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Susceptibility of low-density polyethylene and polyphosphoric acid-modified asphalt binders to rutting and fatigue cracking

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HIGHLIGHTS

- Asphalt binders modified with PE and PPA were evaluated in the MSCR and LAS tests.
- Asphalt binder modification increases damage tolerance of the unmodified material.
- For low strains, the modified binders are less susceptible to fatigue after aging.
- The AC + PPA formulation showed the highest fatigue and rutting resistances.
- The formulations have higher elastic response and lower susceptibility to rutting.

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ABSTRACT

Fatigue and rutting properties of asphalt binders modified with low-density polyethylene and polyphosphoric acid (PPA) were investigated. The modifier contents were chosen such that the high-temperature performance grade is the same for all formulations in the Superpave® specification (PG 76-xx). The linear amplitude sweep (LAS) for fatigue and the multiple stress creep and recovery (MSCR) for rutting were performed. The modified binders have better rheological properties than the base material and show different rutting and fatigue behaviors, even though their high PG grades are the same. The results indicated that PPA is a great alternative to be used as binder modifier.

1. Introduction

Asphalt binder modification is an alternative to improve the original properties characteristics of the material and therefore increase its resistance to the main pavement distress mechanisms such as fatigue cracking and rutting. Polyphosphoric acid (PPA) and polyethylene (PE) are some examples of binder modifiers available for application. There is evidence that the incorporation of PPA into the asphalt binder can improve the rheological behavior of the material at high-temperatures [1,2]. Other authors observed that, despite the benefit of the presence of PPA in the formulation, this modifier may negatively affect the resistances of the unmodified material to fatigue and low-temperature cracking [3]. PE is one of the most popular plastics around the world and is renowned for its excellent chemical and good fatigue resistances [4]. The addition of PE can also reduce creep rate of asphalt mixtures at high temperatures [5] and increase the original Superpave® rutting parameter $G^*/\sin\delta$ (complex modulus G^* divided by the sine of phase angle δ) [6], thereby reducing the susceptibility of the bituminous material to rutting.

Fatigue cracking is one of the most common distress mechanisms of asphalt pavements. It is caused by the application of cyclic loads at intermediate temperatures [7]. Several researchers have made effort to understand the fatigue behavior of asphalt binders by using different theoretical models, criteria and laboratory tests [8,9]. The Superpave® specification for asphalt binders establishes maximum allowed values for the parameter $G^*\sin\delta$ (G^* multiplied by the sine of δ) in an attempt to avoid the premature growth of fatigue cracking in asphaltic layers. However, the literature suggests that this parameter is not adequate to characterize the fatigue behavior of asphalt binders [7,8].

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Alternative tests have emerged with the aim of replacing the parameter $G^* \cdot \sin\delta$ and providing a better description of the fatigue behavior of asphalt binders [10–12]. One of these alternatives is the time sweep test [10]. It provides a reasonable analysis of the fatigue behavior of the material, even though it is a time-consuming. To overcome this problem, an accelerated test called linear amplitude sweep (LAS) was proposed [11]. Recently, modifications in the LAS test protocol have been introduced in both the loading scheme and the procedure to analyze the results [12].

Another distress commonly found in asphalt pavements is the accumulation of permanent deformation in the wheel paths, which is referred to as "rutting" in the North American convention. The contribution of the asphalt binder to the resistance of the hot-mix asphalt (HMA) mixture to rutting was initially evaluated in the Superpave® specification by means of the parameter $G^*/\sin\delta$ [13]. Some years later, this parameter was replaced by the nonrecoverable compliance J_{nr} obtained in the multiple stress creep and recovery (MSCR) test due to several shortcomings, e.g., lack of correlation with rutting measurements on asphalt mixtures, loading type, loading level and strain levels measured in the binder [14,15].The percent recovery R obtained in the MSCR test can directly measure the elastic response of the asphalt binder under creep and recovery loading. Percent recovery values are also used to indicate the presence of a polymer network in the formulation [15,16].

The current MSCR test utilizes a dynamic shear rheometer (DSR) to first apply a constant load for 1-s loading time, followed by a 9-s recovery time in which no load is applied. This creep–recovery procedure is repeated 10 times at each of the 0.1 and 3.2 kPa stress levels, and the test is started at the lowest level. The R and the J_{nr} values obtained in the cycles are averaged to yield the final results, and the J_{nr} values at 0.1 and 3.2 kPa are used to determine the percent difference in nonrecoverable compliances ($J_{nr,diff}$). This parameter is used in the Superpave® specification as a criterion to reject asphalt binders that are too stress sensitive, which is not desirable for paving applications due to a greater susceptibility of such materials to rutting in unfavorable temperature and/or loading conditions [17].

By considering these recent developments in the characterization of asphalt binders, the fatigue and rutting behaviors of modified asphalt binders were analyzed in the LAS and the MSCR tests. The modifiers were added to a 50/70 base asphalt binder to achieve the same high-temperature performance grade. In order to evaluate the behavior of the material under several climate and aging conditions, such as those actually found in the field, various test temperatures were used in the MSCR test and two aging conditions were considered in the LAS test.

2. Materials and methods

To prepare the modified asphalt binders, the following materials were used: (a) a 50/70-penetration grade base asphalt binder supplied by the Replan–Petrobras refinery (Paulinia, Sao Paulo, Brazil) and graded as PG 64-xx; (b) low-density PE designated as UB-160C; (c) PPA designated as E200. The mixtures were prepared using a Fisatom 722D low-shear mixer. Table 1 shows the modifier contents and the processing conditions. The modifier contents were selected in order to achieve the same high-temperature performance grade for all the formulations – PG 76-xx – according to the version of the Superpave® specification in the AASTHO standards [18]. The LAS and the MSCR tests were performed on a DSR model AR-2000ex.

2.1. Linear amplitude sweep (LAS) test

The LAS test utilizes the parallel plate geometry of 8 mm in diameter and 2 mm in gap height. The procedure that was recently standardized by AASTHO [19] consists of applying a reverse cyclic loading in two stages: (a) a frequency sweep with the application of a constant strain of 0.1% and frequencies ranging from 0.2 to 30 Hz; and (b) a linear amplitude sweep with linear strain increments from 0% to 30% within a time interval of 300 s and at constant frequency of 10 Hz. The tests were conducted at 25 and 35 °C and in two aging conditions, i.e., short-term aging (RTFOT, ASTM D2872-04 [20]) and long-term aging (PAV, ASTM D6521-08 [21]).

Two analyzes can be made based on the test results: (a) the viscoelastic continuum damage (VECD) approach [11]; and (b) the fracture analysis and the damage tolerance index [12]. In the first analysis, power models are fitted based on the general model given by Eq. (1):

$$N_f = A_{35} \times \gamma^B, \tag{1}$$

where N_f is the number of cycles to failure, γ is the applied shear strain and the parameters A_{35} and B are experimentally defined. The failure criterion in the second analysis is the parameter a_f, that is, the minimum local point of the relationship between da/dN (variation rate of crack length a with the number of cycles N) and a (the crack length). This a_f value corresponds to the point before a rapid increase in the crack growth rate is observed [12].

2.2. Multiple stress creep and recovery (MSCR) test

The MSCR tests (ASTM D7405-10a [22]) were conducted on the same DSR used on the fatigue tests. Samples with a diameter of 25 mm and a gap height of 1 mm were subjected to standardized loading–unloading conditions – 1-s creep time, 9-s recovery time, 10 creep–recovery cycles and stress levels of 0.1 and 3.2 kPa – and the averages of the results of two replicates (R and J_{nr}) were calculated for each formulation. The $J_{nr,diff}$ values were determined based on the final results of the nonrecoverable compliance values at 0.1 and 3.2 kPa.

3. Results and discussion

3.1. Fatigue behavior based on the LAS test

As stated previously, the fatigue behavior in the LAS test (numerical values given in Table 2) is based on two analyzes: (a) viscoelastic continuum damage (VECD) with the experimental results of parameters A_{35} and B; and (b) the fracture analysis with the damage tolerance parameter a_f. These results correspond to the average of two replicates for each material, which results in a maximum coefficient of variation of 15%.

In the VECD analysis, the parameter A_{35} represents the variation in the integrity of the material due to the accumulated damage [11]. It is desirable that the material keep its integrity throughout the cycles as measured by the loss modulus (G''). If this is observed, the A_{35} value will be high. However, if the asphalt binder undergoes a rapid decrease in the G'' values, the parameter A_{35} will be low. The B value is associated to the sensitivity of the asphalt binder to an increase in the strain level. Higher slopes (higher absolute B values) indicate that the fatigue life of the material decreases at a

Table 1
Modifier contents and processing variables.

Formulation	Continuous grade (°C)[a]	Formulations (% by mass)				Processing variables		
		Binder (AC)	PE	PPA	Shear level	Speed (rpm)	Temperature (°C)	Mixing time (min)
AC + PPA	77.8	98.8	–	1.2	Low[b]	300	130	30
AC + PE	77.7	94.0	6.0	-	Low	440	150	120
AC + PE + PPA	76.6	96.5	3.0	0.5	Low	400	150	120[c]

[a] The continuous grade of the 50/70 base asphalt binder is equal to 67.0 °C.
[b] The three formulations were prepared in a Fisatom 722D low-shear mixer.
[c] The polyphosphoric acid was added to the AC + PE after 60 min of mixing time.

Table 2
Linear amplitude sweep (LAS) test results.

Asphalt binder	Short-term aging (RTFOT)			Long-term aging (PAV)		
	Parameters of the VECD analysis		Damage tolerance parameter	Parameters of the VECD analysis		Damage tolerance parameter
	A_{35}	B	a_f (mm)	A_{35}	B	a_f (mm)
Results of LAS test at 25 °C						
Base binder (AC)	100,853	−2.81	0.71	213,831	−3.28	1.08
AC + PPA	545,802	−3.60	0.97	2534,063	−4.28	1.22
AC + PE	314,606	−3.26	0.92	1395,468	−4.06	1.11
AC + PE + PPA	351,763	−3.45	0.93	1363,456	−4.10	1.20
Results of LAS test at 35 °C						
Base binder (AC)	159,715	−2.34	0.31	256,299	−2.69	0.51
AC + PPA	877,003	−3.23	0.70	2247,696	−3.79	1.01
AC + PE	444,345	−2.91	0.55	488,067	−3.09	0.61
AC + PE + PPA	476,767	−2.99	0.67	1349,549	−3.51	0.90

higher rate when the strain amplitude increases. Likewise, smaller slopes (lower absolute B values) indicate that the fatigue life of the asphalt binder decreases at a lower rate. With respect to the analysis of the damage tolerance, higher a_f values indicate higher damage tolerance, that is, the material can show a longer crack before a rapid crack propagation [12].

The results of the parameter a_f at 25 and 35 °C indicate that the AC + PPA has the highest tolerance to fatigue damage in both the short- and long-term aging conditions, followed by the AC + PE + PPA, the AC + PE and the base binder. However, the a_f values are quite similar at 25 °C for the formulations with PE and PE + PPA in the short-term aging condition. The accelerated aging (either short- or long-term procedure) also causes an increase in the parameter a_f, which indicates that this factor could have a positive effect on the fatigue life of asphalt binders. On the other hand, the VECD analysis shows that these positive effects are observed only when the material is subjected to low shear strains levels (Fig. 1).

In addition to these observations, the numerical values presented in Table 2 also indicates that the changes in a_f between the short- and long-term aging conditions are different for each modified material. This indicates that the addition of modifiers to the base asphalt binder may lead to different fatigue responses after aging. With respect to the variations in the fatigue tolerance at 25 °C due to the aging level, the material that showed the lowest variations after long-term aging was the AC + PE, since there was an increase of only 21% in the a_f value when compared with the RTFO-aged condition. The AC + PPA showed an increase of 26% after the PAV aging and the AC + PE + PPA showed an increase of 29%. The base asphalt binder had the greatest change in a_f with aging (52%). At 35 °C, the material that showed the lowest variations after long-term aging was the AC + PE, since there was an increase of only 12% in the a_f value when compared with the RTFO-aged condition. The AC + PPA showed an increase of 45% after the PAV aging and the AC + PE + PPA showed an increase of 35%. The base asphalt binder had the greatest change in a_f with aging (62%). The results at the two temperatures assessed shown that the unmodified material is the most sensitive to aging and the AC + PE is the less sensitive to aging at both test temperature.

The fatigue law of the materials using the VECD approach is depicted in Fig. 1. These plots give the number of cycles to failure (N_f), which is an indicator of the volume of traffic that would be supported by the material as a function of the applied shear strain. This represents the conditions to which the material could be subjected inside in a given pavement structure. It can be seen in Fig. 1(a) and (c) that, in the short-term aging condition at 25 and 35 °C, the material that shows better fatigue behavior when subjected to low strain levels is the AC + PPA, followed by the AC + PE + PPA, the AC + PE and the base binder (worst fatigue performance).

The aforementioned ranking is inverted when the shear strain levels are higher, i.e., the base binder shows better fatigue performance than the modified ones. In the short-term aging condition and for low strain levels, the fatigue behavior of asphalt binders modified with PE and PE + PPA were very similar. However, for high strain levels, the AC + PE had a better fatigue behavior than the AC + PE + PPA and the AC + PPA.

After long-term aging in the PAV (Fig. 1(b) and (d)), the AC + PPA still has the best fatigue behavior when subjected to low strain levels, followed by the AC + PE + PPA and the AC + PE. Again, the unmodified asphalt binder has the worst fatigue behavior. However, the three modified asphalt binders showed worse fatigue performance than the unmodified material and quite similar results among them when for shear strains are higher. In other words, the best fatigue behavior at higher shear strain levels was found in the base asphalt binder.

The analysis of the test results based on the VECD approach highlights the benefits of the incorporation of modifiers to the asphalt binder, particularly at low shear strain levels. In the short-term aged condition at 25 °C, the benefits are more visible when the strain levels are lower than 5%, by increasing the temperature to 35 °C this benefits become more evident at strain levels lower than 4%. When the binder is in the long-term aged condition at 25 °C, these benefits are more apparent for strain levels lower than 7%, at 35 °C it is an evident for strain levels lower than 6%.

In Fig. 1, it can be seen that increasing temperature from 25 to 35 °C resulted in increasing N_f values (vertical shift in the curves) and slope decrease (B values) of fatigue models (see Table 2). This suggests that higher temperatures can decrease the sensitivity of the asphalts binders to fatigue cracking to the increase of the strain levels. On the other hand, the effect of aging can be mainly characterized by an increasing of the B values of fatigue models and this can be interpreted as a higher susceptibility of the material to fatigue cracking at different shear strain levels.

The VECD approach clearly shows that the fatigue behavior of an asphalt binder is highly dependent on the presence of modifier, as well as their types and contents. Modified asphalt binders are recommended only when the pavement is subjected to low strain levels, which are typical of found in thicker structures. Whereas, the use of conventional binders provides more benefits to the fatigue resistance of the pavements that the modified ones when the strain levels are higher (typical of thinner structures).

3.2. Rutting behavior based on the MSCR test

Fig. 2 depicts the percent recoveries (R) of the unmodified and modified asphalt binders. The addition of modifiers led to an increase in the elastic response, i.e., the presence of modifiers was responsible for the reduction in the amount of unrecovered strain of the bituminous material at typical high pavement temper-

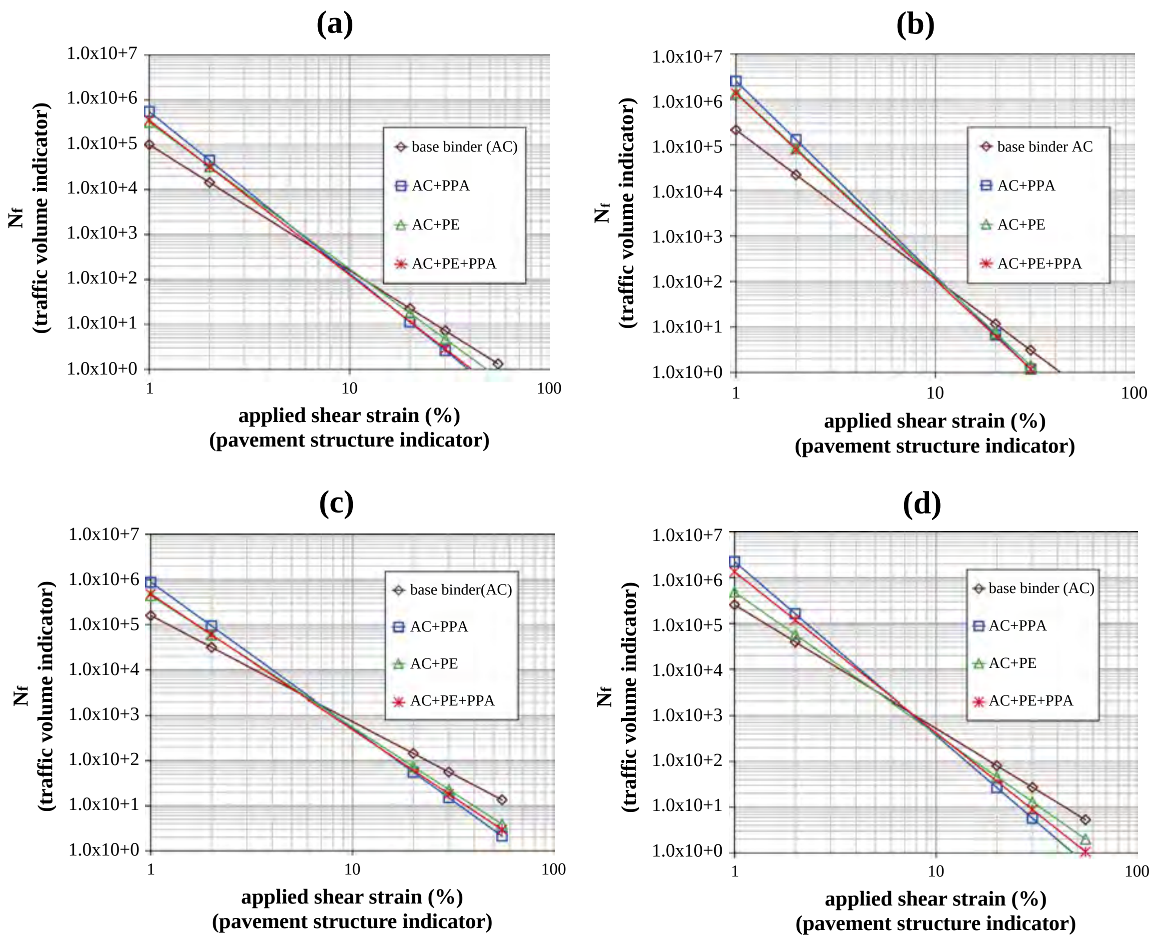

Fig. 1. Fatigue models from the VECD analysis: (a) short-term aging at 25 °C; (b) long-term aging at 25 °C; (c) short-term aging at 35 °C; (d) long-term aging at 35 °C.

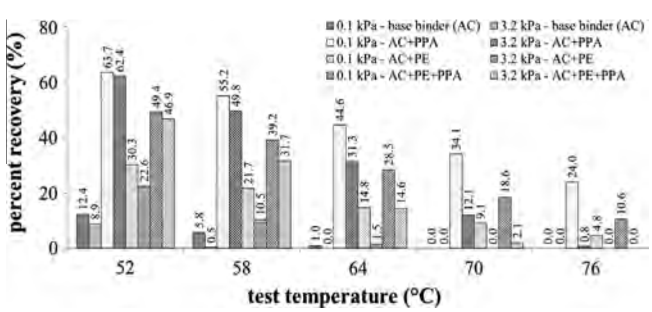

Fig. 2. Percent recoveries of asphalt binders.

atures. The AC + PPA shows the highest percent recoveries and the two formulations with PE show the lowest ones under the MSCR test conditions used in this study. From the point of view of the asphalt binder, the results indicate that asphalt mixtures prepared with the AC + PPA will show minor levels of rutting after subsequent loading–unloading cycles when compared with the ones prepared with the 50/70 base material, the AC + PE and the AC + PE + PPA. The R values are no greater than 50% for the two formulations with low-density PE in the whole temperature range, and they can overcome 49% for the AC + PPA at 52 and 58 °C.

One curious aspect of the results of the AC + PPA, the AC + PE and the AC + PE + PPA is the fact that the *R* values are all null or close to zero (lower than 1%) under the most severe test conditions, i.e., stress level of 3.2 kPa and temperature of 76 °C. In other words, the effects of binder modification with PE, PPA or PE + PPA on its percent recovery are not easily recognized when the test conditions are more severe. In such cases, higher percent recoveries may be obtained by selecting higher modifier contents. However, the high PG grades may not remain the same (PG 76-xx) for all of the formulations, especially if the continuous grade is close to 82 °C.

Fig. 3 shows the nonrecoverable compliances of the asphalt binders. The presence of modifiers decreased the J_{nr} values, especially at higher temperatures and stress levels. Since the nonrecoverable compliance is an indicator of the susceptibility of the asphalt binder to rutting, it can be said that the AC + PPA, the AC + PE and the AC + PE + PPA are less prone to the accumulation of unrecovered strain under creep and recovery loading than the unmodified material. The results are lower than 5.3 kPa^{-1} for the modified asphalt binders, and they can overcome 6.0 kPa^{-1} for

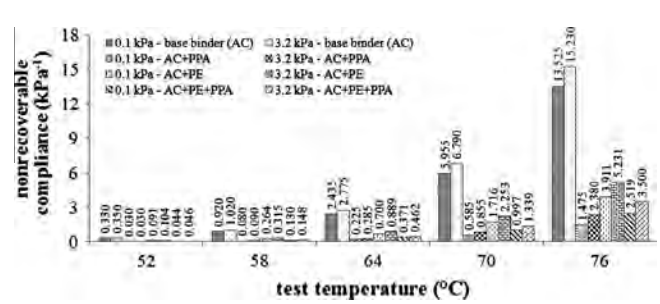

Fig. 3. Nonrecoverable compliances of asphalt binders.

the base binder at 70 and 76 °C. The J_{nr} values are lower for the AC + PPA than for the two formulations with PE in the whole range of temperatures and stress levels, and this is more visible at temperatures higher than 58 °C. By considering only the rheological properties of the asphalt binder, this indicates that the lowest rutting levels may be obtained when the AC + PPA is used in the asphalt mixture.

Although major differences between the J_{nr} values of the formulations can be highlighted at temperatures of 64 °C or higher, the same cannot be said for the two lowest ones (52 and 58 °C). The nonrecoverable compliances of the AC + PPA, the AC + PE and the AC + PE + PPA are quite similar at such test temperatures, and therefore it is difficult to examine the effects of the addition of modifiers (PE, PPA or both) in detail. This may be explained by the observation of very low strain levels in the bituminous materials at 52 and 58 °C, which makes it difficult to clearly distinguish between one formulation and the other. As the temperature and the strain level increase, the effects of each modification type become more noticeable. By not considering elements such as the aggregate gradation and the aggregate type, it can be inferred that asphalt mixtures prepared with the AC + PPA, the AC + PE and the AC + PE + PPA would have quite similar rutting performance at 7-day maximum expected pavement temperatures of 52 and 58 °C. Similarly, this rutting performance would reflect key differences among the three asphalt mixtures if the high pavement temperatures were equal to 64, 70 or 76 °C.

As previously observed, the J_{nr} values presented in Fig. 3 indicate that the formulation with PE + PPA is less susceptible to rutting than the one with PE, and this can be seen at all test temperatures and stress levels. In other words, the reduction in the PE content from 6.0% to 3.0% b w^{-1} and the addition of 0.5% b w^{-1} of PPA could increase the rutting resistance of the AC + PE by more than 30% at the test temperatures and stress levels considered in the study. However, these facts cannot be explained only by the addition of PPA or the decrease in the PE content because both modifier contents changed. What is possible to say is that these effects on the J_{nr} values are to some extent related to the presence of PPA in the formulation, especially when one observes the impact of 1.2% b w^{-1} of PPA on the nonrecoverable compliances of the unmodified asphalt binder.

In addition to the values of the nonrecoverable compliances at 0.1 and 3.2 kPa, the Superpave® asphalt binder specification also establishes a procedure for analyzing the stress sensitivity of the material at the high PG grade. Basically, this procedure consists of determining the percent difference in nonrecoverable compliances ($J_{nr,diff}$) and comparing its result with the maximum limiting value of 75% found in the specification. Asphalt binders with $J_{nr,diff}$ values higher than this upper limit are considered overly stress sensitive, that is, such materials are highly prone to rutting when unusual traffic loadings are applied on the pavement surface or unexpected pavement temperatures are observed in the field. It is important to point out that this high stress sensitivity can be found even when the asphalt binder meets the other PG criteria [17]. In other words, one modified asphalt binder with high degree of stiffness (PG grade) does not ensure that the rutting levels in the pavement will fall within a certain level, since the $J_{nr,diff}$ values may be sufficiently high to mitigate the benefits of the addition of these modifiers with respect to the resistance to rutting.

Table 3 displays the $J_{nr,diff}$ values of the asphalt binders. None of the bituminous materials exceeded the maximum value of 75% at the high pavement temperatures of 64, 70 and 76 °C, and therefore they cannot be considered overly stress sensitive. The AC + PPA was the only formulation that got closer to this upper limit ($J_{nr,diff}$ value of 61.4% at the temperature of 76 °C). These values are lower than or equal to 14% for the 50/70 base asphalt binder and are no greater than 39% for the AC + PE and the AC + PE + PPA. In a general context, the addition of modifiers caused an increase in the stress sensitivity (higher $J_{nr,diff}$ values) of the asphalt binder, especially at 70 and 76 °C. These increases are more significant for the AC + PPA and the AC + PE + PPA at the highest temperatures (70 and 76 °C) and are more significant for the AC + PE at the lowest temperatures (from 52 to 64 °C). In no case, however, was the presence of modifiers was extremely detrimental to the susceptibility of the asphalt binder to rutting under unforeseen temperature and/or loading conditions.

Table 3
Percent differences in nonrecoverable compliances ($J_{nr,diff}$, %) of asphalt binders.

Asphalt binder	52 °C	58 °C	64 °C	70 °C	76 °C
Base binder (AC)	6.1	10.9	14.0	14.0	12.6
AC + PPA	0.0	12.5	26.7	46.2	61.4
AC + PE	13.8	19.3	27.0	31.3	33.8
AC + PE + PPA	5.1	13.3	24.5	34.3	38.9

4. Conclusions

This paper presents the results of the rheological properties of asphalt binders at intermediate (susceptibility to fatigue cracking) and high pavement temperatures (susceptibility to rutting). The following conclusions can be reached with respect to the outcomes of the linear amplitude sweep (LAS) and the multiple stress creep and recovery (MSCR) tests:

- the addition of PE, PPA or PE + PPA to the asphalt binder can significantly improve the fatigue performance of the material at low shear strain levels. The AC + PPA has the best fatigue behavior in both aging conditions evaluated in the study (short-term and long-term), followed by the AC + PE + PPA, the AC + PE and the base binder. However, the base binder shows better fatigue performance than the modified ones at high strain levels;
- despite the beneficial effects that aging may have in the fatigue life of modified asphalt binders at low shear strains, it is important to note that higher strains can lead to premature failure of the material in the VECD analysis;
- the addition of modifiers to the base asphalt binder increased the percent recoveries (R) and decreased the nonrecoverable compliances (J_{nr}) of the material at high pavement temperatures from 52 to 76 °C, and these degrees of improvement are higher for the AC + PPA than for the AC + PE and the AC + PE + PPA; higher R values and lower J_{nr} values can be translated into higher elastic responses of the modified asphalt binders and lower susceptibility to the accumulation of permanent strain (rutting) in the field;
- the MSCR test results are better for the AC + PE + PPA than for the AC + PE at many temperatures and both 0.1 and 3.2 kPa stress levels; this, however, cannot be solely attributed to the reduction in the PE content or to the addition of PPA because the two modifier contents change from one formulation to the other;
- the modified materials are more prone to rutting under unexpected temperature and/or loading conditions – higher percent differences in nonrecoverable compliances ($J_{nr,diff}$) – than the unmodified one, but they cannot be considered overly stress sensitive because their $J_{nr,diff}$ values are all lower than 75%; the AC + PPA shows the highest $J_{nr,diff}$ values at 70 and 76 °C when compared with the AC + PE and the AC + PE + PPA; and
- asphalt binder modification with PPA, PE and PE + PPA is a good alternative to increase fatigue (depending on the strain level) and rutting resistances; a small amount of PPA alone can produce greater degrees of improvement than the ones observed for PE modification (with and without PPA), and this is visible either in the LAS test or the MSCR test.

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