VOL. 17, NO. 3, FEBRUARY 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ASSESSMENT OF THE MECHANICAL RESISTANCE OF AN AGED HOT MIX ASPHALT

Saieth Baudilio Chaves-Pabón[1], Hugo Alexander Rondón-Quintana[2] and Carlos Alfonso Zafra-Mejía[2]
[1]Universidad Militar Nueva Granada, Facultad de Estudios a Distancia, Programa de Ingeniería Civil, Cajicá, Colombia
[2]Universidad Distrital Francisco José de Caldas, Facultad del Medio Ambiente y Recursos Naturales, Bogotá D. C., Colombia
E-Mail: saieth.chaves@unimiltar.edu.co

ABSTRACT

Most studies regarding hot mix asphalts (HMA) are carried out with the purpose of evaluating their short-term mechanical resistance (in their initial state, just manufactured in the laboratory). However, the mechanical parameters of said mixes change when they age. This study carried out an experimental phase aimed at evaluating the effects of aging in mechanical resistance (under monotonic and cyclic load), moisture damage resistance and abrasion resistance of an HMA. For this purpose, Marshall, Indirect Tensile Strength, resilient modulus, permanent deformation, fatigue and Cantabro tests were performed. In order to simulate mix aging, STOA (Short Term Oven Aging) and LTOA (Long Term Oven Aging) processes were carried out as described according to the AASHTO R30 specification. A general conclusion drawn through the study is that when the HMA mix ages, it increases its resistance under monotonic and cyclic load, where it can be considered to have a good performance under certain conditions (e.g., high temperature climates and in pavements with thick asphalt layers). However, in regards to aspects associated to durability, the HMA can display undesirable behaviors (reduction of moisture damage resistance and abrasion resistance).

Keywords: aging, hot-mix asphalt, durability, mechanical properties, STOA, LTOA.

INTRODUCTION

Asphalt binder is a material obtained meanly as a derivate of petroleum. It is comprised by tens of thousands of chemical species and millions of different molecules [1]. This material changes its physical-chemical properties when it oxidizes or ages. When aged, it becomes fragile and brittle and loses its capacity of adhering to the aggregate. It contributes in producing early damage and pavement distresses (e.g. thermal cracking and cracking due to load fatigue, top-down type cracking - TDC, stripping, raveling, among others). This reduces durability in pavement structures, which increases repair and maintenance costs.

Asphalt binder aging mainly occurs during two stages that have been fully identified as “short” and “long” term. Short-term aging occurs mainly during mix manufacturing in the asphalt plant (including asphalt binder storage). During this stage asphalt binder is subjected to high temperatures (generally between 140 and 190 °C depending on asphalt binder viscosity), which generates thermal oxidation, volatilization of light compounds and rearrangement of the asphalt binder micro-structure [2-4]. This stage also includes the mix transportation process (from asphalt plant to construction site), and its placement (extension and compaction). Long-term aging occurs during the service life of the mix within pavement. In this stage, asphalt binder is mainly exposed to photo-oxidation due to the direct exposure to sunlight and ultraviolet (UV) radiation [5-6], accompanied by the oxidation produced by climate effects (temperature changes, moisture, evaporation, among others) [7]. According to [8-9], changes in micro-mechanical properties, adhesion properties and chemical properties are the more significant in long-term aging than in short-term aging.

There are several techniques for simulating asphalt binder aging [2, 10]. Some simulate asphalt binder aging and others simulate asphalt (mixture) aging. The most used for simulating short and long-term asphalt binder aging are thin film tests in RTFOT (Rolling Thin Film Oven Test; AASHTO T 240) and PAV (Pressure Asphalt Vessel, EN 14769), respectively. For the case of asphalt mixtues, the most used methods for such purposes are standardized STOA (Short Term Oven Aging) and LTOA (Long Term Oven Aging) procedures, respectively, which are proposed in AASHTO R30, based on studies carried out by [11-12]. In theory, STOA+LTOA processes simulate mix aging between 7 to 10 years of service [13].

Several studies have been carried out throughout the world in order to evaluate the effects of aging on mechanical properties of asphalt binders and asphalt mixtures. Some, more limited than others, but all of them aimed at continuing to deepen the discussion around the topic. This study aimed at this purpose, and because of this, it designed an experimental phase intended to evaluate the change undergo in mechanical properties of a hot-mix asphalt (HMA) when it ages. Likewise, aspects associated to mix durability were evaluated. Durability understood as the long-term capacity of a material to resist climate changes, aging, and the abrasive action of traffic [14-15]. For such purpose, tests for resistance under monotonic load (Marshall, Indirect Tensile Strength - ITS) and cyclic (Resilient modulus, permanent deformation and fatigue) were carried out in an unaged mix (named control), and likewise for short (STOA) and long (STOA+LTOA) term aged mixes. Moisture damage resistance tests were carried out (using the TSR resistance parameter - Tensile Strength Ratio) and wear resistance (abrasion loss in Cantabro test).

MATERIALS AND METHODS

Materials

The properties of the aggregate are shown on Table-1. The acronyms Sg, Abs, LA, M-D, 10%F, Fp, SA, PI, FI and EI denote specific gravity (AASHTO T 84, 91), absorption (AASHTO T 84, 91), Los Angeles Machine test (AASHTO T 96), Micro-Deval test (AASHTO T327), 10% of fines (crushing value, DNER-ME 096), fractured particles (ASTM D 5821-01), soundness of aggregate (AASHTO T 104), plasticity index (ASTM D4318), flattening index and elongation index (ASTM D 4791), respectively. The aggregate complies with the quality requirements established by [16] specification for manufacturing HMA mixes.

Asphalt cement (AC) is an AC 60/70 (65.2 mm of penetration at 25 °C, 100 g, 5 s - ASTM D5). Other properties of AC 60/70 are: softening point (ASTM D36) = 51.1 °C; penetration index (NLT 181/88) = -0.28; specific gravity (AASHTO T 228) = 1.01; ductility (25 °C, 5cm/min - ASTM D113) > 105 cm. The properties of AC 60/70 after subjecting it to aging processes in RTFOT (Rolling Thin Film Oven Test, ASTM D 2872) and RTFOT+PAV (Pressure Aging Vessel, ASTM D6521) are shown on Table-2. Regarding the unaged 60/70 asphalt cement (control) and subjecting it to aging processes in RTFOT and RTFOT+PAV viscosity tests were carried out (Figure-1) using a Rotational Viscometer (ASTM D4402). A notable increase in asphalt binder stiffness was observed when it ages (increases viscosity and softening point and decreases penetration). These physical changes in asphalt binder are coherent with those reported broadly in the referenced literature [5, 17-22]. The increase of Sg in aged asphalt binder is mainly due to the increase of molecular weight [23] and LMS (large molecular size) [9, 21, 23].

Table-1. Aggregate properties.

Test	Requirement	Value
Sg and Abs (coarse fraction)	-	2.63 and 1.4%
Sg and Abs (fine fraction)	-	2.54 and 1.7%
LA at 500 revolutions	25% maximum	22.2%
M-D	25% maximum	20.7%
10%F (dry condition)	110 kN minimum	135 kN
Fp (1 face); Fp (2 faces)	85%; 70% minimum	91%; 86%
SA (magnesium sulfate)	18% maximum	11%
PI	No plastic	No plastic
FI	10% maximum	7.1%
EI	10% maximum	4.0%

Table-2. AC 60/70 properties after RTFOT and RTFOT+PAV procedures.

Test	Method	Unit	Value
RTFOT			
Mass loss	ASTM D2872	%	0.36
Penetration (25 °C, 100 g, 5 s)	ASTM D5	0.1 mm	51.0
Softening point	ASTM D36	° C	55.3
Sg	AASHTO T 228	-	1.018
RTFOT+PAV			
Penetration (25 °C, 100 g, 5 s)	ASTM D5	0.1 mm	32.7
Softening point	ASTM D36	° C	59.8
Sg	AASHTO T 228	-	1.03

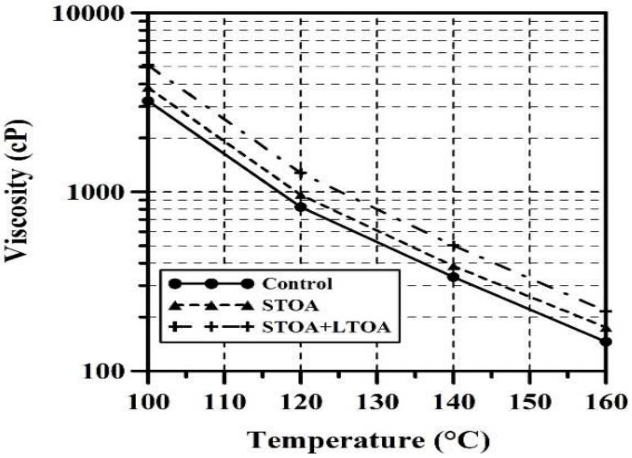


Figure-1. Viscosity curves.

Control Asphalt Mix Design

The control mix is type HMA with a maximum particle size of 19 mm (HMA-19 according to [16]). This is the type of mix that is most used in Colombia in order to comprise surface asphalt layers. The granulometry is shown in Figure-2. In order to manufacture HMA-19 mixes, the asphalt binder and aggregate were mixed and compacted (at 75 blows per face) at a temperature of 150 and 145 °C respectively, considering the results shown in the viscosity curve of control AC 60/70 (Figure-1). The samples manufactured were Marshall type and guidelines established by AASHTO T 245 were followed.

In regards to the mix design, four asphalt binder percentages (with relation to mass) were used (4.5, 5.0, 5.5 and 6.0%). For each asphalt binder percentage, five Marshall samples were manufactured and tested with the purpose of determining resistance under monotonic load (stability - S, flow - F, S/F ratio) and the volumetric composition (mainly air void content - Av and voids filled with asphalt - VFA). The results of the Marshall test are presented on Table-3. Considering the design criteria established by [16], the optimum asphalt content (OAC) is of 5.3%. This OAC was used in posterior phases of the project.

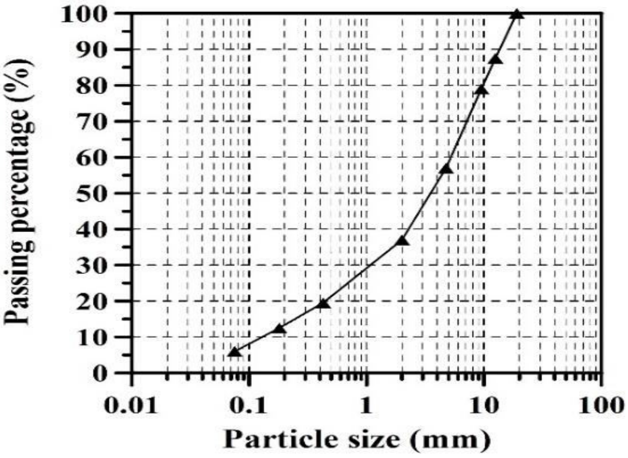


Figure-2. Particle size distribution curve.

Table-3. Marshall test for HMA-19 mixtures design.

AC (%)	Va (%)	VMA (%)	VFA (%)	S (kN)	F (mm)	S/F (kN/mm)
4.5	5.55	15.80	64.88	11.35	3.86	2.94
5.0	4.23	15.70	73.08	12.25	3.78	3.24
5.5	3.17	15.83	79.98	12.81	3.62	3.54
6.0	2.72	16.49	83.54	11.64	3.94	2.95

Short-Term and long-Term Aging Simulation

Using the OAC of 5.3%, short-term (STOA) and long-term (STOA+LTOA) Marshall samples were manufactured following the guidelines established by AASHTO R30. Those samples that were manufactured in the traditional manner (without aging) were named control. In order to conduct STOA processes, the asphalt mixture in a loose state was subjected to 135 °C in an oven for 4 hours and then compacted by applying 75 blows per face. In order to simulate long term aging process, each sample was initially subjected to the same STOA aging process previously described. Posteriorly each sample was subjected to a temperature of 85 °C in an oven for 5 days. These samples (control, STOA and STOA+LTOA) were used for the posterior phases of the study.

Marshall and ITS Tests

In order to evaluate monotonic load resistance of mixes, Marshall tests and Indirect Tensile Strength (ITS) were performed on the samples (control, STOA and STOA+LTOA) that were manufactured using the OAC. During both tests, AASHTO T 245 (Marshall test) and AASHTO T 283 (ITS test) guidelines were followed. Each parameter of the Marshall test (S, F, S/F, Av, VFA) was obtained by averaging the results obtained on three samples. On the other hand, the ITS test is generally performed on samples manufactured with an air void content between 7±0.5%. However, in this study, ITS was evaluated on samples that were manufactured based on their air void content obtained by design. As per each type of analyzed mix, three conditioned specimens were failed (ITSC) and other three under unconditioned specimens (ITSU). With the results obtained, moisture damage resistance was evaluated using the TSR ratio (Tensile Strength Ratio, in percentage) = (ITSC/ITSU) x 100.

Resilient Modulus, Permanent Deformation and Fatigue Resistance

In order to evaluate stiffness under cyclic load, resistance to permanent deformation and fatigue resistance on control mixes STOA and STOA+LTOA, Resilient Modulus tests were performed - RM (ASTM D4123), permanent deformation (UNE-EN 12697-25) and fatigue (UNE-EN 12697-24). These tests were carried out in a Nottingham Asphalt Tester (NAT). The test temperatures used in order to determine the RM were 10, 20 and 30 °C, and the load frequencies were of 2.5, 5.0 and 10.0 Hz. The accumulation of permanent deformations was measured on samples subjected to 40 °C and applying 3600 load cycles under a stress of 100 kPa and frequency of 0.5 Hz. Fatigue resistance was measured by applying the load mode in stress-controlled, under a test temperature and a load frequency of 20 °C and 10 Hz, respectively. Stress-controlled mode was chosen because in Colombia, HMA-19 mixes are generally used in order to comprise asphalt layers with a thickness superior to 3 inches. The failure criterion used in fatigue tests was capturing the number of cycles in which the total rupture of the sample was obtained (N_f). Each RM was determined based on the average of the results obtained on three samples. The accumulation of permanent deformations was obtained in a likewise manner. For the case of fatigue tests, each curve was determined based on the results obtained in nine samples.

Cantabro Test

Abrasion wear resistance in the Los Angeles machine for each sample (Cantabro Test) was calculated by following the guidelines established in the NLT 352 specification and measuring each 100, 300 and 500 cycles or spins around the drum. The percent of weight loss (Cantabro loss - CL) of each sample was calculated through the relationship of mass lost in the test after applying cycles and the sample's initial mass. The CL of each analyzed mix (control, STOA and STOA+LTOA) was calculated by averaging the results of three samples.

RESULTS

Marshall and ITS Tests

The results of the Marshall test is shown in Table-4. It is possible to observe a slight increase in the content of Av and a reduction of VFA when samples are subjected to STOA and STOA+LTOA aging processes. This behavior was also observed in the samples manufactured for the rest of tests. No mention in relation to this was found in the referenced literature. However, this increase in Av and decrease in VFA can be due to: i) during aging processes (oven heating), part of the components that are volatile, oleous and lighter in the asphalt binder are lost [19], even the asphalt binders Sg increases because asphaltenes begin to prevail [25-26] and molecular weight increases [23]; ii) additionally, a small content of asphalt binder is lost when adhered to the oven's grill that holds the samples when carrying out the STOA+LTOA process; iii) since the asphalt binder and aggregates remain in high temperature for longer periods, the probability of penetrating and adhering more easily to superficial pores increases. Despite the slight increase of Av, resistance under monotonic load of mixes increases (S increases and F decreases) as there is a greater aging induced upon mixes. This is mainly because of the increase of the asphalt binder stiffness as a product of its aging. S/F ratio increases 1.092 and 1.184 times with relation to the control mix when subjected to STOA and STOA+LTOA procedures, respectively. When comparing with the STOA process, S/F ratio is 1.084 times greater when samples are subjected to STOA and LTOA.

Table-4. Marshall test results.

Mixture	AC (%)	Av (%)	VMA (%)	VFA (%)	S (kN)	F (mm)	S/F (kN/mm)
Control	5.3	3.66	15.83	76.89	12.44	3.70	3.36
STOA	5.3	4.56	16.99	73.16	12.91	3.52	3.67
STOA+LTOA	5.3	4.64	17.00	72.74	13.59	3.42	3.98

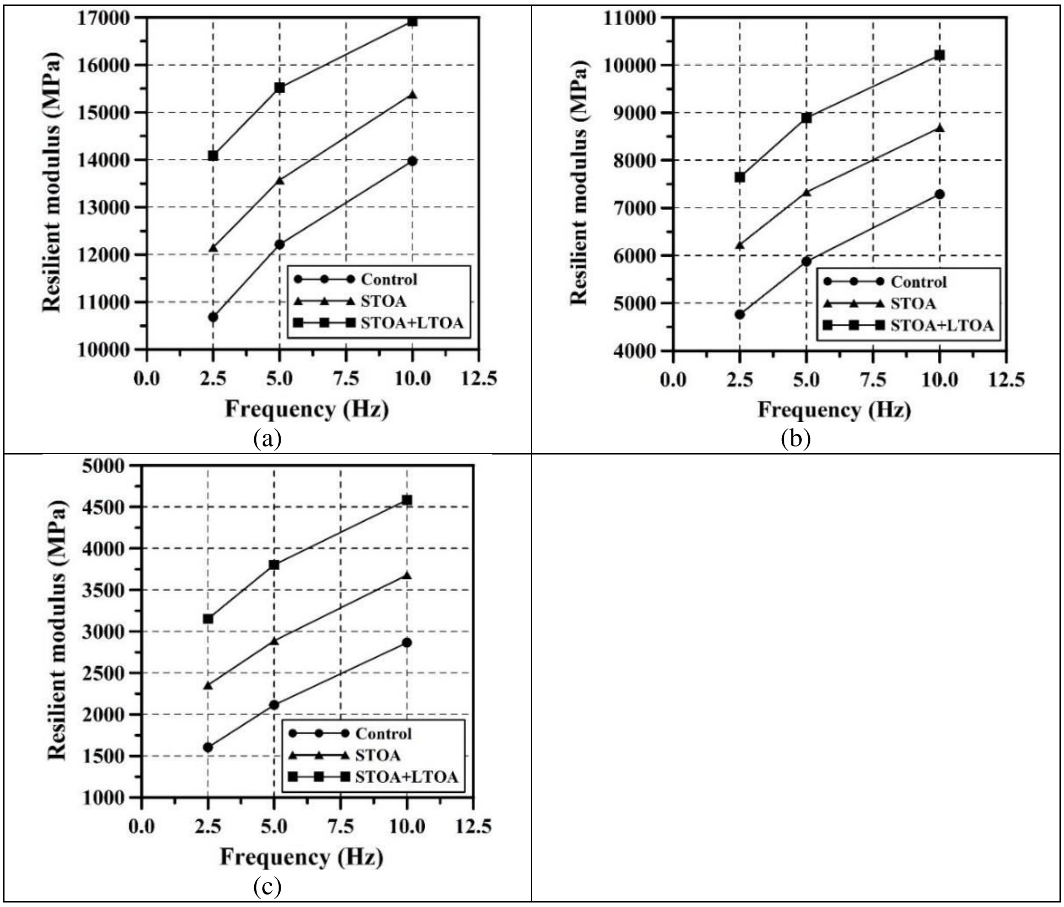
The results of the ITS test are shown on Table-5. An increase is observed in the ITS-U and ITS-C parameters as the aging of the mix increases. This is because, generally there is an increase reported in said parameters when the mix increases its stiffness [27-28]. Despite the above a drop in the TSR parameter is observed when the mix ages, which is an indicator of a decrease in moisture damage resistance. This can occur because during aging, asphalt binder reduces its capacity to adhere to aggregates [13, 29-32], as a product of the loss of oleous components in the asphalt binder that contribute with manageability, as well as the prevalence of asphaltenes (which increase stiffness) over other components that contribute with adherence such as resins [26, 33-35].

Table-5. ITS test results.

Mixture	AC (%)	Av (%)	ITS-U (kPa)	ITS-C (kPa)	TSR (%)
Control	5.3	3.82	1125.2	1073.1	95.4
STOA	5.3	4.46	1201.7	1078.4	89.7
STOA+LTOA	5.3	4.65	1296.6	1101.0	84.9

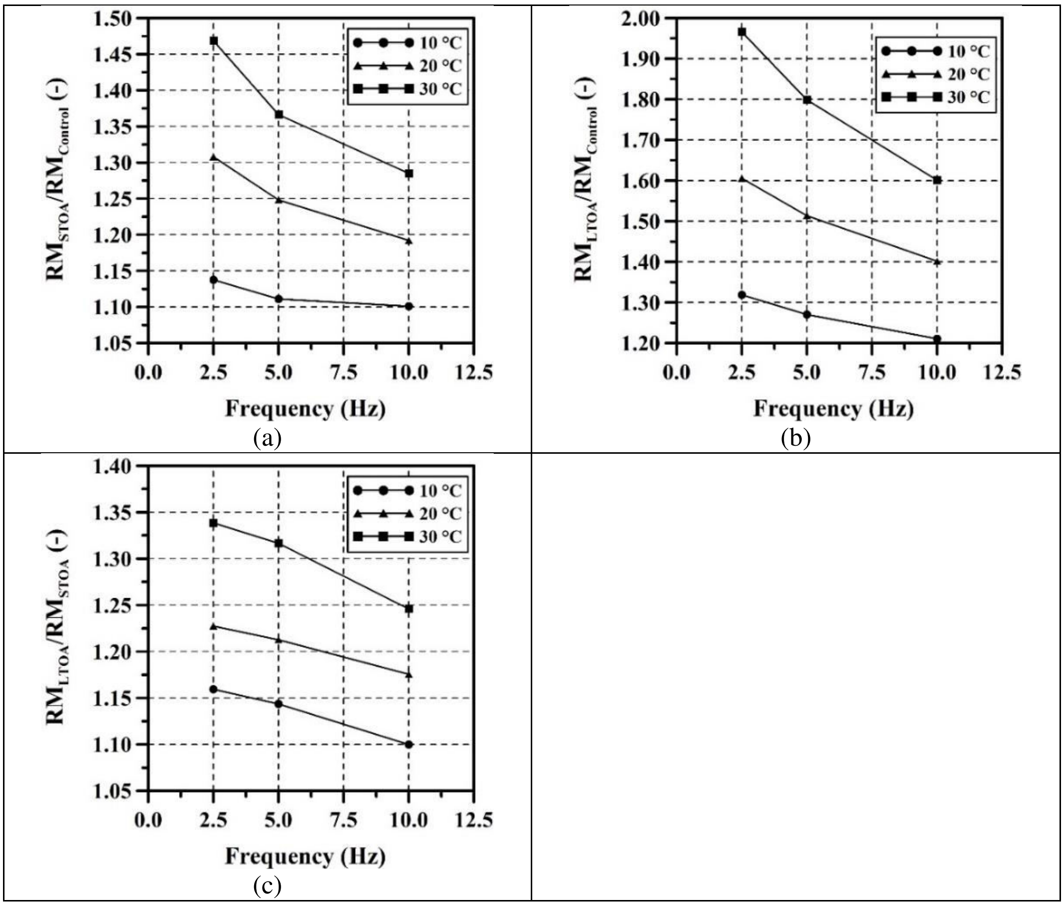
Resilient Modulus and Permanent Deformation

The RM values measured in the control mixes, STOA and STOA+LTOA are presented in Figure-3. When an asphalt ages, it increases its stiffness in such way as described above. A parameter used to evaluate the susceptibility of the mix for aging is the relationship between RM of the aged sample (STOA or STOA+LTOA) and the control mix (unaged) [36]. This relationship or increase of RM is greater when the test temperature increases and load frequency decreases (Figure-4). At 10 °C said relationship was in average (with relation to the values reported in each load frequency) of 1.117±0.019 and 1.267±0.054 times when STOA and STOA+LTOA processes are compared with relation to the control mix (Figure-4). These increases were of 1.249±0.058 and 1.507±0.102 for 20 °C and of 1.373±0.092 and 1.788±0.183 times for 30 °C. Additionally, the increase of RM in samples aged in STOA+LTOA is of 1.134±0.031, 1.205±0.027 and 1.30±0.048 times with relation to the STOA procedure for 10, 20 and 30 °C, respectively.



(a) (b) (c)

Figure-3. Resilient Modulus at a) 10 °C, b) 20 °C, c) 30 °C.



(a) (b)

(c)

Figure-4. Resilient modulus ratios for comparison. a) $RM_{STOA}/RM_{CONTROL}$, b) $RM_{LTOA}/RM_{CONTROL}$, c) RM_{LTOA}/RM_{STOA}.

Increases of asphalt stiffness and RM as a product of aging generate an increase in permanent deformation resistance (Figure-5). Some researchers mention that in some cases, a slight aging of asphalt can be good, given that it increases resistance to permanent deformation in high temperature climates [17, 37-38]. In the control HMA-19, the displacement in 3600 cycles is of 1.17 and 1.90 times with relation to the condition of STOA and STOA+LTOA, respectively. Said displacement is of 1.62 times in the STOA condition when compared to the STOA+LTOA procedure.

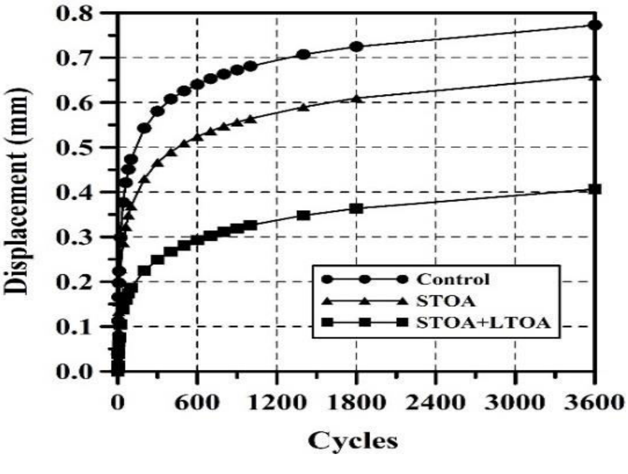


Figure-5. Permanent deformation.

Fatigue Resistance

When the load mode is stress-controlled and stiffness increases in mixes, generally, their fatigue resistance increases [39-41]. Fatigue curves of mixes are shown in Figure-6. A significant increase in fatigue resistance is observed when mixes age. On average, with relation to the control mix, N_f increases 1.694±0.058 and 2.133±0.046 when aged in STOA and STOA+LTOA, respectively. This increase in average is of 1.261±0.07 times when relating the N_f of the mix subjected to

STOA+LTOA with that of the one in STOA. Based on Figure-6, the amplitude of the stress for the material to fail at a million load cycles σ_6 is of 156.2, 251.9 and 343.5 kPa for control mixes, STOA and STOA+LTOA, respectively.

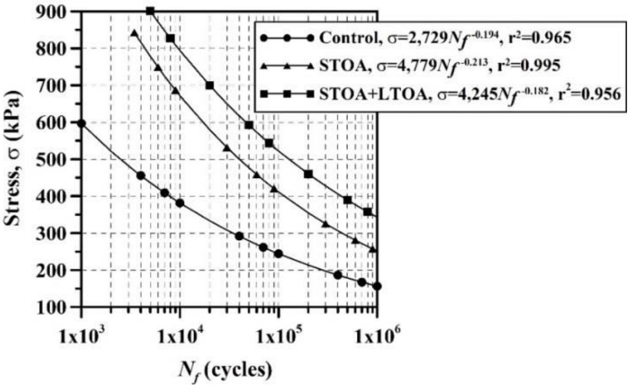


Figure-6. Fatigue Curves.

Cantabro Test

The results of the Cantabro test are showed in Table 6. An increase of the CL parameter is observed as the mix ages. In other words, it undergoes a reduction of abrasion wear resistance when aged. This could be because when asphalt binder ages, it reduces its capacity to adhere to the aggregate [42-46] and makes it more fragile and brittle, which leads it to become more susceptible to cracking under any type of abrasive load [47-49]. Additionally, when asphalt binder ages, the proportion of maltenes/asphaltenes is reduced, which in the end results in a more stiff and brittle binder [50-51].

Table-6. Cantabro test results.

Mixture	AC (%)	Av (%)	CL (%)		
			100 cycles	300 cycles	500 cycles
Control	5.3	4.12	2.20	3.27	4.87
STOA	5.3	4.71	2.55	4.23	5.60
STOA+LTOA	5.3	4.95	3.29	4.77	6.52

CONCLUSIONS

This study measured the changes undergo in mechanical properties, moisture damage resistance and abrasion damage resistance for an HMA mix when aged on short (STOA) and long term (STOA+LTOA). Based on the results obtained, conclusions are the following:

When asphalt binder ages it increases its stiffness. This generates a notable increase in mechanical resistance under monotonic load (increase in S/F ratio in the Marshall test and ITSU and ITSC parameters in the ITS test) and cyclic load (increase of RM, decease of displacement in permanent deformation test and an increase of fatigue life under stress-controlled) of the analyzed HMA. The above mentioned can be seen as an indicator of good performance for resisting vehicle loads in high temperature climates and in thick asphalt layers. However, in low temperature climates and in pavements comprised of thin asphalt layers, the opposite could occur. Additionally, in terms associated to durability, the mix did not undergo a good performance, given that upon aging, it tends to reduce its moisture damage resistance (reduction of TSR in the ITS test) and abrasion wear (increase of CL in the Cantabro test).

ACKNOWLEDGEMENTS

The results presented in this paper were obtained thanks to the financing of the research project INV-DIS-2965 (year 2019), granted by Vicerrectoría de Investigaciones de la Universidad Militar Nueva Granada. We also thank the support obtained from Universidad Distrital Francisco José de Caldas.

REFERENCES

[1] Redelius P. and Soenen H. 2015. Relation between bitumen chemistry and performance. Fuel. 140: 34-43.

[2] Airey G. D. 2003. State of the art report on ageing test methods for bituminous pavement materials. International Journal of Pavement Engineering. 4(3): 165-176.

[3] Chiu C. T., Tia M., Ruth B. E. and Page G. C. 1994. Investigation of laboratory aging processes of asphalt binders used in Florida. Transportation Research Record. 1436: 60-70.

[4] Lu X. and Isacsson U. 2002. Effect of ageing on bitumen chemistry and rheology. Construction and Building Materials. 16: 15-22.

[5] Zadshir M., Hosseinnezhad S., Ortega R., Chen F., Hochstein D., Xie J., Yin H., Parast M. M. and Fini E. H. 2018. Application of a biomodifier as fog sealants to delay ultraviolet aging of bituminous materials. Journal of Materials in Civil Engineering. 30(12): 04018310.

[6] Zhang H., Chen Z., Xu G. and Shi C. 2018. Evaluation of aging behaviors of asphalt binders through different rheological indices. Fuel. 221: 78-88.

[7] Chaves-Pabón S. B., Rondón-Quintana H. A. and Bastidas-Martínez, J.G. 2019. Aging of asphalt binders and asphalt mixtures. Summary part I: effect on physical-chemical properties. International Journal of Civil Engineering and Technology (IJCIET). 10(12): 259-273.

[8] Mikhailenko P., Kou C., Baaj H., Poulikakos L., Cannone-Falchetto, A., Besamusca, J. and Hofko, B. 2019. Comparison of ESEM and physical properties of virgin and laboratory aged asphalt binders. Fuel. 235: 627-638.

[9] Qtaish L. A., Nazzal M. D., Abbas A., Kaya S., Akinbowale S., Arefin M. S. and Kim S. S. 2018. Micromechanical and chemical characterization of foamed warm-mix asphalt aging. Journal of Materials in Civil Engineering. 30(9): 04018213.

[10] Chaves-Pabón S. B., Rondón-Quintana H. A. and Bastidas-Martínez, J. G. 2019a. Aging of asphalt binders and asphalt mixtures. Summary part II: aging simulation and aging reduction techniques. International Journal of Civil Engineering and Technology (IJCIET). 10(12): 274-287.

[11] Bell C., Wieder A. and Fellin M. 1994. Laboratory Aging of Asphalt-Aggregate Mixtures: Field Validation. Strategic Highway Research Program Report No. SHRP-A-390, Washington DC: National Research Council.

[12] Von Quintus, H. L., Scherocman, J. A., Hughes, C. S. and Kennedy, T. W. 1991. Asphalt-aggregate mixture analysis system. NCHRP Report 338, Transportation Research Board, National Research Council, Washington, DC.

[13] Tauste R., Moreno-Navarro F., Sol-Sánchez M., Rubio-Gámez M. C. 2018. Understanding the bitumen ageing phenomenon: A review. Construction and Building Materials. 192: 593-609.

[14] Finn F. N. 1967. Factors involved in the design of asphaltic pavement surfaces. NCHRP Rep. 39, Transportation Research Board, Washington, DC.

[15] Sholz T. V. 2015. Durability of bituminuos paving mixtures. PhD tesis, University of Notthingham, UK.

[16] INVIAS - Instituto Nacional de Vías. 2020. Especificaciones Generales de Construcción de Carreteras. Bogotá D.C., Colombia.

[17] Gómez-Meijide B., Ajam H., Lastra-González P. and Garcia A. 2018. Effect of ageing and RAP content on the induction healing properties of asphalt mixtures. Construction and Building Materials, 179:468–476.

[18] Jiang H., Zhang J., Sun C., Liu S., Liang M. and Yao Z. 2018. Experimental assessment on engineering properties of aged bitumen incorporating a developed rejuvenator. Construction and Building Materials. 179: 1-10.

[19] Nobakht M. and Sakhaeifar M. S. 2018. Dynamic modulus and phase angle prediction of laboratory aged asphalt mixtures. Construction and Building Materials. 190: 740-751.

[20] Qu X., Liu Q., Guo M., Wang D. and Oeser M. 2018. Study on the effect of aging on physical properties of asphalt binder from a microscale perspective. Construction and Building Materials. 187: 718-729.

[21] Zadshir M., Hosseinnezhad S. and Fini E. H. 2019. Deagglomeration of oxidized asphaltenes as a measure of true rejuvenation for severely aged asphalt binder. Construction and Building Materials. 209: 416-424.

[22] Zhang L., Liu Q., Wu S., Rao Y., Sun Y., Xie J. and Pan P. 2018a. Investigation of the flow and self-healing properties of UV aged asphalt binders. Construction and Building Materials. 174: 401-409.

[23] Moraes R. and Bahia H. U. 2015. Effect of mineral filler on changes in molecular size distribution of asphalts during oxidative ageing. Road Materials and Pavement Design. 16(S2): 55-72.

[24] Smith B. T. and Howard I. L. 2019. Comparing laboratory conditioning protocols to longer-term aging of asphalt mixtures in the Southeast United States. Journal of Materials in Civil Engineering, 31(1):04018346.

[25] Hou X., Xiao F., Wang J. and Amirkhanian S. 2018. Identifiation of asphalt aging characterization by spectrophotometry technique. Fuel. 226: 230-239.

[26] Shiau J. M., Tia M., Ruth B. E. and Page G. C. 1991. Characterization of age-hardening potential of asphalt by using Corbett-Swarbrick asphalt fractionation test. Transportation Research Record. 1323: 53-60.

[27] Molenaar A. A. A. and Li N. 2014. Prediction of compressive and tensile strength of asphalt concrete. International Journal of Pavement Research and Technology. 7: 324-331

[28] Teltayev B. and Radovskiy B. 2018. Predicting thermal cracking of asphalt pavements from bitumen and mix properties, Road Materials and Pavement Design. 19(8): 1832-1847.

[29] Kim O. K., Bell C. A., Wilson J. E. and Boyle G. 1987. Development of laboratory oxidative aging procedures for asphalt cements and asphalt mixtures. Transportation Research Record, 1115: 101-112.

[30] Subhy A., Pires G. M., Lo Presti D. and Airey G. 2018. The effects of laboratory ageing on rheological and fracture characteristics of different rubberised bitumens. Construction and Building Materials. 180: 188-198.

[31] Diab A., Enieb M. and Singh D. 2019. Influence of aging on properties of polymer-modified asphalt. Construction and Building Materials. 196: 54-65.

[32] Zhang F., Muhammad Y., Liu Y., Han M., Yin Y., Hou D. and Li J. 2018b. Measurement of water resistance of asphalt based on surface free energy analysis using stripping work between asphalt-aggregate system. Construction and Building Materials. 176: 422-431.

[33] Mastrofini D. and Scarsella M. 2000. The application of rheology to the evaluation of bitumen ageing. Fuel. 79: 1005-1015.

[34] Zaidullin I. M., Petrova L. M., Yakubov M. R. and Borisov D. N. 2013. Variation of the composition of asphaltenes in the course of bitumen aging in the presence of antioxidants. Russian Journal of Applied Chemistry. 86(7): 1070-1075.

[35] Sun S. S., Wang Y. M. and Zhang A. Q. 2011. Study on anti-ultraviolet radiation aging property of TiO2 modified asphalt. Advanced Materials Research. 306-307: 951-955.

[36] Yin F., Arámbula-Mercado E., Epps Martin A., Newcomb D. and Tran N. 2017. Long-term ageing of asphalt mixtures. Road Materials and Pavement Design. 18(sup1): 2-27.

[37] Ab Wahab Y., Sosnovske D., Bell, C. and Ryus P. 1993. Evaluation of asphalt-aggregate mixture aging by dynamic mechanical analysis. Transportation Research Record. 1386: 22-30.

[38] Khalid H. A. 2002. A new approach for the accelerated ageing of porous asphalt mixtures. Proceedings of the Institution of Civil Engineers, Transport. 153(3): 171-181.

[39] Rondón H. A. and Reyes F. A. 2015. Pavimentos - Materiales, Construcción y Diseño [Pavements: Materials, Construction and Design], Ed. ECOE, Bogotá D.C., Colombia.

[40] Rondón-Quintana H. A., Ruge-Cárdenas J. C., Bastidas-Martínez J. G., Velandia-Castelblanco M. Y. and Muniz De Farias, M. 2020. Use of thermally treated bentonite as filler in hot mix asphalt, Journal of Materials in Civil Engineering. 32(5): 1-10.

[41] Muniz de Farias, M., Quiñonez-Sinisterra, F. and Rondón-Quintana, H.A. 2019. Behavior of a hot-mix asphalt made with recycled concrete aggregate and crumb rubber, Canadian Journal of Civil Engineering. 46(6): 544-551.

[42] Hajj E., Sebaaly P. E. and Weitzel D. 2005. Fatigue characteistics of Superpave and Hveem mixtures. Journal of Tranportation Engineering. 131(4): 302-310.

[43] Kemp G. R. and Predoehl N. H. 1981. A comparison of field and laboratory environments of asphalt

durability. Proceedings of Association of Asphalt Paving Technologists. 50: 492-537.

[44] Raad L., Saboundjian S. and Minassian G. 2001. Field aging effects on fatigue of asphalt concrete and asphalt-rubber concrete. Transportation Research Record. 1767: 126-134.

[45] Rahmani E., Darabi E. M., Little D. N. and Masad E. A. 2017. Constitutive modeling of coupled aging-viscoelastic response of asphalt concrete. Construction and Building Materials. 131: 1-15.

[46] Vallerga B. A. 1981. Pavement deficiencies related to asphalt durability. Proceedings of Association of Asphalt Paving Technologists. 50: 481-491.

[47] Ling M., Luo X., Chen Y., Hud S. and Lytton R. L. 2019. A calibrated mechanics-based model for top-down cracking of asphalt pavements. Construction and Building Materials. 208: 102-112.

[48] Luo X., Gu F., Ling M. and Lytton R. L. 2018. Review of mechanistic-empirical modeling of top-down cracking in asphalt pavements. Construction and Building Materials. 191: 1053-1070.

[49] Tarefder R. A. and Arisa I. 2011. Molecular dynamic simulations for determining change in thermodynamic properties of asphaltene and resin because of aging. Energy Fuels. 25(5): 2211-2222.

[50] Moghaddam T. B. and Baaj H. 2016. The use of rejuvenating agents in production of recycled hot mix asphalt: a systematic review. Construction and Building Materials. 114:805–816.

[51] Zhang H., Gong M., Zhang G. and Yang B. 2018c. Analysis of asphalt durability based on inherent and improved performance. Construction and Building Materials. 181: 12-26.