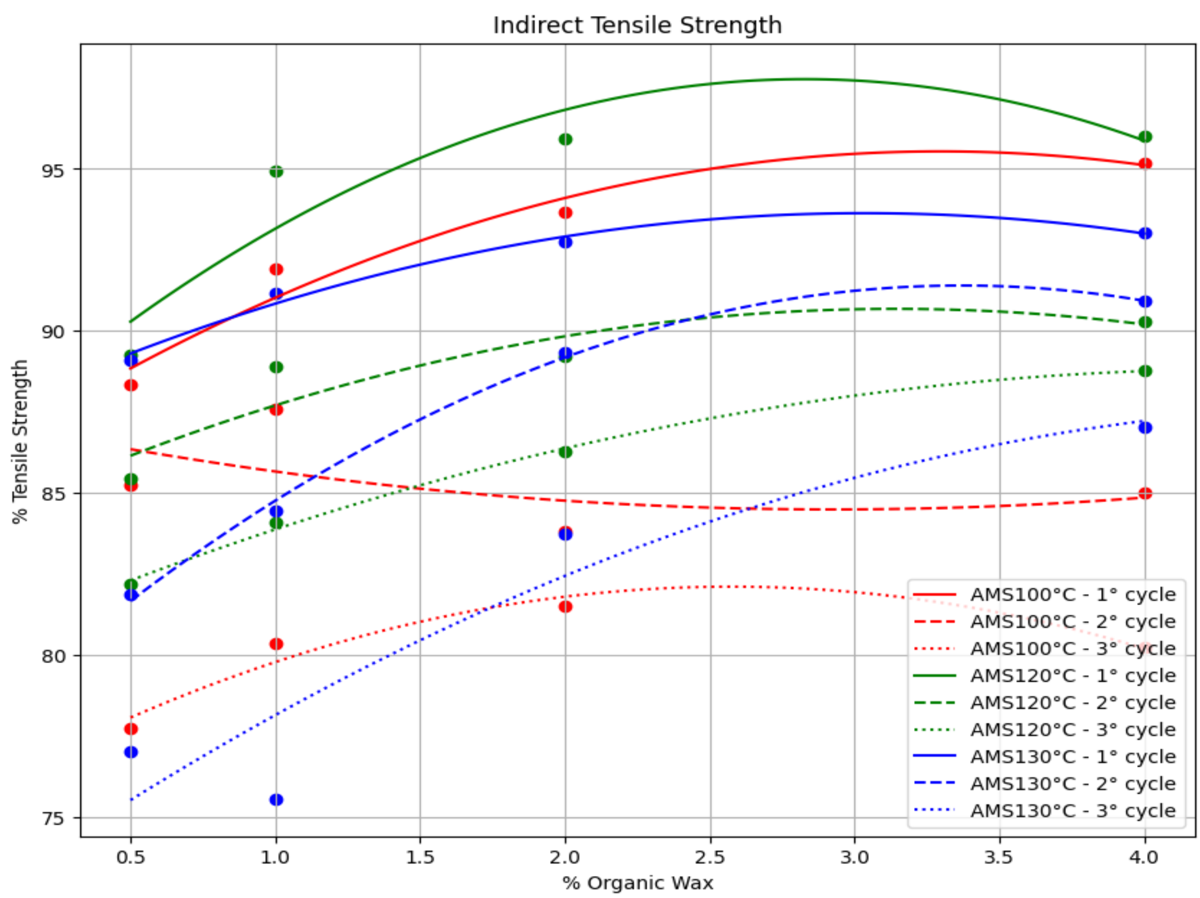

Figure 16. Tensile strength values for the AMS100 ℃, AMS120 ℃ and AMS130 ℃ specimens

Table 7. Average Lottman test results for the AMS samples across three cycles

Specimens	1st Cycle (%)	2nd Cycle (%)	3rd Cycle (%)
AMS100 ℃	92.27	85.41	79.97
AMS120 ℃	94.03	88.48	85.33
AMS130 ℃	91.52	86.64	80.84

Figure 17 illustrates the flow behavior in asphalt mixtures with 0.5% to 4% organic wax at 100 ℃, 120 ℃, and 130 ℃, evaluated across three cycles. At 100 ℃, the flow tends to decrease slightly with increasing wax content, showing greater stability in later cycles. At 120 ℃, a gradual increase in flow is observed with higher wax content, particularly in the third cycle. At 130 ℃, the flow decreases significantly at the beginning but increases with higher wax contents. These results highlight the influence of temperature and the percentage of wax on the mechanical stability and performance of the mixtures.

Regarding the Lottman test, three freeze-thaw cycles were performed. After the first cycle, all mixtures at 100 ℃, 120 ℃, and 130 ℃ exhibited TSR values greater than 80%, indicating that for any wax content between 0.5% and 4%, the mixtures meet the minimum requirement established by asphalt mixture standards. This result suggests that mixtures containing organic wax have good initial resistance to moisture. After the third cycle, TSR values decreased, which aligns with the expected deterioration due to aging and prolonged moisture exposure. However, mixtures with an organic wax content of 1% or higher maintained TSR values above 80% across all tested temperatures (100 ℃, 120 ℃, and 130 ℃). This finding indicates that organic wax at these concentrations enhances the resistance of asphalt mixtures to moisture and freeze-thaw cycles, contributing to greater long-term durability.

Additionally, the results after the first cycle are consistent with those reported by Cetin et al. [8], who found that similar percentages of filler additives, such as class C and F fly ash, improved moisture damage resistance in asphalt mixtures. In contrast, Mistry et al. [38] reported that increasing the content of rice husk ash and fly ash in asphalt mixtures reduced TSR values, suggesting that higher additive quantities do not always yield better results. Furthermore, Usman et al. [39] demonstrated that incorporating palm oil fuel ash as an additive did not achieve TSR values above 80%, the minimum required, reinforcing the suitability of organic wax as a more effective additive.

Regarding the number of cycles proposed for analysis, Mistry et al. [38] conducted seven cycles for their asphalt mixture with additives, which is effective for assessing long-term performance and durability. However, their study focused primarily on evaluating resistance to water-induced damage in both the short and long term. In contrast, our study aims to analyze multiple factors more comprehensively, which is why we limited the analysis to a maximum of three cycles.

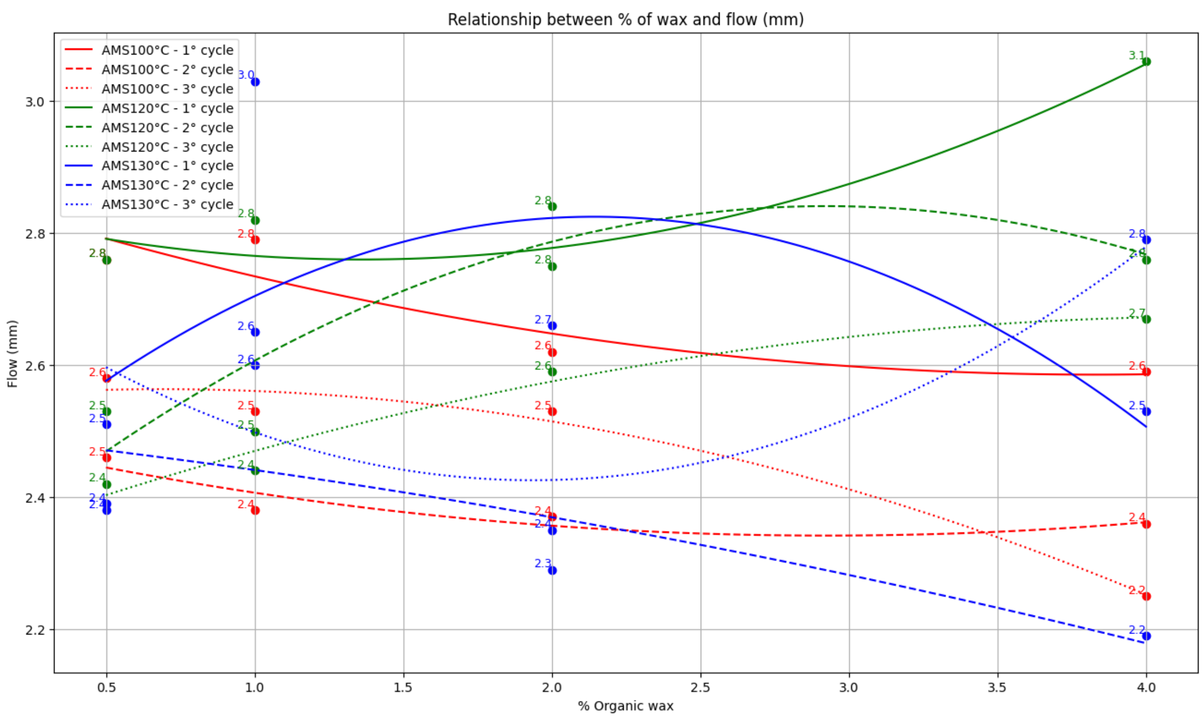

Figure 17. Flow values for the AMS100 ℃, AMS120 ℃ and AMS130 ℃ specimens

In the evaluation using the Lottman test, the TSR values in the SBS-modified asphalt mixture at all tested temperatures were above 91%, indicating a higher initial moisture resistance compared to the asphalt mixture without SBS. Both mixtures met the minimum required 80%. However, after the third cycle, the asphalt mixture without SBS maintained good long-term moisture resistance, as all its samples remained above 80%, whereas this was not the case for the SBS-modified mixture.The SBS content selected for this mixture was 3%, which falls within the recommended range tested in previous studies. For example, Lagos-Vara et al. [9] used 5% SBS, stating that it enhances the mechanical and deformation properties of the binder. Similarly, Hamid et al. [10] incorporated 2% SBS with 8% fly ash, achieving maximum tensile strength and improved crack resistance compared to pure asphalt binder. Another study [40] also used 2% SBS combined with 8% fly ash, demonstrating improved capacity to withstand severe traffic loads.

4. Conclusions

This study has demonstrated that using between 0.5% and 4% OW improves stability, flow, and reduces adhesion loss in PEN85/100 asphalt mixtures and PEN85/100 modified with SBS at temperatures between 100 ℃ and 130 ℃. The AMS120 ℃ samples with 2% OW exhibited optimal values, achieving a stability of 18.51 kN, a flow of 3.10 mm, air voids of 5.31%, and an adhesion loss of 8.55%. This indicates greater resistance to deformation under traffic loads, good adaptability to irregular terrains, and low adhesion loss, which helps maintain the aggregates within the asphalt matrix. It is recommended to maintain a mixing temperature of 120 ℃ when combining PEN85/100 asphalt, SBS, and organic wax to ensure proper consistency. Furthermore, to ensure a tensile strength ratio of at least 80% via the Lottman test at temperatures of 100 ℃, 120 ℃, and 130 ℃ in the asphalt mixtures, it is recommended to use a dosage of no less than 1% organic wax. This is to provide durability and better long-term cracking performance. Additionally, cellulose fibers can be incorporated to enhance deformation resistance, durability, and crack resistance in asphalt mixtures.

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