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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.

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.

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