

# Rutting on asphalt binders and mixtures modified with PPA and Elvaloy®: laboratory aspects and rheological modeling

*Deformação permanente em ligantes e misturas asfálticas preparados com Elvaloy® e PPA: aspectos laboratoriais e modelagem reológica*

Matheus David Inocente Domingos<sup>1</sup>, Adalberto Leandro Faxina<sup>2</sup>, Liedi Légi Bariani Bernucci<sup>3</sup>

<sup>1</sup>Federal University of Technology, Paraná – Brazil, matheusdomingos@utfpr.edu.br

<sup>2</sup>University of São Paulo, São Paulo – Brazil, adalberto@usp.br

<sup>3</sup>University of São Paulo, São Paulo – Brazil, liedidi@usp.br

## Recebido:

1 de julho de 2021

## Aceito para publicação:

24 de janeiro de 2022

## Publicado:

30 de abril de 2022

## Editor de área:

Jorge Barbosa Soares

## Keywords:

Rutting.

Elvaloy terpolymer.

Polyphosphoric acid.

Rheological modeling.

## Palavras-chave:

Deformação permanente.

Terpolímero Elvaloy.

Ácido polifosfórico.

Modelagem reológica.

## ABSTRACT

There has been a lack of proper understanding about the actual rutting performance of asphalt binders/cements modified only with polyphosphoric acid (AC+PPA). Accordingly, this study aimed at evaluating the rutting resistance of the AC+PPA at typical Brazilian high pavement temperatures. Due to promising findings, another formulation with Elvaloy® and PPA (AC+Elvaloy+PPA) was also investigated. Standardized multiple stress creep and recovery tests were performed at 64 and 70°C, whereas the flow number ( $F_N$ ) was determined on dense-graded mixture samples and at 60°C. The AC+PPA (PG 76-22) and the AC+Elvaloy+PPA (PG 76-22) were based on a PG 64-22 original binder. The AC+Elvaloy+PPA could deal with heavier traffic levels and at both scales, as the nonrecoverable compliances were lower than  $1.0 \text{ kPa}^{-1}$  and  $F_N$  exceeded 7,000 cycles. Conversely, the AC+PPA did not show the same pattern of behavior because  $F_N$  was only 17% higher than the one of the original binder.

## RESUMO

Tem-se verificado uma falta de compreensão adequada sobre o desempenho real de ligantes asfálticos modificados apenas com ácido polifosfórico (CAP+PPA) à deformação permanente. Neste sentido, o presente trabalho buscou analisar a resistência do CAP+PPA à deformação permanente e em temperaturas altas típicas dos pavimentos brasileiros. Devido a resultados promissores, outra formulação com Elvaloy® e PPA (CAP+Elvaloy+PPA) também foi investigada. Ensaios padronizados de fluência e recuperação sob tensão múltipla foram realizados a 64 e 70°C, e o flow number ( $F_N$ ) foi determinado em misturas densas e a 60°C. O CAP+PPA (PG 76-22) e o CAP+Elvaloy+PPA (PG 76-22) foram baseados em um CAP puro PG 64-22. O CAP+Elvaloy+PPA pôde lidar com tráfegos mais pesados em qualquer escala, pois suas compliâncias não-recuperáveis não excederam  $1.0 \text{ kPa}^{-1}$  e  $F_N$  superou 7.000 ciclos. Todavia, o CAP+PPA não mostrou igual padrão de comportamento porque  $F_N$  foi apenas 17% maior que o resultado do CAP de base.

DOI:10.14295/transportes.v29i3.2652



## 1. INTRODUCTION

Rutting – or permanent deformation – has been a critical issue to be addressed on Brazilian pavements. This distress mechanism is typically described as surface depressions alongside the wheel paths, and the accumulation of viscous strain in the surface layer is responsible for the majority of rutting in the field pavements (Golalipour, 2020). Higher temperatures and longer loading times are environmental and loading factors that may significantly increase rutting and,

as a consequence, reduce the service life of the pavement. For instance, experiments conducted by Mu et al. (2020) showed that the rate of accumulation of permanent strain increased exponentially with temperature, and also that this rate could be multiplied by 10 when the high pavement temperature increased by 24°C – in this case, from 46-xx to 70-xx. However, the use of mixture design protocols superseded by others (e. g., Marshall) can also lead to poor rutting performance, which was noticed by Bastos et al. (2015) in their investigation on 300-m pavement sections constructed according to the Marshall and Superpave® design methods: while the former showed tracks with more than 12.5 mm of rutting after only four months of loading applications, the latter showed no rutting levels after 42 months of loading applications.

Each component of the asphalt mixture – i. e., asphalt binder and mineral aggregates – has its contribution to the overall rutting resistance. With respect to the binder, researchers have claimed that stiffness is the key property to be considered in the analyses, even though elasticity cannot be neglected at all (Golalipour, 2011; Arshadi, 2013). In turn, the internal structure of the aggregate skeleton – as dictated by parameters such as the number of contact points and the contact lengths and areas – has been reported as the most relevant characteristic to be evaluated in the laboratory (Sefidmazgi, Tashman and Bahia, 2012). The binder properties are assumed to play a major role on the rutting levels of the mixture in the first loading-unloading cycles, while the aggregate properties are assumed to play this major role after some loading applications. The aggregate type – e. g., limestone or gravel – may also influence on the degrees of correlation between binder parameters and mixture rutting (Bahia et al., 2001).

The most precise measurements of the rutting resistances of modified asphalt binders have been determined by following the Multiple Stress Creep and Recovery test procedures – MSCR (Domingos and Faxina, 2021; Liu et al., 2021), and the AASHTO T 350 and the ASTM D7405 protocols have been recently used in the United States to carry out the standardized experiments (ASTM, 2015; AASHTO, 2019a). Many researchers conducted MSCR in their testing programs, and several advantages have been highlighted in these studies: (a) good to excellent correlations between the nonrecoverable creep compliance ( $J_{nr}$ ) from MSCR and mixture rutting parameters, especially Flow Number –  $F_N$  (Golalipour, 2011; Domingos, Faxina and Bernucci, 2017; Klinsky, Bardini and Faria, 2020); (b) appropriate characterization and selection of unmodified and modified asphalt binders for paving applications, depending on the traffic level (Matos, 2017); and (c) appropriate characterization of modified binders from different crude sources and selection of the optimum modifier content (Pamplona et al., 2012). Even though some poor correlations between  $J_{nr}$  and mixture data have also been reported (Bastos, Babadopulos and Soares, 2017), it is believed that increases in the standardized stress level from 3.2 kPa to values of 10 kPa or higher (Wasage, Stastna and Zanzotto, 2011; Golalipour, Bahia and Tabatabaee, 2017) – amongst other refinements – can address these deficiencies.

The Flow Number (FN) tests are the mostly used ones in Brazilian studies (Bastos, Babadopulos and Soares, 2017; Bastos, Soares and Nascimento, 2017). The steps outlined by Witczak et al. (2002) include the application of a 0.1-s creep load followed by a 0.9-s rest period, and the test is interrupted when 10,000 cycles are applied or the mixture reaches the tertiary creep region, whichever comes first. The loads typically considered in the unconfined tests may range from 69 to 207 kPa, whereas the temperatures may vary from 25 to 60°C. This maximum temperature of 60°C has been commonly observed for pavements located in the southern region of Brazil (Fontes et al., 2010; Matos, 2017), thereby requiring binders graded as 64-XX.

However, some regions of the country demand binders graded as 70-XX due to their climatic conditions (Cunha, Zegarra and Fernandes Jr, 2007).

The incorporation of polymers into the binder is a widespread procedure for improving the resistance of the original material against rutting. Among these polymers, the Reactive Ethylene Terpolymers (RETs) such as Elvaloy® offer great benefits to the base binder not only due to the increases in stiffness, but also elasticity, storage stability and moisture resistance (Yildirim, 2007; Bulatović, Rek and Marcović, 2014). Marked decreases in the rutting levels of mixtures and the  $J_{nr}$  values of binders modified with Elvaloy® have been published elsewhere. For example, Bessa et al. (2019) indicated that the  $J_{nr}$  values decreased by one half and the rut depths of the mixture specimens reduced by approximately 49% after the addition of about 2% of Elvaloy® and 0.2% of Polyphosphoric Acid (PPA) in the formulations. Positive laboratory findings were also presented by Fee et al. (2010) after modification of a PG 64-22 base binder with 1.1% of Elvaloy® and 0.3% of PPA: the rut depth was much lower than 5.0 mm after 20,000 loading applications at 50°C in the Hamburg Wheel Tracking test. For comparison purposes, the reference material showed about 20 mm of rut depth after only 15,000 loading-unloading cycles.

Although asphalt binder modification with Elvaloy® yields formulations with high elasticity and much lower susceptibility to rutting, the same cannot be said for modifications only with PPA. In fact, the literature typically does not provide mixture rutting data for PPA-modified binders/cements as good as those obtained for polymeric modification types. More specifically, rutting performance at the mixture scale is not necessarily better than the corresponding one of the neat binder when PPA alone is used in the formulation. This may be noticed either in Accelerated Loading Facilities (Fee et al., 2010; Reinke et al., 2012; Khader, Ramesh and Kumar, 2015; Lv et al., 2019) or creep tests (Tabatabaee and Teymourpour, 2010). Hence, further analyses are required to clarify key issues regarding the rutting behavior of PPA-modified asphalt binders and mixtures, especially because increases in stiffness are commonly observed for such formulations during MSCR (Fee et al., 2010; Li et al., 2011).

In this manner, the present research study dealt with the analyses of the rutting resistances of asphalt binders modified with Elvaloy® and PPA (AC+Elvaloy+PPA) and only PPA (AC+PPA) at high pavement temperatures equal to 64 and 70°C in the MSCR tests, as well as the corresponding dense-graded mixtures in the FN tests and at 60°C. The incorporation of the AC+Elvaloy+PPA into the study was made for comparison purposes, and also due to its promising findings in earlier published investigations. Limitations in the test protocol for FN avoided the use of temperatures higher than 60°C, as it will be discussed later. The following are the secondary objectives of the investigation:

- To correlate binder rutting performance – as provided by  $J_{nr}$  and oscillatory shear-based parameters – with mixture rutting performance (as provided by the FN tests), in an attempt to identify similarities and differences between each ranking;
- To further describe the contributions of the elastic and viscous responses of the binders to their overall responses, as based on the parameters of the Burgers model (Bahia et al., 2001; Golalipour, 2011; 2020); and
- To report rankings of formulations from the highest to the lowest rutting resistances, as based on the binder and mixture data.

## 2. MATERIALS AND TEST METHODS

### 2.1. Preparation of formulations and binder testing protocols

The base binder used in the study was supplied by the Lubnor-Petrobras refinery (Fortaleza, Ceará, Brazil). This binder is graded as 50/70 in the Brazilian penetration grade specification (DNIT, 2006) and 64-22 in the Superpave<sup>®</sup> specification (AASHTO, 2019b). The 4170 Elvaloy<sup>®</sup> terpolymer was provided by DuPont<sup>™</sup>, and its technical characteristics include 8% of glycidylmethacrylate by weight, density of 0.94 g/cm<sup>3</sup> and a maximum processing temperature of 280°C. The Innovalt<sup>®</sup> E200 PPA was supplied by Innophos Inc. (US). The AC+PPA and the AC+Elvaloy+PPA were prepared according to the processing variables and modifier contents summarized in Table 1 to target a high PG grade of 76-xx (AASHTO, 2019b), as well as continuous grades between 76.0 and 78.0°C. This was made to limit the exact degrees of stiffness of each formulation, since binders classified as 76-xx may depict true grades from 76.01 up to 81.99°C.

**Table 1** – Formulations, processing variables, and results of some characterization tests

<i>description</i>	<i>unit</i>	<i>base binder (AC)</i>	<i>AC+PPA</i>	<i>AC+Elvaloy+PPA</i>
binder proportion	% by mass	100.0	98.0	97.9
PPA proportion	% by mass	-	2.0	0.5
Elvaloy <sup>®</sup> proportion	% by mass	-	-	1.6
true grade	°C	66.3	77.8	76.6
mixing temperature	°C	-	130	190
mixing time	min	-	30	120a
rotation speed	rpm	-	300	300
softening point, unaged	°C	50.3	60.1	61.0
penetration, unaged	dmm	52.0	24.0	39.0
Brookfield @ 135°C, unaged <sup>b</sup>	Pa.s	0.39	0.81	1.42
$G^*/\sin\delta$ @ 64°C, aged <sup>c</sup>	kPa	2.98	13.55	6.47
$G^*/\sin\delta$ @ 70°C, aged <sup>c</sup>	kPa	1.33	6.42	3.53

<sup>a</sup> PPA was added to the AC+Elvaloy after a mixing time of 60 min.

<sup>b</sup> The rotational viscosity tests were performed with the spindle 21 and according to ASTM (2006).

<sup>c</sup> Oscillatory tests conducted according to ASTM (2008) and on binders aged in accordance with ASTM (2012).

Both the AC+PPA (76-22) and the AC+Elvaloy+PPA (76-22) were prepared on a Fisatom 722D low-shear mixer. The incorporation of PPA into the AC+Elvaloy has been a common practice in the literature, in that PPA may be used to accelerate the reaction between RETs and the original binder and to reduce the amount of polymer in the formulation (Kodrat, Sohn and Hesp, 2007). The true grade generally increases linearly with the PPA content, and researchers also suggested that the high PG grade of the binder typically boots two grades when 1.0 to 1.5% of PPA is incorporated into the original binder (Fee et al., 2010; Pamplona et al., 2012). This could somehow also be observed in the present investigation, once the high PG grade of the base material increased by two grades after the addition of 2.0% of PPA.

Two test protocols were considered in the experiments with the asphalt binders. Initially, the materials were subjected to oscillatory shear tests (ASTM, 2008) in an AR-2000ex Dynamic Shear Rheometer (DSR) from TA Instruments to determine the complex shear modulus  $G^*$  and the phase angle  $\delta$  at 64 and 70°C – the average value was computed with two replicates for each formulation. Typical illustrations of the reversed loading applications in such tests can be found elsewhere (Roberts et al., 1996). The original Superpave<sup>®</sup> rutting parameter  $G^*/\sin\delta$  was calculated at these same temperatures and in the unaged condition to obtain the high PG grades

and true grades of the binders. The calculations of  $G^*/\sin\delta$  in the short-term aged condition (ASTM, 2012) were performed as a complementary analysis of the susceptibility of the materials to rutting (Table 1). Despite the strong criticisms associated with the applicability of oscillatory shear-based parameters in the prediction of rutting in the mixture (Bahia et al., 2001; Domingos, Faxina and Bernucci, 2017), some experimental findings revealed that this is not always the case (Saboo and Kumar, 2016). Therefore, more correlations are required to gain further insights about this issue.

The MSCR experiments (ASTM, 2015; AASHTO, 2019a) were conducted in the same AR-2000ex DSR and at the same temperatures used in the oscillatory shear tests (64 and 70°C). Further explanations about the loading applications and typical stress-strain curves observed in these experiments can be found in earlier studies (Golalipour, 2020; Liu et al., 2021). Two replicates were considered for each binder type as defined by the ASTM and AASHTO protocols, and the percent recoveries ( $R$ ) and the nonrecoverable compliances  $J_{nr}$  were calculated at both stress levels of 0.1 and 3.2 kPa. The stress sensitivity of these binders was evaluated not only according to the Superpave<sup>®</sup> parameter  $J_{nr,diff}$  (percent difference in compliances, see Equation (1)), but also the percent slope of nonrecoverable compliances ( $J_{nr,slope}$ ) proposed by Stempihar, Gundla and Underwood (2018), refer to Equation (2). Finally, the levels of elastic response of the formulations at each temperature were determined in accordance with the protocol proposed by the TP 70 standard (AASHTO, 2013).

$$J_{nr,diff}(\%) = \frac{J_{nr3200} - J_{nr100}}{J_{nr100}} \times 100 \quad (1)$$

$$J_{nr,slope}(\%) = \frac{J_{nr3200} - J_{nr100}}{3.1} \times 100 \quad (2)$$

where  $J_{nr100}$ : nonrecoverable compliance at 0.1 kPa [kPa<sup>-1</sup>]; and  
 $J_{nr3200}$ : nonrecoverable compliance at 3.2 kPa [kPa<sup>-1</sup>].

## 2.2. Rheological modeling

The four-element Burgers model was fitted to the raw creep-recovery data of the formulations at 0.1 kPa, and each of the spring and dashpot elements was calculated according to the protocol suggested by Liu and You (2009). As a consequence, the instantaneous elastic response (isolated spring element of the Maxwell model  $E_M$ ), the viscous response (isolated dashpot element of the Maxwell model  $\eta_M$ ), and the viscoelastic response (spring element  $E_K$  and dashpot element  $\eta_K$  associated in parallel, both from the Kelvin-Voigt model) could then be estimated. Equation (3) shows the calculations of the strains during the creep portion of the cycle  $\varepsilon_{cr}(t)$ , while Equation (4) describes the calculation of these strains during the recovery portion of the cycle  $\varepsilon_{rec}(t)$ . The accumulated percent differences between the predicted and measured values for all data points – Average Absolute Errors (AAEs) – were also determined.

$$\varepsilon_{cr}(t) = \frac{\sigma_0}{E_M} + \frac{\sigma_0 \times t}{\eta_M} + \frac{\sigma_0}{E_K} \times \left[ 1 - \exp\left(\frac{-E_K \times t}{\eta_K}\right) \right] \quad (3)$$

$$\varepsilon_{rec}(t) = \frac{\sigma_0 \times t_F}{\eta_M} + \frac{\sigma_0}{E_K} \times \left[ 1 - \exp\left(\frac{-E_K \times t_F}{\eta_K}\right) \right] \times \exp\left[\frac{-E_K \times (t - t_F)}{\eta_K}\right] \quad (4)$$

where  $\sigma_0$ : applied stress [kPa];  
 $t$ : test time [seconds]; and  
 $t_F$ : creep time [seconds].

The ratio  $\eta_K$  over  $E_K$  is known as the retardation time  $\lambda$ , and comparisons between its values and the creep times used in the MSCR tests may lead to interesting conclusions about the role

of the delayed elasticity on the creep-recovery response of the binder. When  $\lambda$  is higher than  $t_F$ , this means that a pure steady state response is not reached in the test right in the first applied cycles (Merusi, 2012). As a consequence, more loading-unloading cycles are required to subtract the viscoelastic strain from the total strain accumulated in the material (Bahia et al., 2001; Golalipour, 2011) – which has been considered by ASTM (2015) and AASHTO (2019a) in their quite recent versions of the MSCR standards. One additional possibility may be a substantial increase in  $t_F$  such that  $t_F \gg \lambda$ , which was adopted in the experiments carried out by Merusi (2012).

### 2.3. Mixture specimens and corresponding test protocols

The mixture specimens had 100 mm in diameter and 150 mm in height, and three replicates for each binder type and content were prepared in a Servopac Superpave® gyratory compactor. The technical details of mixture preparation are summarized in Table 2. Basaltic aggregates from the Bandeirantes quarry (São Carlos, São Paulo, Brazil) and with a Los Angeles abrasion of 25% (DNER, 1998) were selected, and a dense-graded curve corresponding to the center points of the “Gradation III” band from the São Paulo State Department of Roads (DER-SP, 2005) was considered. This curve is depicted in Figure 1. The FN tests were carried out according to the steps outlined by Witczak et al. (2002) and described in the Introduction. The applied loads during the creep and recovery times were equal to 204 and 5.2 kPa, respectively. The test temperature was kept constant and equal to 60°C, as it is a representative value of the highest expected pavement temperature in several regions of Brazil (Cunha, Zegarra and Fernandes Jr, 2007; Fontes et al., 2010; Matos, 2017).

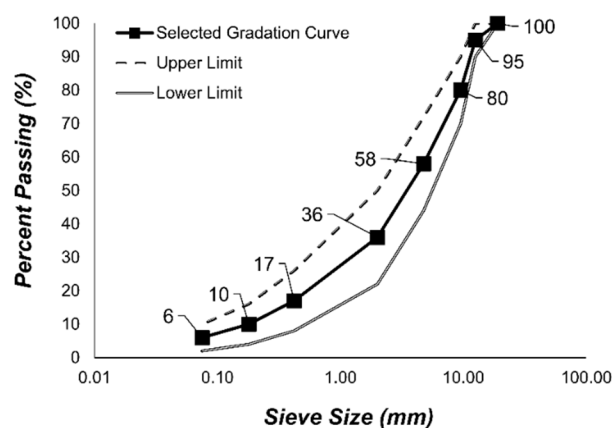
**Table 2** – Information on the mixture specimens

description (variable or parameter)	unit	results or intervals of values		
		base binder (AC)	AC+PPA	AC+Elvaloy+PPA
binder content	%	4.4	4.7	4.8
air voids <sup>a</sup>	%	6.9 to 7.1	6.9 to 7.1	6.8 to 6.9
mixing temperatures <sup>b</sup>	°C	151 to 156	165 to 171	179 to 184
targeted mixing temperature <sup>c</sup>	°C	154	168	177
compaction temperatures <sup>b</sup>	°C	140 to 144	154 to 159	166 to 173
targeted compaction temperature <sup>c</sup>	°C	142	157	170

<sup>a</sup> The targeted air voids in all samples was fixed at 7.0%.

<sup>b</sup> The mixing and compaction temperatures were calculated according to ASTM (2009).

<sup>c</sup> The mixing and/or compaction temperatures were limited to 177°C to avoid overheating and reduce fume emissions.



**Figure 1.** Aggregate gradation curve used in the preparation of the mixture specimens

### 3. PRESENTATION OF FINDINGS AND DISCUSSIONS

#### 3.1. MSCR tests

Table 3 depicts the major outcomes of the MSCR tests ( $R$  and  $J_{nr}$  at 0.1 and 3.2 kPa) for all binders. A well-known effect of modification with polymers and PPA on the stiffness of the binder is its increase, which may be quantified especially by the nonrecoverable compliance at 3.2 kPa ( $J_{nr3200}$ ). As can be seen, the presence of PPA alone decreased the  $J_{nr}$  values by 84-90%, regardless of the applied stress. With respect to the addition of Elvaloy+PPA to the original binder, these decreases in  $J_{nr}$  ranged from 88 up to 91% under all testing conditions. The substantial degrees of improvement in stiffness can also be implied by the appropriate traffic levels assigned to the binders, in that the AC+PPA may deal with heavy to extremely heavy traffic and the AC+Elvaloy+PPA may deal with very heavy to extremely heavy traffic on real pavements. In contrast, the 50/70 base binder cannot cope with traffic levels heavier than the standard one at 64°C. In terms of the numbers of Equivalent Single-Axle Loads ( $N$  values), these traffic levels may be translated into  $N < 10^7$  for the base material at 64°C,  $N > 3 \times 10^7$  for the AC+Elvaloy+PPA at both temperatures and  $10^7 < N < 3 \times 10^7$  for the AC+PPA at 70°C (Anderson, 2014).

Together with the increases in stiffness, the MSCR tests also provide interesting information regarding the degrees of elasticity of the modified binders. As one can see in Table 3, the AC+PPA showed recoveries no greater than 34% in any test condition, even at 0.1 kPa. On the other hand, the AC+Elvaloy+PPA depicted recoveries no lower than 45% both at 64°C or at 70°C. In a general context, the AC+Elvaloy+PPA is stiffer and more elastic than the AC+PPA at the high pavement temperatures of 64 and 70°C, and hence it may be taken as the best formulation within those studied in this investigation. The AC+Elvaloy+PPA is also the only modified binder which depicts high degrees of elasticity according to the criteria prescribed by the TP 70 standard (AASHTO, 2013), refer to Figure 2. Based on earlier studies from D'Angelo and Dongré (2009), the internal structure of the AC+Elvaloy+PPA may be comprised by strong polymer structures and continuous polymer networks within the binder phase, which in turn leads to high recoveries during the MSCR test. It is also hypothesized that PPA helped in developing such networks by accelerating the reaction between Elvaloy® and the base asphalt binder, as pointed out above.

**Table 3** – Percent recoveries ( $R$ ) and nonrecoverable compliances ( $J_{nr}$ ) of the binders

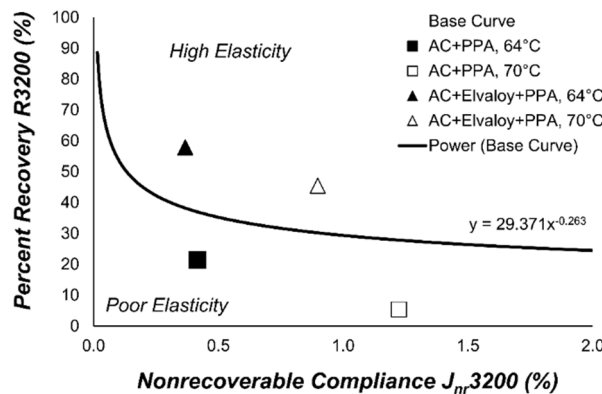
temperature (°C)	stress (kPa)	parameter and unit	results for each material <sup>b</sup>		
			base binder (AC)	AC+PPA	AC+Elvaloy+PPA
64	0.1	R (%)	0.0	33.8	<b>65.3</b>
64	3.2	R (%)	0.0	21.4	<b>57.9</b>
64	0.1	$J_{nr}$ (kPa <sup>-1</sup> )	3.214	0.335	<b>0.304</b>
64	3.2	$J_{nr}$ (kPa <sup>-1</sup> ) <sup>a</sup>	3.352 [S]	0.416 [E]	<b>0.367 [E]</b>
70	0.1	R (%)	0.0	20.8	<b>55.3</b>
70	3.2	R (%)	0.0	5.4	<b>45.5</b>
70	0.1	$J_{nr}$ (kPa <sup>-1</sup> )	7.488	0.906	<b>0.741</b>
70	3.2	$J_{nr}$ (kPa <sup>-1</sup> ) <sup>a</sup>	7.825	1.223 [H]	<b>0.898 [V]</b>

<sup>a</sup> S = standard traffic; H = heavy traffic; V = very heavy; E = extremely heavy traffic level (AASHTO, 2019b).

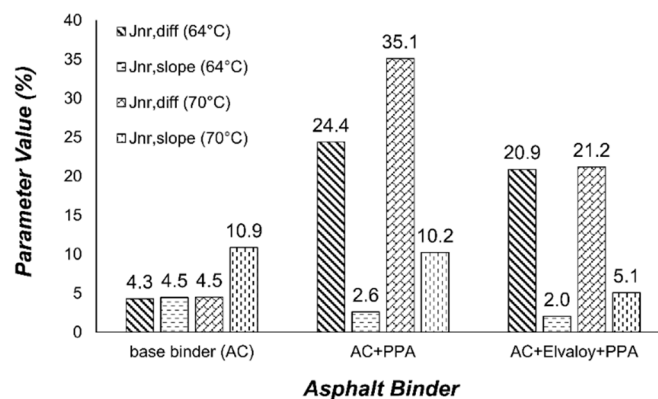
<sup>b</sup> The best results for  $R$  and  $J_{nr}$  (i. e., higher recoveries and lower compliances) are highlighted in bold.

Figure 3 shows the values of the parameters  $J_{nr,diff}$  and  $J_{nr,slope}$  for all binders. On average, the  $J_{nr,slope}$  values are from 70 to 91% lower than the corresponding ones for  $J_{nr,diff}$  and both the AC+PPA and the AC+Elvaloy+PPA. This is in agreement with the main purpose of the development of  $J_{nr,slope}$  by Stempihar, Gundla and Underwood (2018), as some modified binders

with very small  $J_{nr}$  values typically depict  $J_{nr,diff}$  values higher than 75%. In addition, these authors also claimed that  $J_{nr,diff}$  had no correlation with mixture data, whereas the  $J_{nr,slope}$  values depicted good correlations with such data. Neither the AC+Elvaloy+PPA nor the AC+PPA exceeded the maximum allowed  $J_{nr,diff}$  value of 75% set by Superpave® (AASHTO, 2019b) and, other than being in accordance with previous publications (Pamplona et al., 2012; Bessa et al., 2019), the data also indicate that the two formulations may be used for paving applications in the light of the limit for  $J_{nr,diff}$ . The AC+PPA is slightly more stress sensitive than the AC+Elvaloy+PPA, and the differences within their values are lower at 64°C than at 70°C.



**Figure 2.** Levels of elasticity of the AC+PPA and the AC+Elvaloy+PPA at 64 and 70°C and according to their percent recoveries and nonrecoverable compliances at 3,200 Pa



**Figure 3.** Percent differences ( $J_{nr,diff}$ ) and percent slopes ( $J_{nr,slope}$ ) between the nonrecoverable compliances of the binders at 0.1 and 3.2 kPa

### 3.2. Parameters of the four-element Burgers model

Table 4 summarizes the spring elements  $E_M$  and  $E_K$  and the dashpot elements  $\eta_M$  and  $\eta_K$  of the AC+PPA and the AC+Elvaloy+PPA, together with their corresponding  $\lambda$  values. The four-element Burgers model fitted the raw strain data of the formulations quite well, with errors no greater than 3.0% in any case. Since the base binder showed no recovery at any of the studied temperatures (see Table 3), this model was not fitted to its raw data. It is clear from the  $E_M$  values that the instantaneous elastic responses of the AC+Elvaloy+PPA are much greater than those of the AC+PPA – decreases by around 55% in  $E_M$  at 64 and 70°C when moving from the AC+Elvaloy+PPA to the AC+PPA. Also, the role of delayed elasticity on the creep-recovery response of the AC+Elvaloy+PPA is more pronounced than the one of the AC+PPA: the  $\lambda$  values



are about 12% and 235% greater for the Elvaloy-modified binder than for the PPA-modified binder at 64 and 70°C, respectively. This means that the AC+Elvaloy+PPA shows higher elastic responses than the AC+PPA not only due to the instantaneous elastic portion of the total strain, but also the delayed elastic strain with increasing number of cycles.

**Table 4** – Elements of the Burgers model and corresponding retardation times ( $\lambda$ ) and Average Absolute Errors (AAEs)

asphalt binder and temperature	results for each parameter				$\lambda$ (s)	AAE (%)
	$E_K$ (Pa) <sup>a</sup>	$\eta_K$ (Pa.s) <sup>b</sup>	$E_M$ (Pa) <sup>a</sup>	$\eta_M$ (Pa.s) <sup>b</sup>		
AC+PPA, 64°C	3,394.51	7,099.48	30,150.63	2,456.14	2.09	1.00
AC+PPA, 70°C	11,735.04	7,960.25	17,165.74	945.79	0.68	0.38
AC+Elvaloy+PPA, 64°C	900.68	2,120.92	13,414.80	2,057.62	2.35	2.90
AC+Elvaloy+PPA, 70°C	578.20	1,318.37	7,484.77	963.28	2.28	2.32

<sup>a</sup>  $E_M$  = isolated spring of the Maxwell model;  $E_K$  = spring of the Kelvin-Voigt model.

<sup>b</sup>  $\eta_M$  = isolated dashpot of the Maxwell model;  $\eta_K$  = dashpot of the Kelvin-Voigt model.

In addition to depicting greater elastic strains, the AC+Elvaloy+PPA also contains lower viscous strain – higher  $\eta_M$  values – than the AC+PPA at 70°C. This implies that the lower  $J_{nr}$  values of the AC+Elvaloy+PPA at 70°C may be attributed to a combined effect of decreases in the viscous strain and increases in the elastic strain of the material. With respect to the presence of lower  $J_{nr}$  values for the AC+Elvaloy+PPA also at 64°C, they may be explained by a major role of the elastic strain on the overall response of the material. Furthermore, the determination of  $\lambda$  values much greater than 1.0 s – the standardized creep time in the MSCR tests – clearly indicates that the time of 1.0 s is not enough to minimize the influence of delayed elasticity on the responses of the formulations right in the first creep-recovery cycles of MSCR. The calculations of  $R$  and  $J_{nr}$  in the last cycles at 0.1 kPa, as prescribed by ASTM (2015) and AASHTO (2019a), were adopted as an alternative to deal with the delayed elasticity of the formulations, especially those with high levels of elastic responses (Golalipour, 2011).

Another interesting feature of the data reported in Table 4 is the increases in  $E_K$  and  $\eta_K$  (about 245.7% for  $E_K$  and 12.1% for  $\eta_K$ ) with increasing temperature and for the AC+PPA, while a different pattern of behavior may be seen for the AC+Elvaloy+PPA – decreases by 35.8% and 37.8% for  $E_K$  and  $\eta_K$ , respectively. However, the  $\lambda$  values decreased more than 50% for the AC+PPA and only 3% for the AC+Elvaloy+PPA. Based on this, one may see that the maintenance of  $\lambda \approx 2.0$  s for the AC+Elvaloy+PPA suggests the presence of a strong polymeric network within the formulation, even at 70°C. Conversely, the AC+PPA depicted no sufficient elastic responses at higher temperatures such as 70°C, which can be translated as  $\lambda$  values lower than 1.0 s.

### 3.3. Mixture parameters and comparisons with binder parameters

Table 5 provides details on the parameter  $F_N$ , as well as the corresponding Coefficients of Variation (COV's) and rankings of materials from the highest to the lowest susceptibility to rutting. For comparison purposes, the rankings based on  $G^*/\sin\delta$  (Table 1) and  $J_{nr3200}$  (Table 3) at each temperature are also given. The ranges of COV's are in accordance with other papers (Mohammad et al., 2006; Apeageyi, 2014), and the AC+Elvaloy+PPA is the most rut resistant formulation at the mixture scale. According to the criteria developed by Bastos, Soares and Nascimento (2017), the three asphalt mixtures would be suitable for extremely heavy traffic on pavements at 60°C because their  $F_N$  values are all greater than 1,000 cycles. These classifications are similar to those of the AC+PPA and the AC+Elvaloy+PPA at 64°C, as well as the AC+Elvaloy+PPA at 70°C (see Table 3).

**Table 5** – Mixture rutting parameters and rankings of binders and mixtures

description (parameter or ranking)	results for each formulation <sup>b</sup>		
	base binder (AC)	AC+PPA	AC+Elvaloy+PPA
flow number $F_N$ @ 60°C (cycles)	2,167	2,533	7,050
assigned traffic level <sup>c</sup>	E	E	E
coefficient of variation (%)	4.49	8.22	24.82
ranking of mixtures ( $F_N$ ) <sup>a</sup>	3	2	1
ranking of binders ( $G^*/\sin\delta$ @ 64°C) <sup>a</sup>	<b>3</b>	1	2
ranking of binders ( $G^*/\sin\delta$ @ 70°C) <sup>a</sup>	<b>3</b>	1	2
ranking of binders ( $J_{nr3200}$ @ 64°C) <sup>a</sup>	<b>3</b>	<b>2</b>	<b>1</b>
ranking of binders ( $J_{nr3200}$ @ 70°C) <sup>a</sup>	<b>3</b>	<b>2</b>	<b>1</b>

<sup>a</sup> These rankings were developed on a decreasing order of rutting resistance, i. e., materials with higher resistances (higher  $F_N$  and  $G^*/\sin\delta$  values and lower  $J_{nr3200}$  values) received the first positions.

<sup>b</sup> The ranking of mixtures was used as reference to all rankings of binders. Similar positions are highlighted in bold.

<sup>c</sup> Traffic levels recommended to the mixtures according to their  $F_N$  values and the approach proposed by Bastos, Soares e Nascimento (2017). E = extremely heavy traffic ( $F_N > 1,000$  and  $N > 3 \times 10^7$ ).

Similarly to the conclusions drawn by Bahia et al. (2001) and Domingos, Faxina and Bernucci (2017), the outcomes of  $G^*/\sin\delta$  were found unsuitable to estimate the rutting resistance of the mixture according to  $F_N$ . As expected from the literature review, the rankings based on  $G^*/\sin\delta$  and  $F_N$  were totally reversed for the two formulations, which suggests that oscillatory shear tests are not adequate in the prediction of the rutting potential in the mixture scale. On the other hand, the parameter  $J_{nr3200}$  yielded rankings similar to those of the mixtures both 64 and at 70°C, which is in close agreement with opinions expressed by several researchers (Saboo and Kumar, 2016; Domingos, Faxina and Bernucci, 2017; Bessa et al., 2019; Klinsky, Bardini and Faria, 2020).

In a broader context,  $J_{nr3200}$  finds support in this study to be used as a performance-related parameter in the estimation of rutting in the asphalt mixture at high pavement temperatures. However, caution must be taken when considering particular modifiers such as PPA alone: despite the promising results of  $J_{nr3200}$  (binder data), the  $F_N$  values of this formulation were only 17% higher than those of the base material (mixture data). This may be explained by the ordinary elastic properties of the PPA-modified binder, and not specifically its improved degree of stiffness (Lv et al., 2019).

#### 4. MAIN CONCLUSIONS

In accordance with the key findings of the laboratory experiments carried out in this research study, the following conclusions may be reached:

- The MSCR tests provided valuable insights about the levels of elasticity and the degrees of stiffness of modified asphalt binders – as measured by their percent recoveries and the nonrecoverable compliances at 3,200 Pa ( $R_{3200}$  and  $J_{nr3200}$ , respectively) – at high pavement temperatures typically observed in Brazil (64 and 70°C);
- Modification of a 50/70 base binder with PPA and Elvaloy+PPA not only increased its stiffness (lower  $J_{nr}$  values), but also improved its elastic responses (higher  $R$  values). The best outcomes obtained for the AC+Elvaloy+PPA at 64 and 70°C – and confirmed by mixture data and the verification of the degree of elasticity of the material according to the AASHTO TP 70 standard – suggest that several polymer networks were developed in the binder phase, as well as a strong polymeric structure (which could not be seen for the AC+PPA);

- The AC+PPA and the AC+Elvaloy+PPA cannot be interpreted as overly stress sensitive materials according to Superpave®, since their percent differences in compliances ( $J_{nr,diff}$ ) were all lower than 75%. In addition, the AC+PPA was slightly more stress sensitive than the AC+Elvaloy+PPA;
- The percent slope in compliances ( $J_{nr,slope}$ ) proposed by some researchers yielded results from 70 to 91% lower than the corresponding values for  $J_{nr,diff}$ , which is a clear indication that  $J_{nr,slope}$  does not penalize formulations with very small compliances;
- The data derived from the four-element Burgers model pointed to the direction that, in a general context, the AC+Elvaloy+PPA was stiffer and more elastic than the AC+PPA due to its lower viscous strains, higher instantaneous elastic strains and higher levels of delayed elastic responses in each creep-recovery cycle; and
- The rankings of mixtures according to their flow number values at 60°C were similar to those based on  $J_{nr3200}$  at 64 and 70°C. On the other hand, the rankings based on oscillatory shear data showed reversed positions for the AC+Elvaloy+PPA and the AC+PPA. Despite the need for attention while examining the rutting performance of some formulations such as the AC+PPA,  $J_{nr3200}$  finds great support in the present study to be used as a performance-related rutting parameter for asphalt binders.

#### ACKNOWLEDGEMENTS

Grants 2013/20483-6, 2014/17584-8 and 2006/55835-6, São Paulo Research Foundation (FAPESP).

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