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Mechanical performance of an asphalt stabilized base with natural asphalt, hydrated lime and Portland cement

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ABSTRACT

This study aimed to evaluate the mechanical performance of an asphalt stabilized base with natural asphalt mix (ASB-NA) with added contents of 1.0 %, 2.0 %, and 3.0 % of Hydrated Lime (HL) and Portland Cement (PC). Tests were employed under dry and wet conditions to analyze the response to monotonic loading in compression and indirect traction and evaluate the susceptibility to water. Additional tests were conducted to analyze the resistance to cyclic dynamic loading, employing resilient modulus, permanent deformation, and fatigue resistance testing. The results reported that adding HL and PC in ASB-NA significantly increased the mechanical performance under monotonic and dynamic loading. These increases were evidenced by higher compressive strength, indirect tensile strength, resilient modulus, fatigue resistance and permanent deformation. Regarding water susceptibility (durability), higher resistance values to moisture damage were presented for the samples with 2 % HL and PC contents. This paper presents new materials for pavement asphalt base courses, which would reduce asphalt consumption, save energy, cut costs, and protect the environment.

1. Introduction

Asphalt, derived from the distillation of petroleum, is a primary component in the manufacture of Hot Mixture Asphalt HMA used in road, highways, and airport construction [1], due to its attributes of strength, adhesion, stiffness, impermeability, elastic recovery, and durability, among others [2,3]. Despite its widespread use in road construction, the industrialization and growth of infrastructure are seeking environmentally friendly alternatives [4]. Numerous studies have emerged exploring sustainable materials that contribute to preserving and conserving the environment [5,6]. One alternative is using Natural Asphalt NA, Natural Bitumen, or asphalt-impregnated materials, which considerably reduces the asphalt consumption of HMAs and provides an alternative material for pavement construction [4,7].

Los NA son solid black organic material, originating from the solidification of petroleum [8]. Distinguished by their chemical and mineralogical composition, various types of NAs exist, primarily categorized as soluble and pyrobitumens: infusible and insoluble natural hydrocarbon solids [9,10]. Typically found in lakes (e.g. Trinidad Lake TLA) or impregnated in rocks or sand (e.g. gilsonite or uintaite, rock asphalt RA, oil sand, among others) [8], NAs are widely used in pavements due to their compatibility with asphalt, enabling them to replace some polymers. They present advantages over conventional materials, delivering sustainability, environmental friendliness, and cost-effectiveness [11].

The presumed global reserves of NA approximate 1,856,853 billion barrels, with significant reserves located in Canada, Russia, Venezuela, the United States, and China, among others [10]. In Colombia, there are approximately 26 mines that exploit AN. The main departments where the mines are located are Santander, Boyacá, Cesar, Caldas, Cundinamarca, Caquetá, Tolima, and Putumayo [12]. The National Road Institute of Colombia (INVIAS) contemplates using NAs to construction of asphalt layers, bases, and granular sub-bases for the Low-Volume Roadway [13–15]. In some cases, the specifications suggest making granulometric adjustments or adding asphalt materials (e.g., asphalt emulsion) to achieve greater structural capacity of the pavement.

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1.1. Background

Abundant studies have explored the incorporation of NA in the modification of asphalt binders and asphalt mixtures [16–22] evaluated the rheological and physical properties of asphalts modified with NA contents. The analyzed contents are below 24 %, 50 %, and 40 % (reference to the asphalt mass) for gilsonite, TLA, and RA, respectively [11]. The incorporation process of NAs into asphalt is similar to that used in the modification of asphalts with polymers. However, there is no standardized procedure for their incorporation. Temperature ranges of 140ºC to 180ºC, agitation time spanning 30–180 min, and agitation speed ranging from 100 to 5000 rpm were reported in the studies. In general, the results indicated an increase in consistency (increase in penetration tests and softening point), viscosity, and stiffness evidenced by the dynamic shear modulus (G*) in the Dynamic Shear Rheometer (DSR) [17,23–25]. These gains were proportional to the added NA content. This aspect increased rutting and fatigue resistance, generating greater pavement durability, mainly at intermediate and high temperatures [18,22,26–28]. Bending Beam Rheometer (BBR) tests at low temperatures indicated higher resistance to fracture, fatigue and higher elastic recovery under load [29]. Similar outcomes were observed when modifying the asphalt-binder with NA and polymers (Styrene-Butadiene-Styrene SBR, crumb rubber CR, and polyphosphoric acid PPA, among others) to improve performance at low temperatures [25–27,29–35]. The maximum contents of NA and polymer ranged between 15 % and 5 % of the total mass of the mixture, respectively.

Regarding the mechanical performance of HMA, several studies revealed the use of NA with replacement levels of up to 40 % of aggregates (reference to the total mass) [33,35–39]. Some studies opted for partial or complete filler replacement with NA [37–39]. Collective findings from these studies regarding the control mix indicated:

- Increased stiffness evaluated by permanent deformation resistance tests [19,22,35]
- An increased resistance to moisture-induced damage [33,40].
- Increased in fatigue resistance [30,33,35].
- Increased and reduced cracking resistance at intermediate and low temperatures, respectively [35,36].
- Increased resistance to aging [41].
- Reduced workability of the mixture due to the increase in viscosity.

In summary, asphalt binder and/or asphalt mixtures with NA provided higher stiffness at intermediate and high temperatures, possibly due to the increase of asphaltenes [4,7,11]. Nevertheless, the same behavior was not evident at low temperatures [11].

Hydrated Lime (HL) and Portland cement (PC) are widely employed in civil construction for soil stabilization, platform construction, subbase and pavement base treatment, and prefabricated elements, among others [42–44]. These materials provide pozzolanic properties, which improve the physico-mechanical characteristics of materials (e.g. soils, sub-bases, bases, asphalt mixtures, mortars, and concretes, among others) [45,46]. Multiple laboratory and field studies have been conducted using HL in HMA [47,48]. The findings consistently indicate that the incorporation of HL in HMA increased the resistance to moisture-induced damage, resistance to aging, stiffness, and fatigue, as well as reduced rutting, among others [48–52]. Furthermore, technical and economic life cycle evaluations underscore the economic advantages of pavements incorporating HL compared to those using conventional materials [53]. Few studies have illustrated the use of (PC) in HMA due to its high costs [54]. Al-Khateeb and Al-Akhras evaluated the rheological behavior of a PC-modified asphalt by rheological tests, showing increased viscosity and stiffness [55]. Guha and Assaf substituted 2 %, 4 %, and 6 % relative to the total mass of the natural filler of an HMA with PC. The conclusions indicated a significant reduction of air voids and increased resistance to permanent deformation [54].

1.2. Research objective

The literature review shows no evidence of NA studies with HL and PC additions for the manufacture of ASB. Most of the studies cover the behavior of hot mix asphalt (HMA). Therefore, this study innovatively provides new materials that decrease asphalt consumption, save energy, reduce costs, and contribute to the environment. This study specifically analyzed the mechanical behavior of an ASB using 45 % NA and 55 % aggregates a content of the total mass. Furthermore, additions of 1 %, 2 %, and 3 % of HL and PC, respectively (in reference to the total mass were contemplated). Tests were conducted to evaluate the mechanical behavior by applying monotonic loading: compressive and indirect tensile strength; and dynamic loading: resilient modulus, fatigue resistance and permanent deformation at intermediate temperatures.

2. Materials and methodology

This study employed a comprehensive three-stage methodology illustrated in Fig. 1. The initial stage consisted of the characterization tests of materials: NA, aggregates, Hydrated Lime-HL, and Portland Cement-PC. The second stage involved the fabrication of ASB specimens using NA and aggregates according to the guidelines of INVIAS 341 P-17 [14]. Additionally, 1 %, 2 %, and 3 % contents of HL and PC were added. Finally, mechanical performance tests were carried out in the third stage using monotonic loading: Compressive Strength and Indirect Tensile Strength; and dynamic loading: resilient modulus, fatigue resistance and permanent deformation.

2.1. Materials

2.1.1. Natural asphalt

NA used in this study was sourced from the San Pedro mine in the Department of Tolima in Colombia as shown in Fig. 2. Na It is composed stone material impregnated with natural asphalt. The chemical composition obtained by X-Ray Diffraction (XRD) are presented in Table 1. The results reveal high contents of silica oxide SiO_2 (77.03 %) and aluminum Al_2O_3 (18.17 %). Likewise, other oxides were observed in smaller proportions. The presence of SiO_2 (77.03 %) and aluminum Al_2O_3 in asphalt mixtures may contribute to increased stiffness and susceptibility to water [56,57].

Fig. 3 presents the particle size distribution test for NA. According to the Unified Soil Classification System (USCS), NA was classified as well-graded sand (SW). Table 2 presents the results of the physical characterization tests for NA. Furthermore, the asphalt content of the NA was determined to be 11.2 %. The physical characteristics of the extracted asphalt are shown in Table 3. The results indicate that the extracted asphalt has similar characteristics asphalt cement 40–50 original. Since the penetration is between 40 and 50 (0.1 mm), the softening point between 52 and 58ºC and the minimum ductility value is 80 cm.

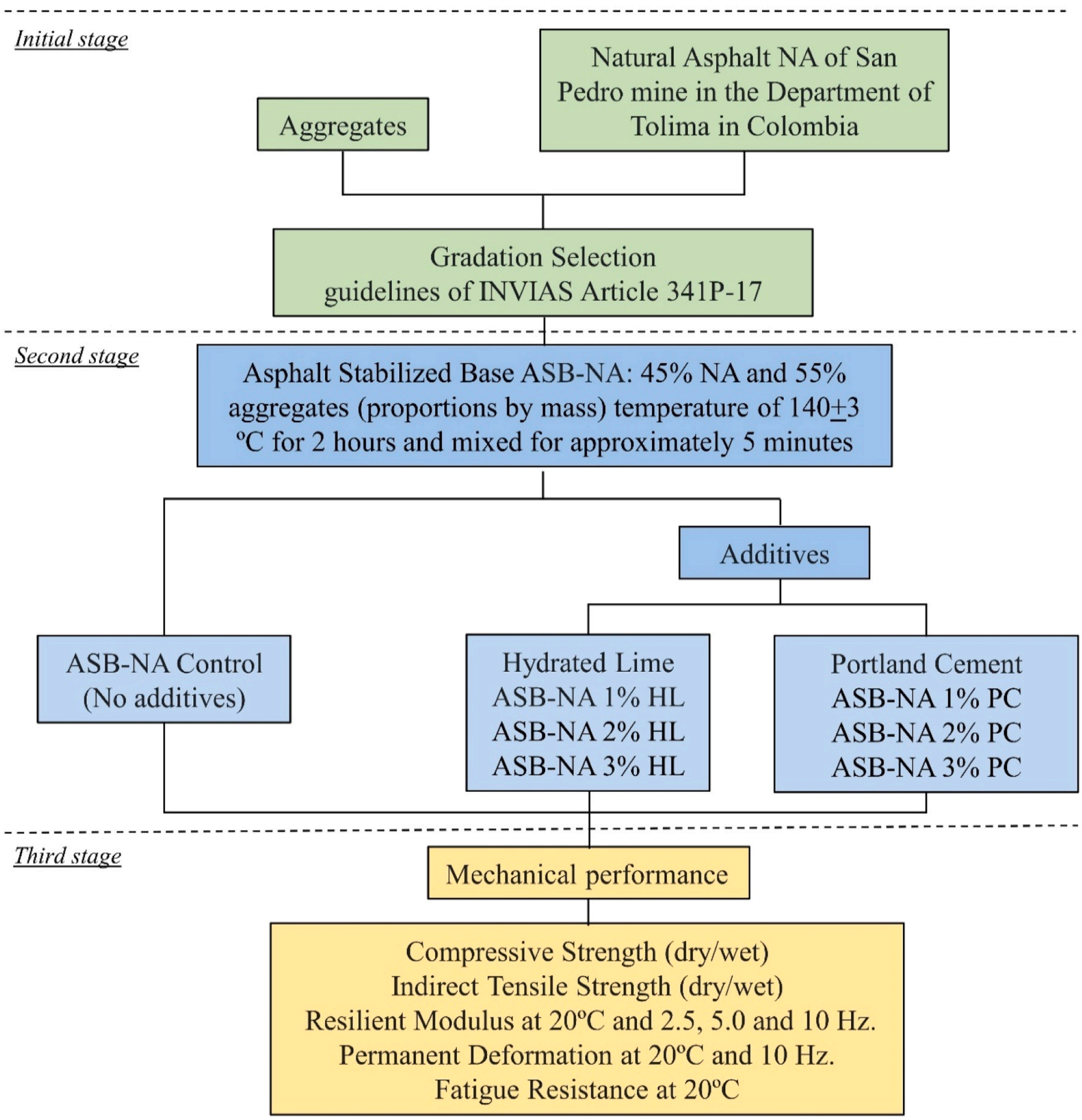

Fig. 1. Materials and methodology.

2.1.2. *Aggregates*

The aggregates used in this study came from the city of Bogota. The physical characterization results are presented in Table 4, and they comply with the quality requirements outlined by INVIAS 341 P-17 for the manufacture of ASB-NA [14].

2.1.3. *Additives*

Hydrated lime (HL) and general-purpose Portland cement (PC) were used as admixtures in this study for ASB-NA, as depicted in (Fig. 4). The chemical compositions and physical properties of the hydraulic admixtures are presented in Tables 5 and 6, respectively. These results were consistent with those obtained in other studies [58].

2.2. *Fabrication of specimens*

In the fabrication of the specimens, particle sizes of the materials (NA and aggregates) were adjusted to the average specification of the ASB-NA 25. Classification according to maximum particle size in mm) of the INVIAS 341 P-17 [14] (Fig. 5). These adjustments are shown in Fig. 5. To this end, 45 % of NA and 55 % of aggregates (proportions by mass) were used. For the Manufacture of the specimens, no additional asphalt binder was included (only the asphalt content of the NA). Subsequently, 1 %, 2 %, and 3 % contents of HL and PC (about the total mass) were added. These contents were informed by the literature, particularly studies employing HL in HMA [50].

A total of 7 types of ASB -NA were performed:

ASB -NA – Control

ASB -NA – 1% HL

ASB -NA – 2% HL

ASB -NA – 3% HL

ASB -NA – 1% PC

ASB -NA – 2% PC

ASB -NA – 3% PC

The materials were heated in an oven at a temperature of 140+3 °C for 2 h and mixed for approximately 5 min to manufacture the ASB-NA;

Fig. 2. NA, San Pedro Mine in the department of Tolima (Colombia).

Table 1
NA chemical composition.

Oxide	SiO_2	Al_2O_3	SO_3	TiO_2	Fe_2O_3	CaO	Others
Composition (%)	77.03	18.17	1.58	1.48	0.97	0.33	0.44

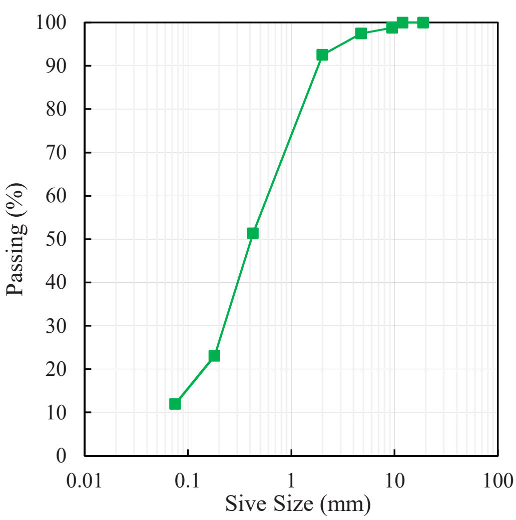

Fig. 3. Gradation of NA.

Table 2
NA physical characterization tests.

Test	Method	Result
Specific Gravity Gs	AASHTO T 84	2.36
Asphalt Content (%)	ASTM D2172	11.2
Liquid Limit and Plastic Limit (%)	ASTM D4318	NL - NP
Plastic Index (%)	ASTM D4318	0
Sand equivalent (%)	AASHTO T 176	65.4
Methylene Blue Value (ml/g)	ASTM C1777	1.28
Fine Aggregate Angularity (%)	ASTM C1252	43.6

the heating temperature was determined based on recommendations from previous studies focused on optimizing the production of asphalt mixtures [38,40]. The mixing process exhibited observable characteristics of adequate particle coverage and material workability, ascribed to the natural asphalt binder content. HL and PC underwent the same temperature and time heating conditions for the samples with adding

Table 3
Properties of extracted asphalt binder from NA.

Test	Procedure	Result
Penetration at 25 °C (0.1 mm)	ASTM-D5	47.3
Softening point (ring and ball) (°C)	ASTM-D36	52.5
Ductility (cm)	ASTM-D113	83

Table 4
Coarse aggregates physical characterization tests.

Test	Method	Result	Specification
Abrasion in los Ángeles (%)	AASHTO T 96	32	maximum 50
Soundness - magnesium sulfate (%)	AASHTO T 104	9.2	maximum 18
Liquid Limit (%)	ASTM D4318	NL	maximum 9
Plastic Index (%)	ASTM D4318	NP	maximum 35
Sand equivalent (%)	AASHTO T 176	76	minimum 20

Fig. 4. Additives: PC (left) and HL (right).

additives. Two types of specimens were made: i) Type I specimens were made with 2400 g of material in a mold of 100 mm and 150 mm in diameter and height, respectively. Compaction was performed in a press, applying a monotonic load of up to 120 kN. These specimens were used for compressive strength tests. ii) Type II specimens correspond to Marshall-type briquettes with 1200 g of material of 63.5 mm and 100 mm in height and diameter, respectively. Compaction was performed with a hammer, applying 75 blows per layer, according to the Marshall methodology for HMA design. Indirect tensile strength, resilient modulus, fatigue resistance, and permanent deformation tests were performed on these specimens. The specimen fabrication process is shown in Fig. 6.

Compacted specimens type I and II were used to evaluate the volumetric properties. The bulk specific gravity of compacted mix (Gmb) and the theoretical maximum density (Gmm) of the uncompacted mix was determined in accordance with ASTM D 3203 specifications. The air voids content (Va) in the compacted specimen was determined using the corresponding values of Gmb and Gmm as in the Eq. 1.

$$Va = 100 \left(1 - \frac{G_{mb}}{G_{mm}}\right) \quad (1)$$

2.3. Mechanical behavior performance

2.3.1. Compressive strength

The Compressive Strength Test, performed by ASTM D1074–17, is illustrated in Fig. 7. Type 1 specimens were subjected to monotonic loading in a press until failure. The test was performed in dry and wet conditions to analyze the susceptibility to water. In the dry condition, specimens were subjected to 20°C for two hours before failure. In the wet condition, the specimens were subjected to 60°C and 20°C for 24 and 2 h, respectively. The loading rate of the test was 5 mm/minute. In total, 42 specimens were used, encompassing seven types of ASB, each

Table 5
Chemical composition of HL and PC.

Additives	CaO	Na_2O_3	MgO	SO_3	SiO_2	Fe_2O_3	Al_2O_3	Others
HL	91.01	2.7	1.63	1.56	0.91	0.89	0.61	0.69
PC	65.66	0.56	0.87	0.91	21.85	3.87	5.43	0.85

Table 6
Physical properties of HL and PC.

Additives	Specific Gravity Gs
HL	2.70
PC	3.15

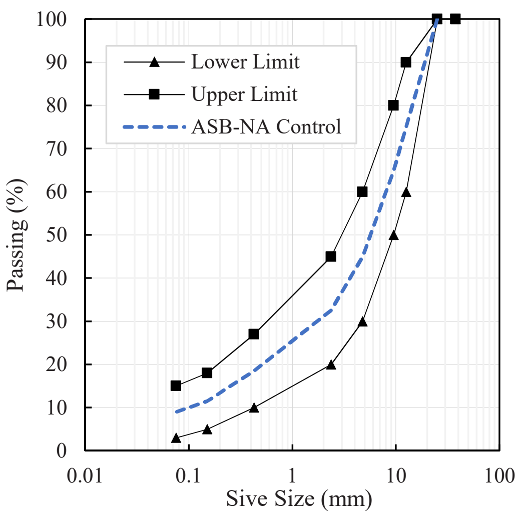

Fig. 5. Specification limits ASB-NAM INVIAS 341 P-17 (INVIAS 2017).

tested under two conditions (dry and wet), with three repetitions for each condition.

2.3.2. Indirect tensile strength (ITS)

ITS test was conducted following ASTM D6931–17 methodology to analyze the indirect tensile response, as shown in Fig. 8. The specimens were subjected to monotonic loading until failure in a press. The loading rate is 50 mm/minute. ITS in kPa was determined through Eq. 2, where P corresponds to the maximum load in N; H and E correspond to the thickness and diameter of the briquette in mm, respectively. Similar to the compressive strength test, the test was performed under dry and wet conditions to analyze the susceptibility to water. In total, 42 specimens were used, encompassing seven types of ASB, each tested under two conditions (dry and wet), with three repetitions for each condition. Resistance to induced humidity damage is also calculated by Tensile Strength Rat (TSR) using Eq. 3.

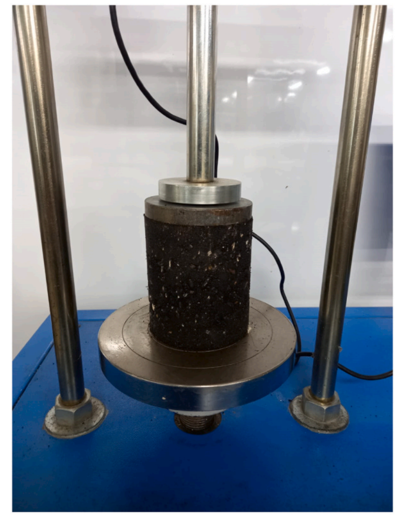

Fig. 7. Compressive Strength.

$$ITS = \frac{2000 \bullet P}{D \bullet H \bullet \pi} \quad (2)$$

$$TSR = \frac{ITS_w}{ITS_d}.100 \quad (3)$$

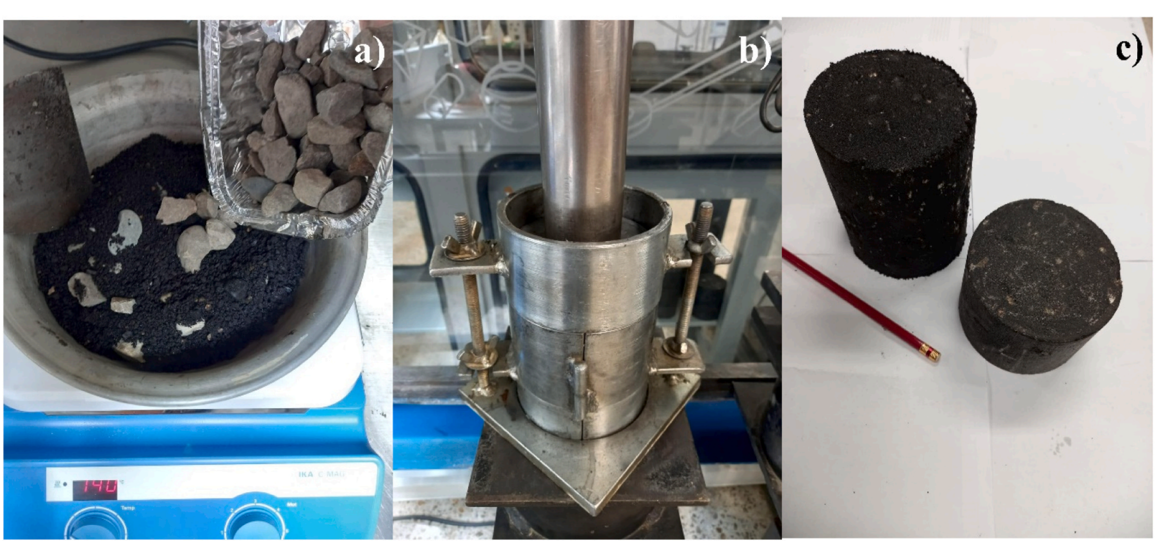

Fig. 6. Methodology for the design of SBC-NA: a) addition of stone aggregates to the NA b) compaction c) types of specimens.

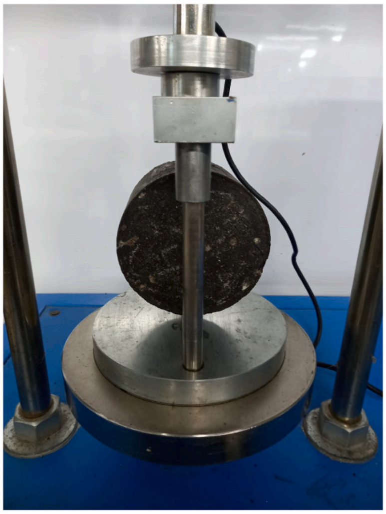

Fig. 8. Indirect Tensile Strength test.

2.3.3. Resilient modulus, fatigue resistance and permanent deformation test

Resilient modulus, fatigue resistance and permanent deformation tests were performed to determine the response to cyclic dynamic loading in a Universal Testing Machine - UTM for all materials. Resilient modulus tests are presented in Fig. 9a, which were performed through diametral compression according to ASTM D 4123–82, involved. These tests were performed by applying a cyclic load of 1200 N at a temperature of 20 °C. The load application frequencies for these tests were set at 2.5 Hz, 5 Hz, and 10 Hz, respectively. In total, 21 tests were performed: 7 materials and 3 repetitions. Fig. 9b shows the permanent deformation test, where an axial load producing a controlled stress of 100 kPa was applied for 7200 cycles. The load application frequency was 10 Hz. Considering that asphalt bases are not subjected to direct weathering, the test was conducted at a temperature of 20 °C. A total of 21 tests were performed: 7 materials and 3 repetitions. The fatigue test was performed under controlled stress to failure (Fig. 9c). Three stress levels of 400 kPa, 300 kPa, and 200 kPa were used. The stress levels were performed using a haversine waveform with a loading frequency of 1.0 Hz. In total, 63 specimens were used: 7 types of ASB, 3 stress levels, and 3 repetitions.

3. Results and discussions

3.1. Volumetric properties

Average value and coefficient of variation (COV) of air voids for compacted specimens type I and II is shown in Table 7. Type I specimens present greater Va, which is associated with the compaction process by monotonic load. That is, type I specimens have greater volume and quantity of material, which can generate emptier with air between the particles. The addition of HL and PC causes greater accommodation of particles, reducing is in reference to the control specimens. Variation coefficients are adequate, in all cases they are lower than 7.2 %.

3.2. Compressive strength test

The compressive strength of ASB with HL and PC is shown in Fig. 10 and Fig. 11, respectively, for both dry and wet conditions. All specimens met the minimum compressive strength requirement of 2.5 MPa and the dry/wet strength ratio of 60 % specified by INVIAS 341 P-17 [14]. The results show that the admixtures increase the compressive strength of the ASB. Compared to the control sample, the samples with HL increased by 36 % and 41 % in dry and wet conditions, respectively, while the samples with PC increased by 37 % and 35 %, respectively. The rise in strength under monotonic loading can be attributed to NA cohesion at 140 °C during the manufacturing process, as well as the additives' pozzolanic characteristics and physicochemical interactions.

Regarding the resistance to mixture damage (dry/wet), the samples with PC increased by 37 % and 35 %, respectively. However, the highest

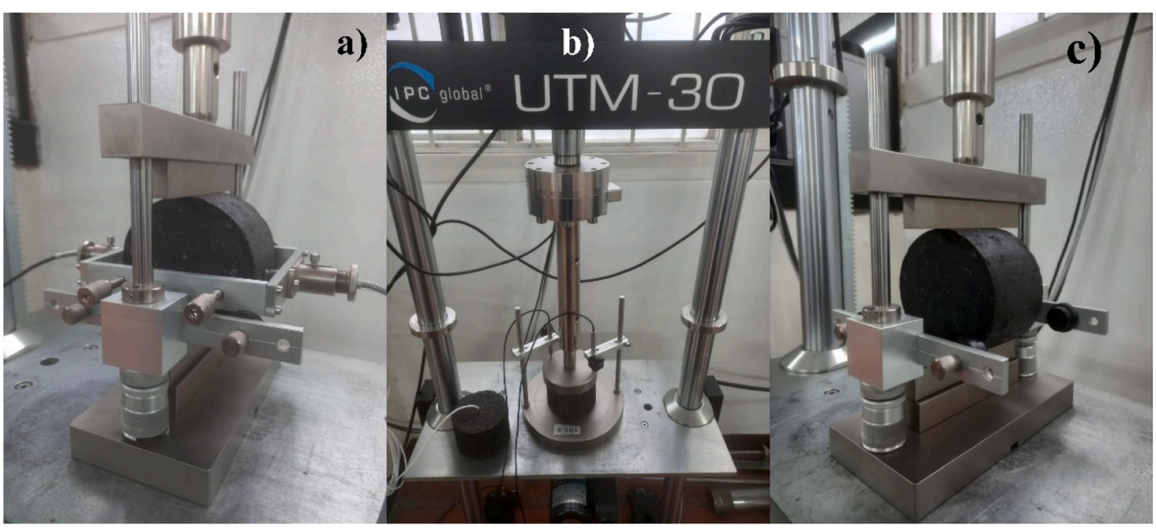

Fig. 9. Dynamic load tests: a) resilient modulus b) permanent deformation c) fatigue resistance.

Table 7
Volumetric properties.

Specimen	Parameter	ASB-NA Control	ASB-NA 1 % HL	ASB-NA 2 % HL	ASB-NA 3 % HL	ASB-NA 1 % PC	ASB-NA 2 % PC	ASB-NA 3 % PC
Type I	Average value (%)	8.7	8.5	8.2	7.7	7.7	7.5	7.5
	COV (%)	1.3	1.3	1.6	1.3	0.6	1.0	1.4
Type II	Average value (%)	5.5	5.3	4.8	4.9	5.5	5.1	5.0
	COV (%)	4.2	4.3	2.8	4.6	3.3	4.7	4.2

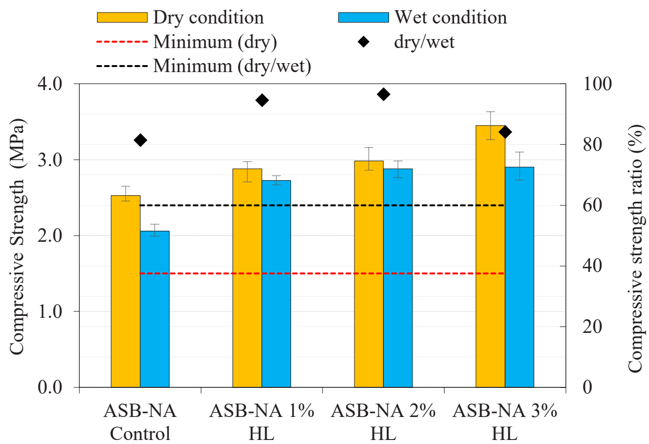

Fig. 10. Evolution of compressive strength with addition of HL.

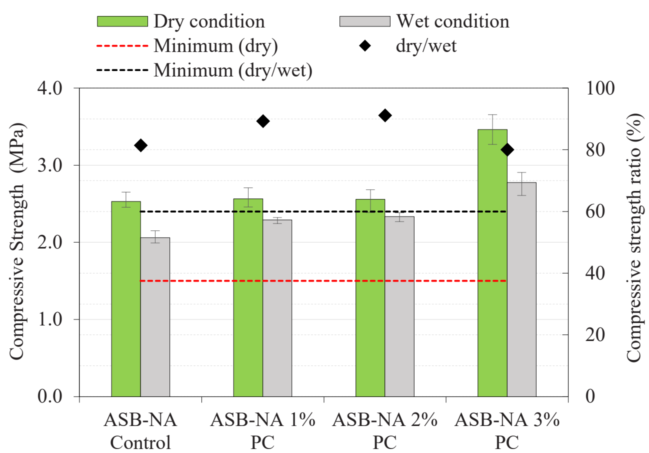

Fig. 11. Evolution of compressive strength with PC.

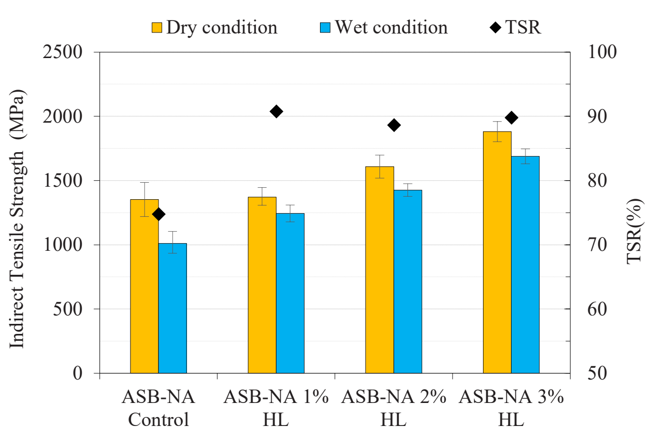

Fig. 12. Indirect tensile strength tests under dry conditions.

values were obtained for the 2 % content of HL and PC. Therefore, the presence of the additives contributes to increased adhesion. The increases in compressive strength for the PC and HL samples can be considered similar.

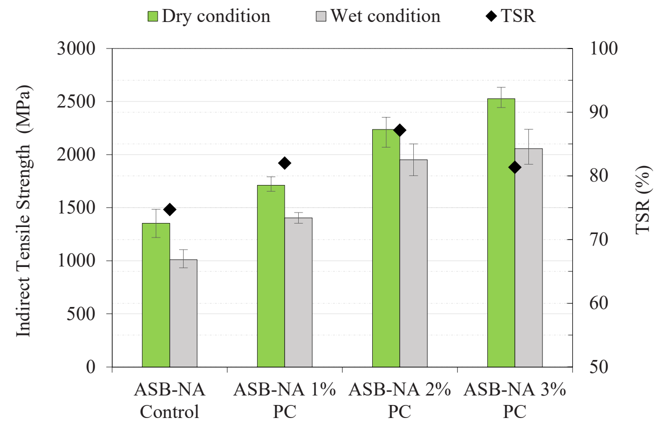

Fig. 13. Indirect tensile strength tests under wet conditions.

3.3. Indirect tensile strength tests

The indirect tensile strength of ASB with HL and PC is shown in Fig. 12 and Fig. 13, respectively. The results show that ITS in dry and wet conditions increased with the additive content compared to the control sample. These increments were up to 87 % and 104 % in dry and wet conditions, respectively, for PC, while the samples with HL had a lower increase, reaching 39 % and 67 %, respectively. Thus, it is evident that PC provides higher indirect tensile strength. In wet conditions, the additive is activated with water, which generates greater adhesion between particles about the wet control material. Regarding water susceptibility, the additives increased the TSR test values. The most significant increases were obtained for the 2 % contents. To such a degree, these materials can be used in areas with high precipitation levels and shallow water tables. Studies on asphalt mixtures report with AN report increased ITS and TSR in reference to mixtures with natural aggregates [19,30,33].

3.4. Resilient modulus test

Fig. 14 a and b present resilient modulus results for the HL and PC specimens, respectively. The results indicated a considerable increase in stiffness under cyclic dynamic loading of the materials with additives at 20 °C and for the test frequencies. The maximum average increases for HL and PC were approximately 82 % and 69 %, respectively. Therefore, the addition of HL improved the stiffness of the ASB more than the addition of PC. This response indicated increased stiffness, which could reduce thickness in pavement structural layers. Yilmaz et al., they also found significant increases of the resilient module in HMA by adding NA [30,33].

3.5. Fatigue resistance test

Fatigue results are presented in Fig. 15. A remarkable increase in fatigue resistance strength was observed when PC and HL were used. This increase was proportional to the additive content. The increase in fatigue resistance can be explained by the increase in stiffness, as illustrated in the mechanical behavior tests: compressive strength, indirect tensile strength and resilient modulus, compared to the ASB-NA control. The increase in fatigue resistance could be related to the mixture's response to the type of loading by controlled stress since the stiffness of the mixtures affects their service life and fatigue resistance under this type of loading. The stiffer the mixtures, the longer they last and the

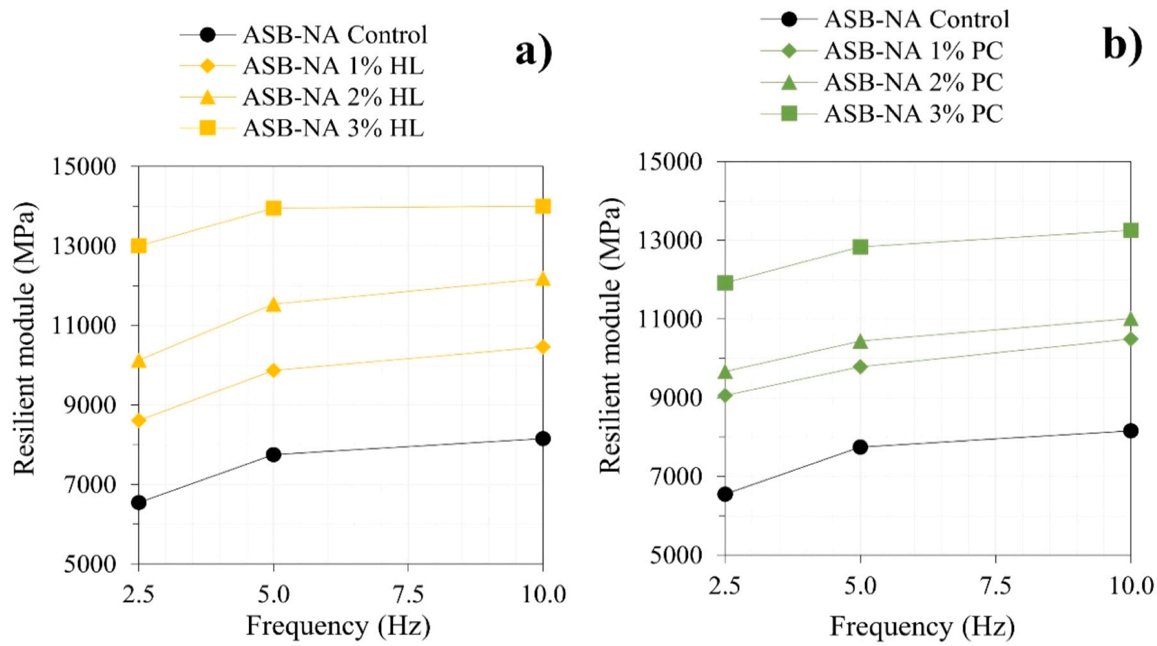

Fig. 14. Resilient modulus test: a) HL b) PC.

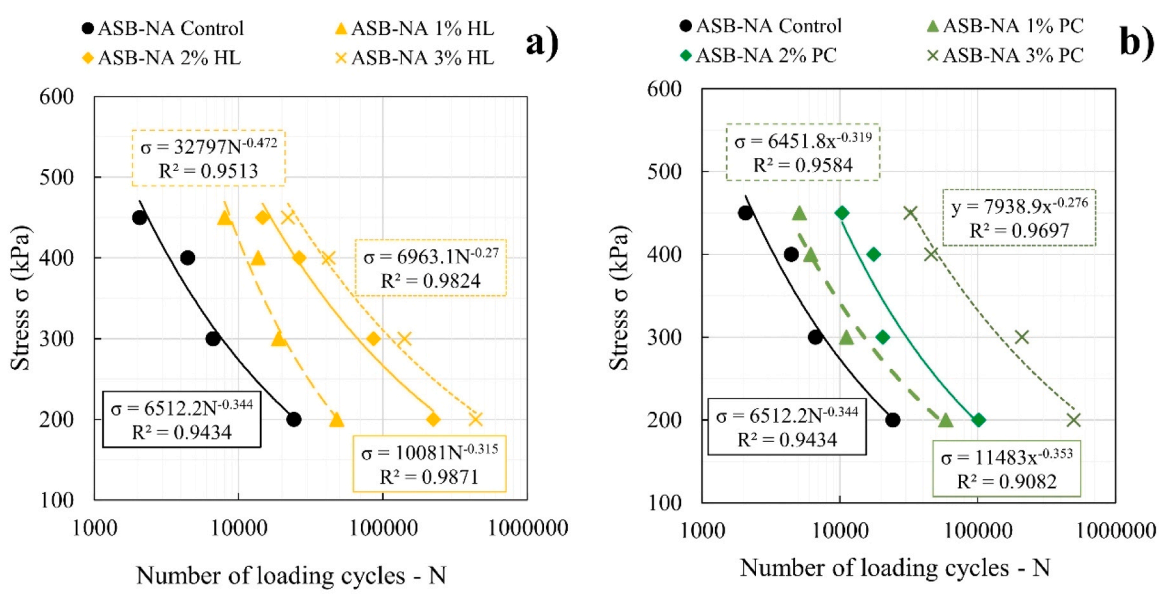

Fig. 15. Fatigue resistance test: a) HL b) PC.

more they resist fatigue [59–61]. Some studies report increases in fatigue resistance in SMA (Stone Mastic Asphalt) and HMA mixtures with NA in reference to conventional aggregates [19,26].

3.6. Permanent deformation

The permanent deformation tests for the HL and PC specimens are presented in Fig. 16a and Fig. 16b, respectively. The results show that the additives contributed to an increase in the resistance to permanent deformation of the control mixture, as evidenced by the lower displacement at the end of the test. The samples with HL and PC had similar permanent deformation resistance, consistent with their compressive strength and resilient modulus results, indicating higher resistance and stiffness to monotonic and cyclic loading, respectively. These results also agree with the literature, where NA increased the stiffness of asphalt mixtures [19,33]. Likewise, the physicochemical interactions of the additives with NA contributed to the significant rise in stiffness.

4. Conclusions

This study evaluated the mechanical performance of ASB-NA by adding 1.0 %, 2.0 %, and 3.0 % Hydrated Lime and Portland Cement. The laboratory tests consisted of monotonic load application tests and dynamic loading. Based on the laboratory tests, the following conclusions and suggestions for future research were drawn:

- Adding HL and PC resulted in significant growth in the mechanical behavior of an ASB-NA (55 % aggregates with Natural Asphalt). It was observed that the ASB with additive presented greater resistance

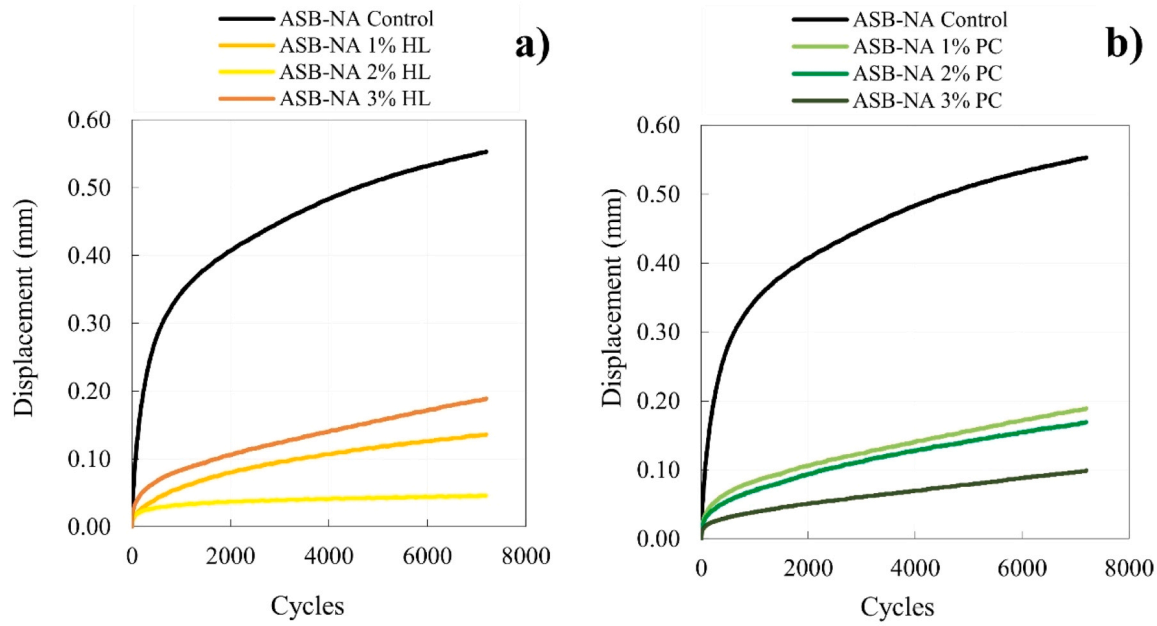

Fig. 16. Permanent deformation test: a) HL b) PC.

to the action of monotonic loading under compressive strength and indirect tensile strength. Likewise, the behavior under dynamic loads (higher values of resistant modulus, fatigue resistance and resistance to permanent deformation) was improved compared to the control material. These increases were proportional to the additive content. In addition, the NA used in the study was mainly composed of 9.2 % asphalt binder, which provided good compatibility and adhesion with the aggregates and additives studied. The NA also contained silica and aluminum oxides, contributing to the ASB's strength and stiffness.

- The presence of HL and PC increased the water susceptibility of ASB-NA, as shown by the higher compressive strength and indirect tensile strength in wet conditions than the control mix. The best performance was obtained for the 2.0 % content of HL and PC. Therefore, the additives studied may develop greater stability in the presence of water. This characteristic can increase the durability of the pavements and be beneficial for pavement structures in areas with high rainfall or shallow water tables, where the granular base layer could be exposed to moisture conditions close to saturation.
- As suggested in this study, using HL and PC in the NA mixture with aggregates is a feasible technique from both technical and environmental perspectives. The admixtures reduce the amount of asphalt binder required for the fabrication of the ASB, promoting the use of environmentally friendly materials, which benefits the preservation and conservation of the environment in terms of renewable energies. However, further studies are needed to validate the technique, considering factors such as long-term durability tests, different types of NA, granulometries, fabrication temperatures, and additives.

This study's results only apply to the ASB analyzed, and do not represent the behavior of other asphalt bases. Therefore, further studies are recommended to understand the mechanical behavior of other asphalt bases, considering different granulometries and NA. It is also necessary to further study the ordinary filler and compare the mixture with traditional HMA with the same gradation and asphalt content. Moreover, alternative materials (e.g., reclaimed asphalt pavement - RAP, construction and demolition wastes – CDW, recycled concrete aggregates RCA, etc.) could be explored. Finally, larger-scale laboratory and field tests are recommended to obtain more definitive conclusions.

CRediT authorship contribution statement

Camilo Herrera-Cano: Writing – review & editing, Investigation, Conceptualization. **Juan Carlos Ruge:** Writing – review & editing, Investigation, Conceptualization. **Juan Gabriel Bastidas-Martínez:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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