Binder performance and testing

Evaluation of the fatigue life of modified bitumens aged under ultraviolet radiation

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Abstract

Bitumen aging has a great influence on asphalt mechanical properties, and due to this fact, current specifications establish limits for some indexes or aging parameters in an attempt to avoid the excessive hardening of the bitumen. However, such specifications do not take into account the effects of ultraviolet (UV) radiation on bitumen aging. The objective of this study is to assess the impact of thermo-oxidative and photo-oxidative aging methods on the rheological properties of a base bitumen and six modified bitumens, including the following modifiers: polyphosphoric acid, crumb rubber, SBS copolymer and low-density PE. The samples were previously aged in the rolling thin-film oven (RTFO). The fatigue performance was assessed by means of the results of the Linear Amplitude Sweep (LAS) test performed in the dynamic shear rheometer (DSR) at 25°C. An innovative approach based on the Linear Elastic Fracture Mechanics (LEFM) was used in the analysis of the results of the LAS test, which proved to be a good tool. The results pointed out that for low pavement strains (or deflections), the effect of the modifiers on the fatigue resistance is positive, particularly under UV radiation. The bitumen+rubber, followed by the bitumen+SBS, presented the best fatigue performance, and the neat binder presented the worst.

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1. INTRODUCTION

The thermoviscoplastic characteristics of the bitumen make it a semi-solid material at low temperatures, a viscoelastic material at room temperatures, and liquid at high temperatures [1]. Such material properties are very important, since the bitumen must be fluid enough to be pumped at high temperatures, along with being rigid enough to withstand the heavy traffic at high pavement temperatures – avoiding permanent deformation – and, at the same time, it must be elastic at intermediate and low temperatures – to resist fatigue and thermal cracking, respectively [2]. Such severe conditions to which the bitumen is subjected, during production operations and throughout the pavement lifespan, causes the natural hardening of the material, which impairs the mechanical behaviour of the asphalt. Bitumen hardening is related to changes in its composition that occur during aging in the plant and in the field, which involves the conversion of aromatics to asphaltenes, and the increase in the functional groups of carbonyls and sulfoxides [3].

In the bitumen aging process, UV radiation contributes to the reactions that occur on the pavement surface, forming an oxidized and brittle layer [4]. In order to evaluate the aging mechanism generated by exposure to UV radiation, Yamaguchi et al. [5] irradiated the components of the bitumen separately with UV light and observed that the saturated and aromatic are converted to resins and asphaltenes, resulting in carbonyl groups (functional groups containing oxygen), although saturates and aromatics are converted by different mechanisms. Those authors added carbon black to the bitumen, and found that it is able to prevent the conversion of saturates into carbonyls by the action of UV radiation. Taking into account the effects of additives and UV aging, Liu et al. [6] concluded that an asphalt prepared with a bitumen modified with layered double hydroxides (LDHs) showed higher fatigue resistance as compared to the asphalt containing neat bitumen. The authors also concluded that the bitumen containing LDH had higher resistance to oxidation and UV radiation than the unmodified ones.

Most of the studies of bitumen durability performed up to now are totally based on empirical measurements. However, these measurements may not provide adequate representation of the complex nature of the viscoelastic properties of the bitumen or even the changes caused by aging. In 2010, Johnson [7] proposed the Linear Amplitude Sweep (LAS) test to assess the ability of the bitumen to resist fatigue damage through reversible cyclic loading of increasing amplitude – such artifice has been used to accelerate damage. In 2013, the AASHTO TP 101-12-UL standard introduced a modification in the loading scheme proposed by Hintz [8] in 2012. Two procedures of analysis are described in the AASHTO TP 101-12-UL: the one using the viscoelastic continuous damage (VECD) theory, as proposed by Johnson [7], and another one using the damage tolerance index, as proposed by Hintz [8]. Another procedure of analysis, making use of an approach based on the Linear Elastic Fracture Mechanics (LEFM), was recently proposed by Nuñez et. al. [9] as an alternative to materials whose damage tolerance indices are not clearly defined.

The objective of this study is to analyze the impact of thermo-oxidative and UV aging methods on the rheological properties of a base bitumen and six bitumens prepared with additives (polymers, crumb rubber and polyphosphoric acid). The LAS test was employed in this study as a tool to assess the effect of aging, taking into account that aging is a factor that can impair the bitumen fatigue resistance. According to Bahia et al. [10], the fatigue damage of the bitumen increased after PAV aging, especially under low strains. Studies including a variety of modified bitumens are needed, as the influence of additives on the resistance to photo-oxidative aging is still not entirely known.

2. MATERIALS AND TEST PROCEDURES

In this experiment, six modified bitumens and one neat bitumen were short-term aged in the rolling thin film oven (RTFO), and subsequently subjected to two different long-term aging procedures: thermo-oxidative and photo-oxidative. The LAS test was performed in the aged residues in order to evaluate the effects of aging on the resistance to fatigue damage.

2.1 Materials

The formulations and the process conditions are detailed in Table 1. The following materials were used in the production of the modified bitumens: (i) the base bitumen supplied by the Replan-Petrobras Refinery (Paulinia, Sao Paulo, Brazil); (ii) the crumb rubber obtained by chopping tread peels of scrap passenger vehicle tires, with particles passing mesh #30; (iii) the polyphosphoric acid commercially designated Innovalt E-200 supplied by Innophos; (iv) the SBS copolymer, type TR-1101, with a polystyrene content of 31% (in mass), a density of 0.94, a tensile strength of 33 MPa, and an elongation at break of 880%; and (v) the low-density polyethylene type UB160-C.

2.2 Aging Procedures

The short-term aging was performed in the RTFO according to the procedure ASTM D 2872-12. The long-term thermo-oxidative aging was performed in the pressure aging vessel (PAV) according to the procedure ASTM D 6521-13. The method suggested in this work for the long-term thermo-oxidative aging is based on the exposure of a bitumen film to UV radiation, in an attempt to simulate the bitumen film that covers the mineral aggregate. The film thicknesses of the samples ranged from 0.43 to 0.44 mm. These thicknesses were calculated by multiplying 30 grams of bitumen by its density and dividing the result by the tray area (688 cm²).

The equipment used was the wetherometer produced by Q-LAB, model Q-SUN Xe-3, in which a set of filters is capable of cutting the light emanating from the xenon lamps at the wavelength of 295 nm. The spectrum of light radiated by the lamp comprises wavelengths from 295 to 800 nm, covering part of the UV-B range, the full UV-A range, the end of the visible light range, and the beginning of infrared range.

The photo-oxidative aging process was performed by setting a control point of irradiance at 0.68 W/m², which represents the maximum possible irradiance at a wavelength of 340 nm. Such an irradiance level was chosen to accelerate the degradation of the samples, but it does not correspond to the total irradiance applied to the samples. The total irradiance is the sum of the irradiance at each wavelength of the whole spectrum applied by the xenon arc lamp during the experiment time. The exposure time of the bitumen film to UV irradiation was 10 days (240 hours), and the temperature was set to 60°C for the black panel and 40°C for the chamber (air temperature). Such temperatures are intended to reproduce the high temperatures, respectively, on the top of the pavement and of the air in a hot climate. Figure 1 illustrates the trays with bitumen inside the wetherometer before conditioning and after the UV aging.

Table 1. Formulations and Process Conditions

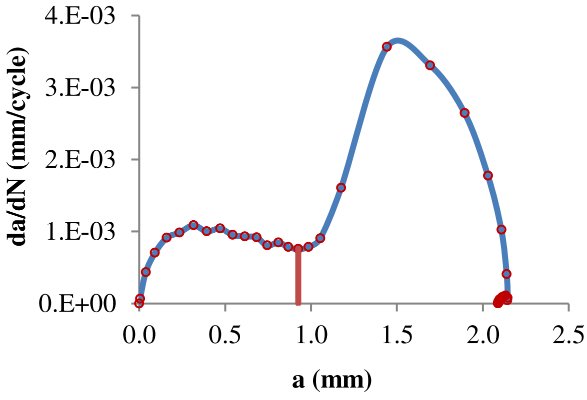
sample	percentages (in mass)			rotation (rpm)	temperature (°C)	time (minutes)
	AC	polymer	PPA			
bitumen+rubber	86.0	14.0	-	4.000	190	90
bitumen+rubber+PPA	88.5	11.0	0.5	4.000	190	120, PPA at 90
bitumen+SBS	95.5	4.5	-	4.000	180	120
bitumen+SBS+PPA	96.5	3.0	0.5	4.000	180	120, PPA at 60
bitumen+PE	94.0	6.0	-	440	150	120
bitumen+PE+PPA	96.5	3.0	0.5	400	150	120, PPA at 60

Figure 1: Bitumen films conditioned in the wetherometer under UV aging

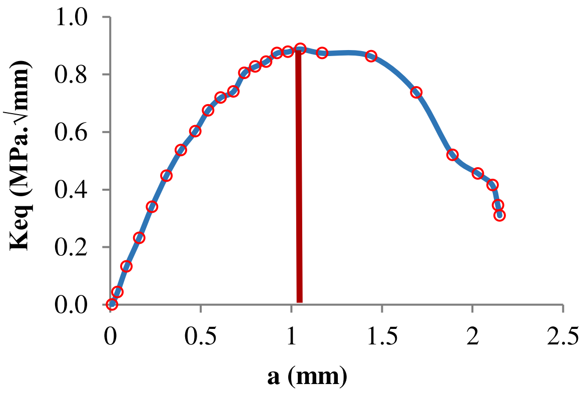
2.3 Linear Amplitude Sweep (LAS) Test

The LAS test was performed in a dynamic shear rheometer (DSR), according to the AASHTO TP 101-14, using the parallel-plate geometry of 8 mm in diameter and 2 mm in gap. The temperature of 25°C was adopted, as widely used in fatigue tests [11-13]. In the first step of the test, a frequency sweep from 0.2 to 30 Hz at a strain of 0.1% is applied to measure the rheological properties in the linear-viscoelastic region. In the second step, an amplitude sweep with linear increase ranging from 0.1 to 30% over 300 loading cycles during 300 seconds at 10 Hz is applied to determine the rheological properties in the damage region. The tests were performed in duplicate to ensure variability below 15%. Tests performed previously have shown that the stiffer the sample the higher the variability. The results were used to obtain the fatigue damage tolerance index (a_f) and to adjust the fatigue model $N_f = A.\gamma^{-B}$, where N_f is the number of cycles to failure, γ is the strain and A and B are material-dependent model constants. The results were also used to obtain the fatigue parameter based on Linear Elastic Fracture Mechanics (LEFM) as proposed by Nuñez et al. [9].

The constant A determines the integrity level of the material at failure with basis either on the trough of the curve da/dN versus a or on the peak of the material stress-strain curve. In turn, the constant B is related to the sensitivity of the bitumen to strain. Higher B values are associated with higher slopes of the fatigue curve, which indicate that the material is more sensitive to variations in pavement strains [14, 15]. The parameter a_f [8] represents the critical crack length at failure, and it is obtained as the trough in the curve of rate of crack growth (mm/cycle) versus crack length (mm). According to this criterion, the longer the crack length at failure the greater the fatigue tolerance, since it indicates that the bitumen can tolerate a larger cracking before failure. Figure 2(a) depicts an example of the determination of the parameter a_f, where the point indicated by the red line corresponds to a_f. In turn, the approach suggested by Nuñez et al. [9] uses the LEFM concepts to consider the macro-crack propagation in the material observed during the test. The failure criterion is the peak of the curve stress intensity factor (K) versus crack length (a). This parameter intends to represent the decrease in the stress amplitude due to rapid crack propagation and specimen failure by fatigue. Figure 2 (b) depicts an example of the determination of the parameter based on the LEFM approach, where the point indicated by the red line corresponds to the peak of the K vs a curve.



(a)



(b)

Figure 2: Determination of (a) the Fatigue Tolerance Index a_f, and (b) the Fatigue Parameter Based on LEFM - Tests Performed at 25°C Using a Pure Bitumen Aged Under UV Radiation at 0.68 W/m²

3. RESULTS AND FINDINGS

3.1 Damage tolerance index (a_f)

The damage tolerance indices for the three aging levels are shown in Table 2. In this table, the highest and the lowest indices are presented in bold. The damage tolerance indices of some materials were not presented because it was not possible to determine them. A possible explanation for such limitation, according to Safaei e Hintz [16], is the occurrence of adhesion problems between the sample and the metal plate or the predominance of flow over the cohesive fracture due to fatigue.

By comparing the damage tolerance indices for the three aging levels, one can observe that all modified bitumens showed a_f values greater than those of the base bitumen. In general, the a_f values of the samples aged in long-term are greater than those obtained for the samples aged in short-term. This shows that, for most materials, the higher the aging level the greater the tolerance of the materials to damage. By comparing the results of the samples aged in the PAV to those exposed to UV radiation, one can observe that all samples aged in the PAV presented a higher tolerance to damage.

Table 2. Damage Tolerance Indices

bitumen	RTFOT	PAV	UV
base bitumen	**0.95**	**0.96**	**0.87**
bitumen+rubber	**1.34**	1.18	**-**
bitumen+rubber+PPA	1.18	1.21	**-**
bitumen+SBS	1.10	1.30	**1.17**
bitumen+SBS+PPA	1.13	**1.35**	1.16
bitumen+PE	0.98	1.02	0.94
bitumen+PE+PPA	1.14	1.18	1.13

3.2 Analysis based on the viscoelastic continuum damage (VECD) theory

Table 3 presents the coefficients A and B of the fatigue model $N_f = A\gamma^{-B}$. The analysis of these data shows that the integrity of the materials, measured by the coefficient A, is higher after long-term aging PAV and UV, as compared to the short-term aging (RTFOT). For all aging levels, the base bitumen presented the lowest integrity. These results show that bitumen modification is able to increase the integrity of the base bitumen, and that integrity increases after long-term aging, both in the PAV and under UV radiation. Furthermore, the addition of PPA has improved the material integrity.

The results in Table 3 also show that long-term aging, both in the PAV and under UV radiation, acts to increase the B values, as compared to the results obtained with the materials aged only in short-term. In other words, the bitumens became more sensitive to pavement strain after long-term aging, what may impair the asphalt fatigue resistance. The base bitumen resulted the material with less sensitivity to pavement strain for all levels aging. These results show that bitumen modification increases the strain sensitivity of the materials, in direct opposition to the observed benefits of bitumen modification on integrity of the base bitumen. Figure 3 depicts a comparison of the estimated material fatigue life (N_f) at the strain levels of 3% and 30%. The low strain level is representative of pavements with low deflections, whose behavior resembles that of a rigid pavement, whereas the high strain level is representative of a pavement with high deflections, whose behavior resembles that of a flexible pavement. At a low strain level (3%), it is observed that the bitumen+rubber presents the longest fatigue life for both long-term aging levels. For high pavement strains (30%), the bitumen+rubber also presents the best performance for both long-term aging levels. The base bitumen presented low fatigue life at 3%, but it stands out well positioned at high strains in all the aging conditions. The results show that bitumen modification is generally positive at low strains, but only some modifiers are able to increase the fatigue life under high pavement strains.

Table 3. Coefficients A and B of the Fatigue Model $N_f = A.\gamma^{-B}$ - Results at 25°C

bitumen	RTFOT	PAV	UV
base bitumen	$4.5x10^5\gamma^{-3.35}$	$6.1x10^5\gamma^{-3.50}$	$5.0x10^5\gamma^{-3.36}$
bitumen+rubber	$4.1x10^6\gamma^{-3.72}$	$4.8x10^6\gamma^{-4.49}$	$2.6x10^7\gamma^{-4.45}$
bitumen+rubber+PPA	$5.2x10^6\gamma^{-3.70}$	$6.6x10^6\gamma^{-3.83}$	$5.4x10^7\gamma^{-5.24}$
bitumen+SBS	$6.7x10^5\gamma^{-3.62}$	$1.5x10^6\gamma^{-4.01}$	$1.6x10^6\gamma^{-3.65}$
bitumen+SBS+PPA	$9.1x10^5\gamma^{-3.64}$	$2.6x10^6\gamma^{-4.44}$	$3.4x10^6\gamma^{-3.96}$
bitumen+PE	$7.5x10^5\gamma^{-3.59}$	$1.2x10^6\gamma^{-3.81}$	$1.2x10^6\gamma^{-3.60}$
bitumen+PE+PPA	$1.3x10^6\gamma^{-3.87}$	$2.7x10^6\gamma^{-4.30}$	$1.5x10^6\gamma^{-3.94}$

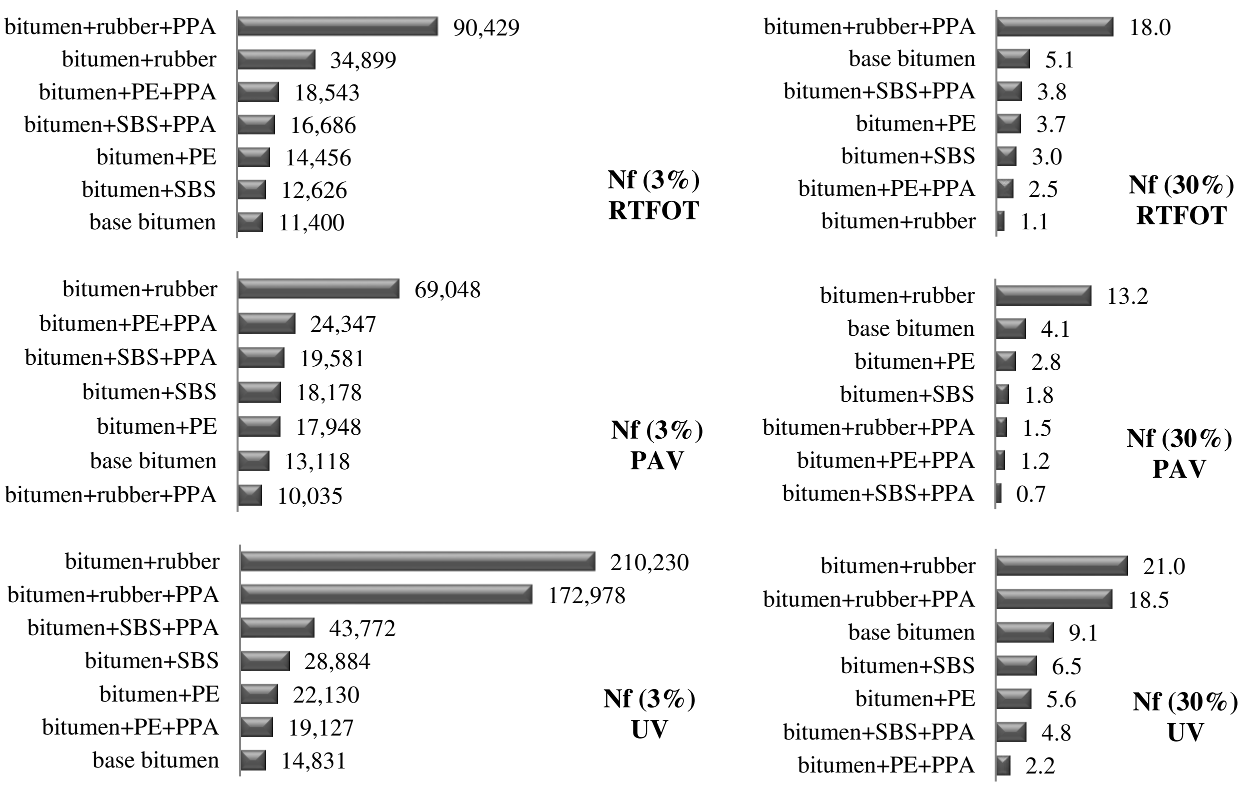


Figure 3: Ranking Order of N_f Values Estimated for a Strain Level of 3% and 30%

3.3 Analysis Based on the Linear Elastic Fracture Mechanics (LEFM) Approach

The crack length at failure given by the LEFM approach represents the reduction of the stress intensity factor due to the rapid increase of the crack length. In other words, it represents the specimen failure due to fatigue. In this analysis, the longer the crack length at failure the greater the bitumen fatigue resistance. The results of crack lengths at failure for the three aging levels are shown in Table 4.

Table 4. Crack Lenght at Failure According to the LEFM Approach

bitumen	RTFOT	PAV	UV
base bitumen	1.19	1.18	1.04
bitumen+rubber	1.46	1.26	1.37
bitumen+rubber+PPA	1.31	1.31	1.35
bitumen+SBS	1.18	1.34	1.40
bitumen+SBS+PPA	1.26	1.36	1.29
bitumen+PE	1.17	1.15	1.17
bitumen+PE+PPA	1.28	1.22	1.28

The results in Table 4 show that the crack length at failure of the modified bitumens is greater than those of the base bitumen, except for the bitumen+PE. This indicates that the use of modifiers increases the fatigue resistance, which complies with the conclusions drawn from the analyses based on the a_f and N_f values. The comparison between the results of the RTFO-aged samples with the PAV-aged ones did not show a clear trend. By comparing the results of the PAV-aged samples with the UV-aged samples, one can observe that most materials presented crack lengths at failure higher than those obtained for the PAV-aged samples, except for the base bitumen and the bitumen+SBS+PPA.

Given that it was not possible to obtain the parameter a_f of some materials, the use of the procedure based on the LEFM approach showed to be effective. According to the LEFM approach, all materials had their crack lengths at failure determined. As an example, Figure 4 (a) shows a curve of rate of crack growth versus crack length where the parameter a_f for the bitumen+rubber+PPA could not be clearly determined. On the other hand, it was possible to obtain the crack length of this material by applying the LEFM approach, as depicted in Figure 4 (b).

3.4 Ranking Order of the Materials Based on the Values of a_f, N_f (3%), N_f (30%), and a_{LEFM}

The rank order of the materials that are less sensitive to long-term aging (PAV and UV) was obtained considering the results for a_f, N_f at 3% strain, N_f at 30% strain, and the crack length based on the LEFM approach. The materials were ranked assuming that the best ones are those with the highest a_f values, the highest fatigue lives (N_f) and the highest crack lengths at failure based on the LEFM approach. As shown in Figure 5, the bitumen with the best fatigue performance is the bitumen+rubber, followed by bitumen+SBS. The neat bitumen occupies the last position in the ranking order, followed by the bitumen+PE. In the ranking order, it is also possible to see that most formulations without PPA are better positioned when compared with the formulations with PPA, which shows that the use of PPA in the formulations increased the susceptibility to long-term aging.

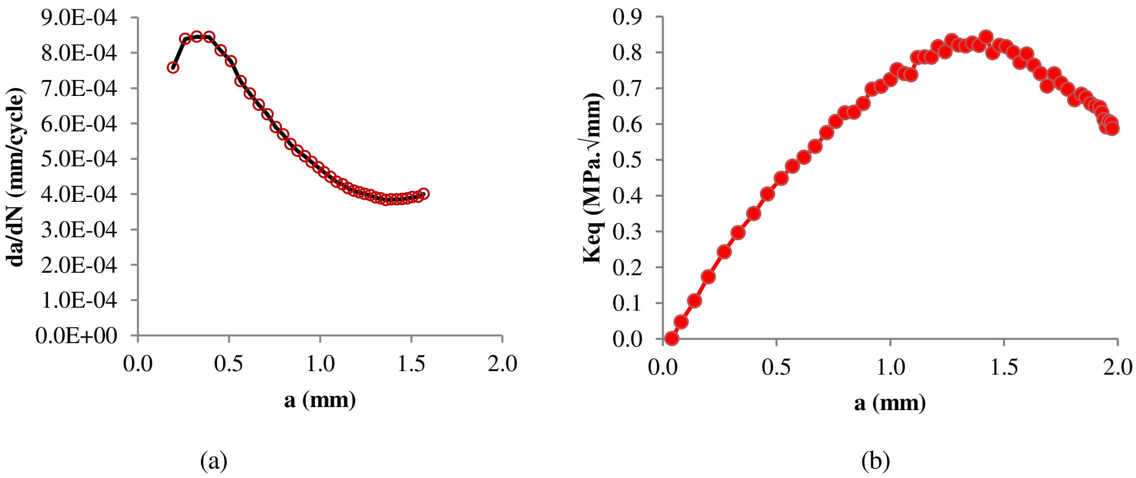


Figure 4: Comparison of the Application of the a_f and LEFM Approaches for the bitumen+rubber+PPA after UV aging

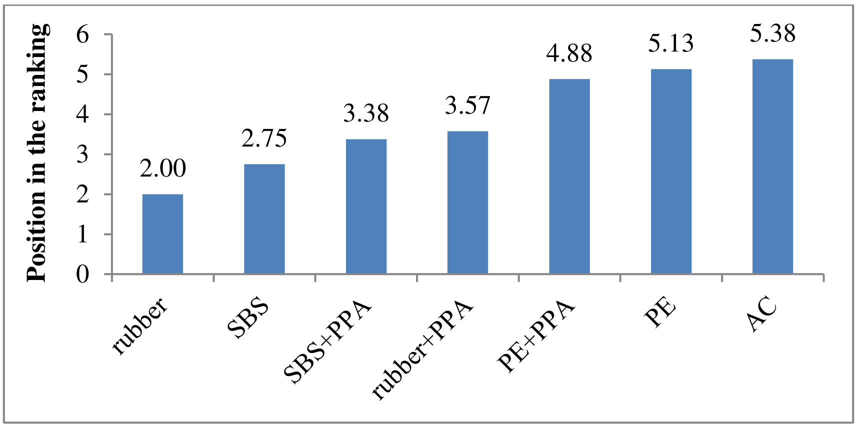


Figure 5: Final Ranking Order of the Materials Including All Long-term Aging Conditions

4. CONCLUSIONS

The following conclusions were drawn from this study:

- long-term aging (PAV) increased the damage tolerance index (a_f) as compared to short-term aging (RTFOT);
- bitumen modifiers were capable of increasing the damage tolerance indices: all modified bitumens presented higher a_f values as compared to the base bitumen;
- long-term aging (PAV and UV) increased the integrity (coefficient A of the fatigue model) of the bitumens; on the other hand, long-term aging increased the material strain dependency (parameter B) as compared to the short-term aged materials;
- for low strain levels (3%), the effect of the modifiers on the bitumen fatigue resistance is positive, particularly under UV radiation;
- at high pavement strains (30%), only some modifiers are able to increase the bitumen fatigue life, namely, rubber and rubber+PPA;
- the employment of the innovative analysis based on the LEFM approach showed to be an effective tool as compared to the analysis based on the damage tolerance index (a_f), mainly for those materials to which the former approach does not work;
- the ranking order based on the highest results of a_f, N_f at 3% strain, N_f at 30% strain, and the crack length using the LEFM approach indicated that the best fatigue performance was obtained by the bitumen+rubber, followed by the bitumen+SBS; the same ranking order indicated that the neat bitumen presented the worst fatigue performance, followed by the bitumen+PE; and
- the final ranking order showed that the addition of PPA to the formulations is detrimental, since it increased the sensitivity to long-term aging.

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REFERENCES

[1] Bernucci, L. B., L. M. G. Motta, J. A. P. Cerati and J. B. Soares. Pavimentação asfáltica: formação básica para engenheiros. Rio de Janeiro: *Petrobrás: ABEDA*, 2008.

[2] Lesueur, D. La Rhéologie des Bitumes: Principes et Modification. *Rhéologie*, Vol. 2, 2002, pp. 1-30.

[3] Qin, Q., J. F. Schabron, R. B. Boysen and M. J. Farrar. Field aging effect on chemistry and rheology of asphalt binders and rheological predictions for field aging. *Fuel*, Vol. 121, 2014, pp. 86-94. DOI: 10.1016/j.fuel.2013.12.040

[4] Silva, L. S., M. M. C. Forte, P. Bartolomeo, F. Farcas and F. Durrieu. Envelhecimento UV de ligantes asfálticos. *Revista Transportes.* Vol. XIII, No. 2, 2005, pp. 5-20. https://doi.org/10.14295/transportes.v13i2.100

[5] Yamaguchi, K., I. Sasaki and S. Meiarashi. Mechanism of asphalt binder aging by ultraviolet irradiation and aging resistance by adding carbon black. *Journal of Japan Petroleum Institute*, Vol. 47, No. 4, 2004, pp. 266-273. https://doi.org/10.1627/jpi.47.266

[6] Liu, X., S. Wu, L. Pang, Y. Xiao and P. Pan. Fatigue properties of Layered Double Hydroxides modified asphalt and its mixture. *Advances in Materials Science and Engineering*, Vol. 2014, 2014, 6 p. http://dx.doi.org/10.1155/2014/868404

[7] Johnson, C. M. *Estimating asphalt binder fatigue resistance using an accelerated test method*. Dissertation (Doctorate) – University of Wisconsin, Madison, 2010.

[8] Hintz, C. *Understanding Mechanisms Leading to Asphalt Binder Fatigue.* Dissertation (Doctorate) – University of Wisconsin, Madison, 2012. https://doi.org/10.1080/14680629.2013.818818

[9] Nuñez, J. Y. M., E. D. Leonel, A. L. Faxina. Fatigue characteristics of modified asphalt binders using fracture mechanics. *Engineering Fracture Mechanics.* Vol. 154, 2016, pp. 1-11. https://doi.org/10.1016/j.engfracmech.2016.01.001

[10] Bahia, H. U., H. Zhai, K. Bonnetti and S. Kose. Non-linear viscoelastic and fatigue properties of asphalt binders. *Association of Asphalt Paving Technologists*, Vol. 68, 1999, pp. 1-34.

[11] Bahia, H. U., D. I. Hanson, M. Zeng, M. Zhai, M. A. Khatri and R. M. Anderson. *Characterization of Modified Asphalt Binders in Superpave Mix Design*. National Cooperative Highway Research Program (NCHRP), Report 459, Washington, D.C, 2001.

[12] Shenoy, A. Fatigue Testing and Evaluation of Asphalt Binders using the Dynamic Shear Rheometer. *Journal of Testing and Evaluation*, Vol. 30, No. 4, 2002, pp. 03-312. DOI: 10.1520/JTE12320J

[13] Martono, W., H. U. Bahia and J. D´Angelo. Effect of Testing Geometry on Measuring Fatigue of Asphalt Binders and Mastics. *Journal of Materials in Civil Engineering*, Vol. 19, No. 9, 2007, pp. 746-752. https://doi.org/10.1061/(ASCE)0899-1561(2007)19:9(746)

[14] Nuñez, J. Y. M. *Caracterização à Fadiga de Ligantes Asfálticos Modificados Envelhecidos a Curto e Longo Prazo*. Dissertation (Master's degree). Engineering School of Sao Carlos, University of Sao Paulo. São Carlos, SP, 2013. DOI 10.11606/D.18.2013.tde-19112013-171029

[15] Pamplona, T. F. *Efeito da adição de ácido polifosfórico em ligantes asfálticos de diferentes fontes.* Dissertation (Master's degree). Engineering School of Sao Carlos, University of Sao Paulo. São Carlos, SP, 2013. DOI: 10.11606/D.18.2013.tde-29112013-084714

[16] Safaei, F. and Hintz, C. Investigation of the effect of temperature on asphalt binder fatigue. In Asphalt Pavements - *Proceedings of the International Conference on Asphalt pavements*, ISAP 2014, Vol.2, 2014, pp.1491-1500. DOI: 10.1201/b17219-181

Annex

ERRATA

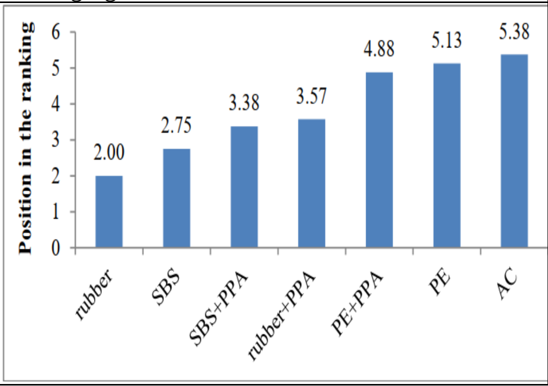
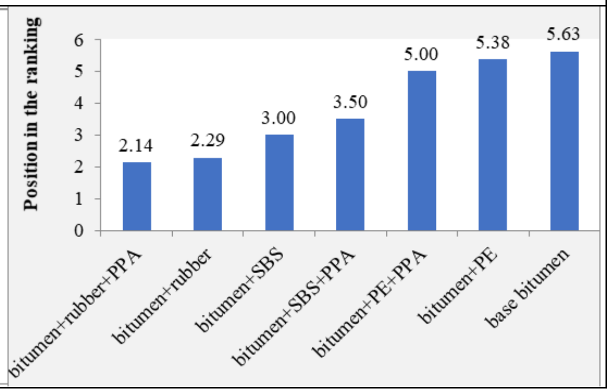
Abstract:

	In the paper	Corrected version
Line 13	The results pointed out that for low pavement strains (or deflections), the effect of the modifiers on the fatigue resistance is positive, particularly under UV radiation. The bitumen+rubber, followed by the bitumen+SBS, presented the best fatigue performance, and the neat binder presented the worst.	The results pointed out that at low pavement strains (or deflections), the effect of the modifiers on the fatigue resistance is positive for all aging conditions. The bitumen+rubber+PPA, followed by the bitumen+rubber, presented the best fatigue performance, and the neat binder presented the worst one.

Section 3.2 (Analysis based on the viscoelastic continuum damage (VECD) theory):

	In the paper	Corrected version
Figure 3	Nf (3%) PAV – bitumen+rubber+PPA = 10,035	Nf (3%) PAV – bitumen+rubber+PPA = 97,832
Figure 3	Nf (30%) PAV – bitumen+rubber+PPA = 1.5	Nf (30%) PAV – bitumen+rubber+PPA = 14.5
Line 14	At a low strain level (3%), it is observed that the bitumen+rubber presents the longest fatigue life for both long-term aging levels. For high pavement strains (30%), the bitumen+rubber also presents the best performance for both long-term aging levels.	At low strain level (3%) and high strain level (30%), the bitumen+rubber+PPA presents the longest fatigue life for the PAV condition, while the bitumen+rubber presents the longest fatigue life for the UV condition at both strain levels.

Section 3.4 (Ranking Order of the Materials Based on the Values of af, Nf (3%), Nf (30%), and aLEFM):

<table>
<tr><th></th><th>In the paper</th><th>Corrected version</th></tr>
<tr><td>Line 4</td><td>As shown in Figure 5, the bitumen with the best fatigue performance is the bitumen+rubber, followed by bitumen+SBS.</td><td>As shown in Figure 5, the bitumen with the best fatigue performance is the bitumen+rubber+PPA, followed by bitumen+rubber.</td></tr>
<tr><td>Line 6</td><td>In the ranking order, it is also possible to see that most formulations without PPA are better positioned when compared with the formulations with PPA, which shows that the use of PPA in the formulations increased the susceptibility to long-term aging</td><td>Most of the formulations with PPA are better positioned in the ranking order when compared with the formulations without PPA, which shows that the use of PPA decreased the susceptibility to long-term aging.</td></tr>
<tr><td>Figure 5</td><td>
</td><td>
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Section 4 (Conclusions):

	In the paper	Corrected version
Line 8	for low strain levels (3%), the effect of the modifiers on the bitumen fatigue resistance is positive, particularly under UV radiation;	at low strain levels (3%), the effect of the modifiers on the bitumen fatigue resistance is positive for all aging levels;
Line 15	the ranking order based on the highest results of af, Nf at 3% strain, Nf at 30% strain, and the crack length using the LEFM approach indicated that the best fatigue performance was obtained by the bitumen+rubber, followed by the bitumen+SBS;	the ranking order based on the highest results of af, Nf at 3% strain, Nf at 30% strain, and the crack length using the LEFM approach indicated that the best fatigue performance was obtained by the bitumen+rubber+PPA, followed by the bitumen+rubber;
Line 19	the final ranking order showed that the addition of PPA to the formulations is detrimental, since it increased the sensitivity to long-term aging.	the final ranking order showed that the addition of PPA to the formulations is positive since it decreased the sensitivity to long-term aging.