Laboratory performance analysis of Nano-Silica modified hot mix asphalt

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ABSTRACT

The study aims to evaluate the effect of nano-silica (NS) on hot mix asphalt (HMA) performance by means of Hamburg Wheel-Tracking Test (HWT), Repeated Semicircular Bending Test (RSCB), Indirect Tensile Strength Test (ITS) and Dynamic Modulus Test (E*). As part of the investigation, one aggregate source (river gravel) was used and one un-modified control asphalt binder which corresponds to a PG64-22. Three 12.5 mm and three 9.5 mm nominal maximum size (NMAS) mixtures were designed following the Superpave methodology, containing NS modified binder at 0% (control mixtures), 3% , and 6%.

NS modified HMA presented an increase in stiffness, which relates to a decrease in permanent deformation at high temperatures, but can lead to a reduction of fatigue life at intermediate and lower temperatures. All modified HMA exhibit an improved moisture damage resistance. Based on the overall ranked performance, the 12.5 mm mix with 6% NS showed the best performance, followed by the 12.5 mm mix with 3% NS. However, when considering the manufacturing process, transportation, placement and the economic cost of using NS as modifier, the 12.5 mm mix with 3% NS can be recommended, since the incremental benefits with the 6% NS modified mix were marginal.

Keywords: HMA, Nano-silica, Asphalt, Performance, HWT, RSCB, IDT, DM.

1. I NTRODUCTION

Pavements are subjected to frequent failure mechanisms due to increase in highway traffic loads and climatic effects, reason why there is a constant search for solutions to reduce them. One method being considered is the application of modifiers in hot mix asphalt (HMA).

Nano-materials have taken a very important role in the investigation and industry area, thanks to their excellent mechanical, thermal and electrical properties. Likewise, their use has also been considered a feasible option to modify HMA since market prices have tended to decrease as a result of the massive production generated by the nano-material industry [1]. Modifications with hydrated nano-lime, carbon nano-tube, nano-clay, nano-organosilane, nano-silica (NS), among others, are also currently being implemented to enhance the HMA performance [2,3].

Silica or silicon dioxide (SiO_2) is a chemical compound formed by oxygen and silicon, it is most commonly found in nature as sand, quartz or in cell walls of diatoms [4]. Nano-sized silica is a particle where at least one of its dimensions is between 100 nm or less [5]. Due to its high adsorption, large surface area, good dispersal ability, high chemical purity and excellent stability, besides its low cost production, nano-silica has been used as an additive, catalyst carrier, rubber strength agent, plastic filler and most recently as a modifier to improve the HMA performance [6,7].

Previous research conducted on NS modified HMA have given favorable results in terms of the overall performance of HMA [2,3,8-11]. However, it is important to study its effect for various binder source, since each nano-material can generate different behaviors or effects in the asphalt binder or the asphalt mixture depending on the nano-material chemical composition and physical properties, as well as how their incorporation to the asphalt binder vary, depending on their nature [1].

The objective of this study was to evaluate the performance of HMA with 9.5 mm and 12.5 mm nominal maximum size (NMAS) gradation, modified with 3% and 6% of NS by weight of the asphalt binder, using the following laboratory tests: Hamburg Wheel-Tract Test (HWT), Repeated Semicircular Bending Test (RSCB), Indirect Tensile Strength Test (IDT) and Dynamic Modulus Test (E*).

2. MATERIALS USED IN THE STUDY

2.1 Asphalt Binders

The asphalt binder used is the only type Costa Rican National Petroleum Refinery (RECOPE) produces; an AC-30 according to viscosity grade or PG64-22 according to performance grade (PG), its density at 25 °C is 1.027 g/cm^3 and the specific gravity is about 1.03. The nano-silica used was produced in Germany, and consists of a white solid powder, synthetic, hydrophilic and produced via flame hydrolysis, the density at 20 °C is around 2.2 g /cm^3 and the superficial area is about 225 m^2/g.

The NS was used without any further treatment, the particles were added to the control asphalt binder at concentration of 3% and 6% (by weight of the asphalt binder), and mixed in a low shear stirrer at 175 °C, with a shear rate of 700 revolutions per minute for two hours.

2.2 Compacted mixtures

The mixtures were designed using the Superpave methodology, following the procedures of AASHTO M 323-13 and AASHTO T 312-14, for a traffic load range of 3 million to 30 million ESALs. Table 1 summarizes the mixing and compaction temperatures of the control and modified asphalts based on their viscosities, as well as the performance grade for each asphalt binder.

TABLE 1 Mixing and compaction temperatures, as well as PG for the asphalt used

Asphalt Type	Mixing Temperature (°C)	Compaction Temperature (°C)	PG (High and Intermediate temperatures)
Control Asphalt	153-158	144-148	PG 64[25]
Control Asphalt + 3% NS	180-185	168-173	PG 76[28]
Control Asphalt + 6% NS	207-214	194-200	PG 82[28]

The aggregate used in this study was extracted from Guapiles River, Costa Rica. Two types of gradation were selected, both coarse dense graded, with nominal maximum size of 12.5 mm and 9.5 mm, since they are some of the most commonly used gradation types in Costa Rica. Table 2 shows the selected gradation of the aggregate and their bulk specific gravity (G_{sb}), apparent specific gravity (G_{sa}) and the percentage of absorbed asphalt (%Abs).

In total, six HMA mixtures were obtained, with three types of asphalt binder and two types of aggregate gradation. All the mixtures met the volumetric parameters requirements established in the Superpave design methodology. The asphalt content was from 6.2% to

7.0% (by total mass of mix), the voids in mineral aggregate (VMA) were around 14.3% to 15.8%, the voids filled with asphalt (VFA) ranged from 72.8% to 74.7% and the dust portion (DP) was on average 1.17.

The HMA samples for each laboratory test were compacted with the Superpave Gyratory Compactor (SGC), obtaining specimens with approximately 7% voids, considering the tolerance that each test permits.

TABLE 2 Gradation of aggregates used in the study and their G_{sb}, G_{sa} and %Abs

Sieve	Size (mm)	12.5 mm NMAS			9.5 mm NMAS		
		% Passing	Specification	PCS	% Passing	Specification	PCS
3/4"	19	100	100	-	100	-	-
1/2"	12.5	95.9	90-100	-	100	100	-
3/8"	9.5	84.7	90	-	94.7	90-100	-
N° 4	4.75	48.5	-	-	49.0	90	-
N° 8	2.36	32.6	28-58	39	32.7	32-67	47
N° 16	1.18	22.4	-	-	22.5	-	-
N° 30	0.6	16.0	-	-	16.0	-	-
N° 50	0.3	11.4	-	-	11.4	-	-
N° 100	0.15	7.9	-	-	7.8	-	-
N° 200	0.08	5.6	2-10	-	5.6	2-10	-
G_{sb}		2.612			2.612		
G_{sa}		2.808			2.811		
%Abs		2.673			2.716		

3. LABORATORY TESTS OF COMPACTED MIXTURES

3.4 Dynamic Modulus Test

Dynamic modulus of the asphalt mixture depends on the temperature and the frequency in the load application, given to its viscoelastic behavior. The test was conducted according to AASHTO TP 62-07 standard method on the Asphalt Mixture Performance Tester (AMPT) equipment, applying a sinusoidal compressive axial load and using various temperatures and frequencies [12]. Figure 1 shows the master curves obtained for each mixture at 21 °C reference temperature.

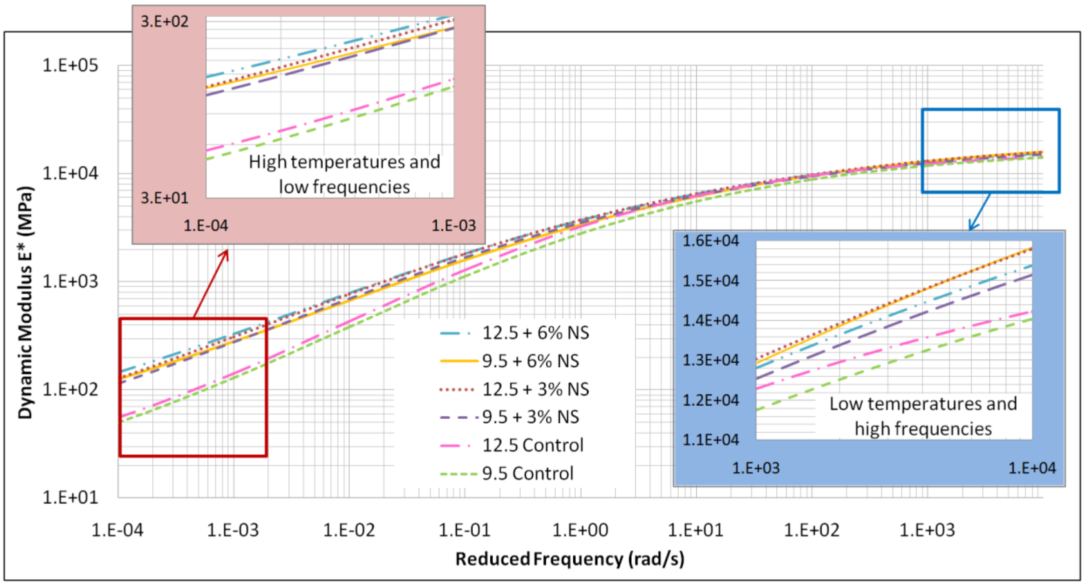

FIGURE 1 Dynamic modulus E* results and master curves of the HMA

Analyzing the dynamic modulus results, the NS modified mixtures exhibit greater modulus compared to the control mixtures. At high temperatures, the greatest increase in stiffness occurs when adding NS, therefore an improvement in permanent deformation resistance in the modified mixtures can be expected. The 12.5 mm mix with 6% NS and with 3% NS could have the best performance at high temperatures. At low and intermediate temperatures, the NS modified mixtures showed a little increase of stiffness in comparison to the control mixtures, which means that the addition of NS does not lead to a significant effect on fatigue and thermal cracking resistance of the HMA. Also, by adding 3% NS or 6% NS generated very little differences among the stiffness of the modified mixtures, therefore this could indicate that the effect of adding 3% NS or 6% NS is very similar.

3.1 Hamburg Wheel Tracking Test

This test quantifies the rutting and moisture damage susceptibility of the HMA. It is carried out by applying a repeated moving concentrated load in the Hamburg Wheel Tracking device and in accordance with AASHTO T 324-14 standard method. The test ends once 20 000 passes are reached or when the specimen reaches 20 mm deformation. This test method measures the rut depth and the number of passes to failure [13].

Figure 2 shows the deformation curves of the analyzed HMA, mixtures of both 9.5 mm and 12.5 mm showed a similar behavior, where the control mixtures presented the highest deformation, followed by the 3% NS mixtures and then the 6% NS mixtures. No inflection stripping point was observed in any of the curves, therefore, it was not possible to evaluate the moisture damage susceptibility by this test.

Analysis of variance (ANOVA) was used to study the effects of NS on the rutting resistance, and it showed that the decrease of the permanent deformation was due to the application of NS as a modifier, and the gradation type was not statistically significant. Also, a Tukey statistical analysis showed that there is no significant difference in the rutting resistance if the asphalt is modified using 3% NS or 6% NS.

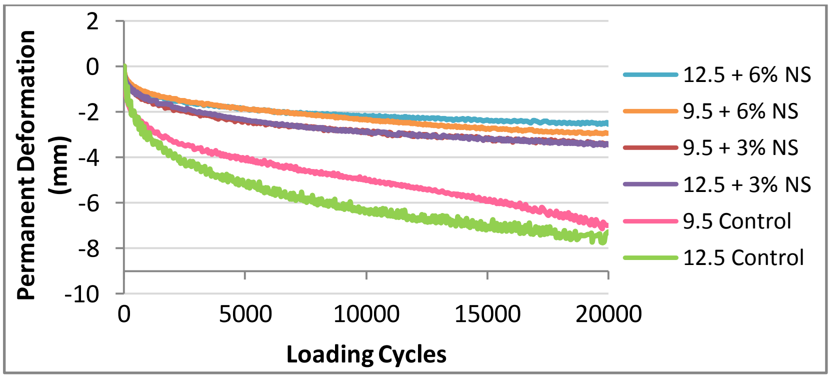

FIGURE 2 Deformation curves of the HMA analyzed

3.2 Repeated Semicircular Bending Test

RSCB test is used to determinate HMA fatigue resistance. This test does not have an official specification method, so the criteria for specimen preparation and test procedures were done following the recommendations made by Arrieta [14].

The test is conducted using a universal testing machine with a capacity of 25 kN (UTM-25), at 20 °C ± 0.5 °C. The test is performed in two stages, the first is known as semicircular bending test (SCB), where the maximum fracture load of the samples is obtained, by the application of a compressive load with a vertical displacement rate of

5 mm/min until the specimen failure. The second stage is the RSCB test, which consists in determining the number of load cycles that the samples resist by applying 50% of the maximum fracture load obtained previously, the load is applied as a haversine load with no rest period at 1 Hz frequency. The samples for both stage of the test were then prepared as a half-disk, with thickness of 40 mm with a notch of 15 mm long and 4 mm wide. Also, the specimens were long term aged (85 °C ± 3 °C for 120 hours) prior to conducting the test [14].

Table 3 summarizes the results of the test, where the 12.5 mm mix with 3% NS withstood the greatest amount of load cycles to failure, followed by the 9.5 mm and 12.5 mm control mixtures. The mix that presented the worst fatigue life resistance is the 12.5 mm mix with 6% NS. It is expected that the mixtures with low stiffness can withstand more load cycles, however the 12.5 mm mix with 3% NS had the highest fatigue resistance according to the RSCB test, despite having one of the highest stiffness among the analyzed mixtures. ANOVA was used to study the effects of NS on the HMA fatigue life, and it shows that addition of NS, gradation type or the interaction of both were not statistically significant.

TABLE 3 RSCB results for the HMA

HMA Type	Maximum fracture load (kN)		Fracture energy (kN*mm)		Number of load cycles	
	Average	Coefficient of variation	Average	Coefficient of variation	Average	Coefficient of variation
9.5 Control	2.29	7.80	6.78	20.55	**647**	17.14
9.5 + 3% NS	2.77	9.16	4.87	23.99	**565**	33.02
9.5 + 6% NS	2.80	14.05	3.43	17.85	**579**	20.74
12.5 Control	2.62	12.17	5.69	9.97	**616**	31.68
12.5 + 3% NS	2.78	4.19	4.73	4.89	**661**	8.99
12.5 + 6% NS	3.25	6.35	5.56	7.35	**411**	34.31

3.3 Indirect Tensile Strength Test

This test is conducted to measure the resistance of asphalt mixtures against moisture damage, according to AASHTO T 283-14 standard method and using dry and conditioned specimens. The test involves applying a compressive load across the diametrical axis of the samples, at a rate of 50.8 mm/min, so a nearly uniform state of tensile stress is achieved across the diametrical plane until failure [15].

At the end of the test, the maximum tensile strength of the dry and conditioned samples was obtained and the tensile strength ratio (TSR) was calculated. The specification stipulates a minimum TSR value of 80% to ensure the HMA resistance to moisture damage, which each of the mixtures satisfied as can be seen in Figure 3. In general, an increase in the TSR of all the modified HMA was obtained, the 12.5 mm mix with 6% NS presented the highest moisture damage resistance followed by the 9.5 mm mix with 3% NS.

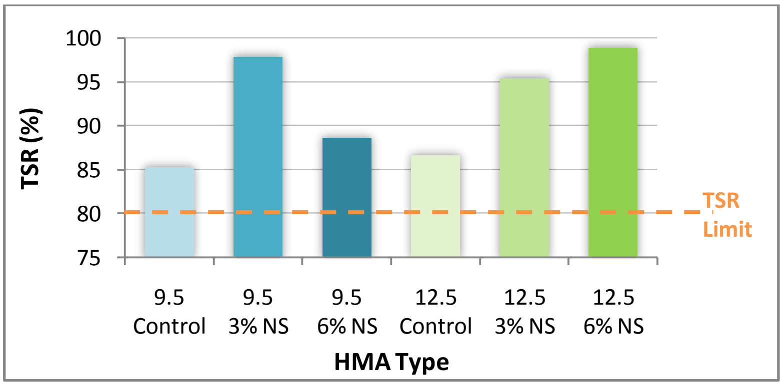

FIGURE 3 Tensile strength ratio of the HMA

3.5 Comparison of HMA performance

Based on the results of laboratory test performance, a ranking analysis was developed to select the mixture with the best overall performance. Table 4 shows all the mixtures ranked from 1 to 6 (1 meaning best performance). Asphalt mixtures modified with NS presented a better performance than control mixtures, and in terms of gradation, the 12.5 mm NMAS mixtures presented better performance. It is generally difficult to identify a mixture capable of resisting all the distresses simultaneously, however based on the overall ranked performance, the 12.5 mm mix with 6% NS showed the best performance followed by the 12.5 mm mix with 3% NS, while the worst score is shared by the two control mixtures.

TABLE 4 HMA performance ranking analysis

HMA Type	Laboratory Performance Test Ranking				Average	Rank
	Stiffness at 40 °C and 10 Hz (MD)	HWT	RSCB	ITS		
9.5 Control	6	5	2	6	4.75	5
9.5 + 3% NS	3	3	5	2	3.25	3
9.5 + 6% NS	4	2	4	4	3.50	4
12.5 Control	5	6	3	5	4.75	5
12.5 + 3% NS	2	4	1	3	2.50	2
12.5 + 6% NS	1	1	6	1	2.25	1

4. CONCLUSIONS

An experimental study has been carried out to characterize the performance of NS modified HMA, based on the study findings, the following conclusions have been drawn:

1. Modification with NS does help improve the performance of HMA. The addition of NS generated increases in HMA stiffness, especially at high temperatures; at low and intermediate temperatures the variation of the stiffness in comparison with the control mixtures is little.
2. An increase in permanent deformation resistance was obtained. The mixtures with 6% NS presented the least deformation, followed by the mixtures with 3% NS and at last the control mixtures. Also, the use of 3% NS or 6% NS does not show a significant difference on the permanent deformation resistance.
3. RSCB test results show that the incorporation of NS does not produce a statistically significant effect on the fatigue life of the mixtures.
4. In terms of moisture damage resistance, all modified mixtures improved, being the 12.5 mm mix with 6% NS the one that has the best resistance, followed by the 9.5 mm mix with 3% NS.
5. Based on the overall ranked performance, the 12.5 mm mix with 6 % NS showed the best performance, followed by the 12.5 mm mix with 3 % NS. However, when considering the manufacturing process of the mixture, transportation, placement and the economic cost of using NS as modifier, the 12.5 mm mix with 3 % NS can be recommended, since the incremental benefits with the 6 % NS modified mix are marginal.

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