RUTTING ON ASPHALT BINDERS AND MIXTURES MODIFIED WITH PPA AND ELVALOY®: LABORATORY ASPECTS AND RHEOLOGICAL MODELING

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ABSTRACT

This study aimed at examining the rutting behavior of asphalt binders/cements (AC) modified with polyphosphoric acid (AC+PPA) and Elvaloy® terpolymer with PPA (AC+Elvaloy+PPA) at the binder scale – multiple stress creep and recovery (MSCR) at 64 and 70ºC – and at the mixture scale (flow number at 60ºC – FN). The four-element Burgers model was fitted to raw strains at 0.1 kPa to further investigate the patterns of response of each material. The base binder was graded as 64-22, and the formulations were graded as 76-22 (AC+PPA) and 76-28 (AC+Elvaloy+PPA). Widespread polymer networks and a strong polymer structure may explain the best outcomes of the AC+Elvaloy+PPA in both the MSCR and FN tests. The AC+PPA showed improved stiffness according to MSCR, but only marginal benefits according to FN. The presence of similar rankings for binders and mixtures offers great support to the use of the nonrecoverable compliance as a performance-related parameter for binders.

RESUMO

Esta pesquisa teve por objetivo a análise do desempenho de ligantes asfálticos modificados com ácido polifosfórico (CAP+PPA) e terpolímero Elvaloy® com PPA (CAP+Elvaloy+PPA) à deformação permanente na escala do CAP – fluência e recuperação sob tensão múltipla (MSCR) a 64 e 70ºC – e da mistura (flow number a 60ºC – FN). O modelo de Burgers foi ajustado aos dados a 0,1 kPa para permitir uma investigação mais aprofundada dos padrões de comportamento dos materiais. O CAP puro tem classificação 64-22 e as formulações, 76-22 (CAP+PPA) e 76-28 (CAP+Elvaloy+PPA). Redes poliméricas resistentes e espalhadas na matriz asfáltica podem justificar os melhores resultados do CAP+Elvaloy+PPA quanto ao MSCR e ao FN. O CAP+PPA apresentou grande resistência segundo o MSCR, mas incrementos pequenos de resistência segundo o FN. Ordenamentos similares para os ligantes e as misturas asfálticas conferem grande suporte ao uso da compliância não-recuperável como um parâmetro de desempenho do CAP à deformação permanente.

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 pavement high 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 (Arshadi, 2013; Golalipour, 2011). 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 significant property to be evaluated in the laboratory (Sefidmazgi *et al.*, 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 so far in the literature by following the Multiple Stress Creep and Recovery (MSCR) test protocols, and the AASHTO T 350 (AASHTO, 2019b) and the ASTM D7405 (ASTM, 2015) standards are currently adopted in the US to carry out the standardized experiments. 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 (Domingos *et al.*, 2017; Golalipour, 2011; Klinsky *et al.*, 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 *et al.*, 2017b), it is believed that increases in the standardized stress level from 3.2 kPa to values of 10 kPa or higher (Golalipour *et al.*, 2017; Wasage *et al.*, 2011) – amongst other refinements – can address these deficiencies.

The Flow Number (FN) tests are the mostly used ones in Brazilian studies (Bastos *et al.*, 2017a, 2017b). 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 60ºC. This maximum temperature of 60ºC has been commonly observed for pavements located in the southern region of Brazil (Fontes *et al.*, 2010; Matos, 2017), thus requiring binders graded as 64-xx. However, some regions of the country demand binders graded as 70-xx due to their climatic conditions (Cunha *et al.*, 2007).

The incorporation of polymers into the binder is a widespread procedure for improving the resistance of the original material against rutting. Amongst 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 (Bulatović *et al.*, 2014; Yildirim, 2007). 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 50ºC 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.

1.1. Gaps and Research Objectives

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; Khader *et al.*, 2015; Lv *et al.*, 2019; Reinke *et al.*, 2012) or creep tests (Tabatabaee e 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 pavement high temperatures equal to 64 and 70ºC in the MSCR tests, as well as the corresponding dense-graded mixtures at 60ºC in the FN tests. These analyses at the binder scale were further correlated with parameters from a rheological model commonly used in the literature, i. e., the four-element Burgers model (Bahia *et al.*, 2001; Golalipour, 2011, 2020) and its corresponding spring and dashpot elements. The following are the secondary objectives of the investigation:

- To correlate binder rutting performance – as provided by the J_{nr} values and oscillatory shear-based parameters – with mixture rutting performance (as provided by the F_N values), in an attempt to identify similarities and differences between the rankings of materials;
- 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; 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, CE, Brazil). This binder is graded as 50/70 in the Brazilian penetration grade specification (DNIT, 2006) and 64-22 in the Superpave® specification (AASHTO, 2019a). The 4170 Elvaloy® terpolymer was provided by DuPont™, which contains 8% of glycidylmethacrylate by weight and presents density of 0.94 g/cm^3 and maximum processing temperature of 280ºC. The Innovalt® 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, 2019a), as well as continuous grades between 76.0 and 78.0ºC. 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 81.99ºC.

Both the AC+PPA (76-22) and the AC+Elvaloy+PPA (76-28) were prepared on a Fisatom 722D low-shear mixer. The incorporation of PPA into the AC+Elvaloy formulation has been a common practice in the technical 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 *et al.*, 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 be observed in the present investigation as well, in that the high PG grade of the base material increased by 12ºC – two grades – after the addition of 2.0% of PPA.

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

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

[a] PPA was added to the AC+Elvaloy after a mixing time of 60 min.
[b] The rotational viscosity tests were performed with the spindle 21 and according to ASTM (2006).
[c] Oscillatory tests conducted according to ASTM (2008) and on binders aged in accordance with ASTM (2012).

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 δ at 64 and 70ºC – the average was computed with two replicates for each formulation. The original Superpave® 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 unaged binders. The calculations of $G^*/sin\delta$ in the short-term aged condition of the binder (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 *et al.*, 2017), some experimental findings revealed that this is not always the case (Saboo e Kumar, 2016). Therefore, more correlations are required to gain further insights about this issue.

The MSCR experiments (AASHTO, 2019b; ASTM, 2015) were conducted in the same AR-2000ex DSR and at the same temperatures used in the oscillatory shear tests. Two replicates were considered for each binder type, and the percent recoveries (R) and the nonrecoverable creep compliances J_{nr} were calculated at both standardized stress levels of 0.1 and 3.2 kPa. The stress sensitivity of these binders was evaluated not only according to the Superpave® 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 *et al.* (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).

$$J_{nr,diff}(\%) = \frac{J_{nr}3200 - J_{nr}100}{J_{nr}100} \times 100 \qquad (1)$$

$$J_{nr,slope}(\%) = \frac{J_{nr}3200 - J_{nr}100}{3.1} \times 100 \qquad (2)$$

where $J_{nr}100$: nonrecoverable compliance at 0.1 kPa [kPa^{-1}]; and
$J_{nr}3200$: nonrecoverable compliance at 3.2 kPa [kPa^{-1}].

2.2. 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 are summarized in Table 2. Basaltic aggregates from the Bandeirantes quarry (São Carlos, SP, 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 60ºC, as it is a representative value of the highest expected pavement temperature in several regions of Brazil (Cunha *et al.*, 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[a]	%	6.9 to 7.1	6.9 to 7.1	6.8 to 6.9
mixing temperatures[b]	ºC	151 to 156	165 to 171	179 to 184
targeted mixing temperature[c]	ºC	154	168	177
compaction temperatures[b]	ºC	140 to 144	154 to 159	166 to 173
targeted compaction temperature[c]	ºC	142	157	170

[a] The targeted air voids in all samples was fixed at 7.0%.
[b] The mixing and compaction temperatures were calculated according to ASTM (2009).
[c] The mixing and/or compaction temperatures were limited to 177ºC to avoid overheating and reduce fume emissions.

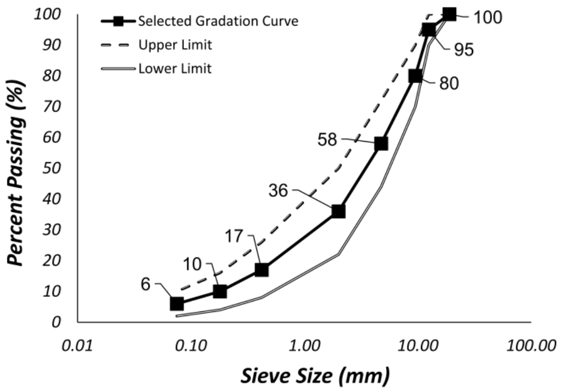

Figure 1: Aggregate gradation curve used in the preparation of the mixture specimens

2.3. 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 e 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 η_M), and the viscoelastic response (spring element E_K and dashpot element η_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.

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

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

where σ_0: applied stress [kPa];
t: test time [seconds]; and
t_F: creep time [seconds].

The ratio η_K over E_K is known as the retardation time λ, 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 λ 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 (2019) in their current versions of the MSCR standards. One additional possibility may be a substantial increase in t_F such that $t_F >> \lambda$, which was adopted in the experiments carried out by Merusi (2012).

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 ($J_{nr}3200$). As can be seen, the presence of PPA 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, the decreases in J_{nr} ranged from 88 up to 91% under all testing conditions. These substantial degrees of improvement in stiffness can also be implied by the appropriate traffic levels assigned to the asphalt binders, in that the AC+PPA may deal with heavy to extremely heavy traffic (depending on the temperature) 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 64ºC. 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 64ºC, $N > 3{\times}10^7$ for the AC+Elvaloy+PPA at both temperatures and $10^7 < N < 3{\times}10^7$ for the AC+PPA at 70ºC (Anderson, 2014).

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

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

[a] S = standard traffic; H = heavy traffic; V = very heavy; E = extremely heavy traffic level (AASHTO, 2019a).
[b] The best results for R and J_{nr} (i. e., higher recoveries and lower compliances) are highlighted in bold.

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% either at 64ºC or at 70ºC. 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 70ºC, 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 depicted 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 reactions between Elvaloy® and the base asphalt binder, as pointed out above.

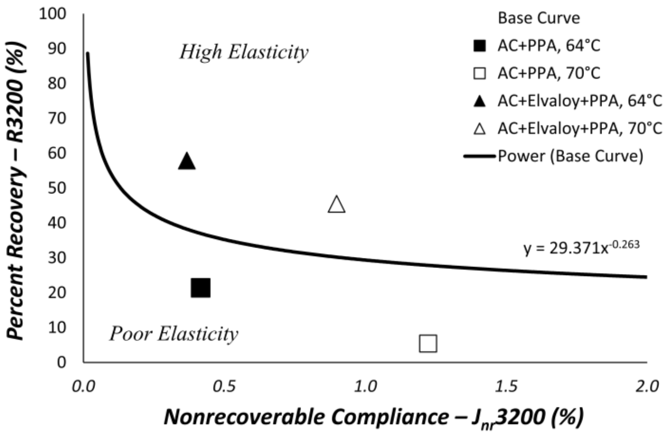

Figure 2: Levels of elasticity of the AC+PPA and the AC+Elvaloy+PPA at 64 and 70ºC

Figure 3 shows the values of the stress sensitivity 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 *et al.* (2018), as some modified binders with very small J_{nr} values typically depict $J_{nr,diff}$ values above 75%. Neither the AC+Elvaloy+PPA nor the AC+PPA exceeded the maximum allowed $J_{nr,diff}$ value of 75% set by Superpave® (AASHTO, 2019a) and, other than being in accordance with previous publications (Bessa *et al.*, 2019; Pamplona *et al.*, 2012), 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 greater at 64ºC than at 70 ºC.

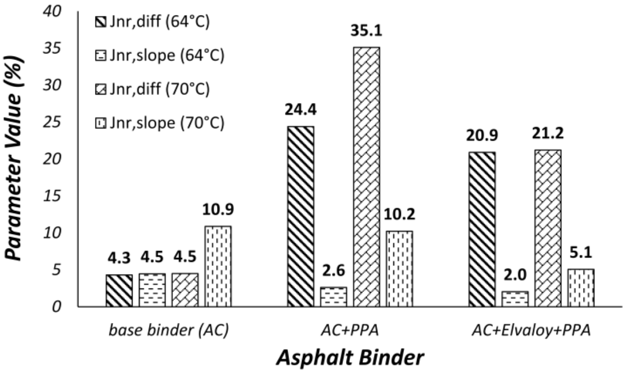

Figure 3: Percent differences ($J_{nr,diff}$) and percent slopes ($J_{nr,slope}$) between the nonrecoverable compliances of the asphalt binders at 0.1 and 3.2 kPa

3.2. Parameters of the four-element Burgers model

Table 4 summarizes the spring elements E_M and E_K and the dashpot elements η_M and η_K of the AC+PPA and the AC+Elvaloy+PPA, together with their corresponding λ 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 70ºC when moving from the formulation with Elvaloy+PPA to the one only with 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 λ values are about 12% and 235% greater for the Elvaloy-modified binder than for the PPA-modified binder at 64 and 70ºC, 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 (λ) and Average Absolute Errors (AAEs)

asphalt binder and temperature	results for each parameter				λ (s)	AAE (%)
	E_K (Pa)[a]	η_K (Pa.s)[b]	E_M (Pa)[a]	η_M (Pa.s)[b]		
AC+PPA, 64ºC	3,394.51	7,099.48	30,150.63	2,456.14	2.09	1.00
AC+PPA, 70ºC	11,735.04	7,960.25	17,165.74	945.79	0.68	0.38
AC+Elvaloy+PPA, 64ºC	900.68	2,120.92	13,414.80	2,057.62	2.35	2.90
AC+Elvaloy+PPA, 70ºC	578.20	1,318.37	7,484.77	963.28	2.28	2.32

[a] E_M = isolated spring of the Maxwell model; E_K = spring of the Kelvin-Voigt model.
[b] η_M = isolated dashpot of the Maxwell model; η_K = dashpot of the Kelvin-Voigt model.

In addition to depicting greater elastic strains, the AC+Elvaloy+PPA also contains lower viscous strain – that is, a higher η_M value – than the AC+PPA at 70ºC. This implies that the lower J_{nr} values of the AC+Elvaloy+PPA at 70ºC 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 64ºC, they may be explained by a major role of the elastic strain on the overall response of the material. Furthermore, the determination of λ 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 the MSCR test. The calculations of R and J_{nr} in the last cycles at 0.1 kPa, as prescribed by AASHTO (2019b) and ASTM (2015), were adopted as an alternative to deal with the delayed elasticity of the formulations, especially those with high levels of elastic responses (Golalipour, 2011).

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 $J_{nr}3200$ (Table 3) at each temperature are also given in the same table. The ranges of COV's are in accordance with other studies such as Apeagyei (2014), and the AC+Elvaloy+PPA is the most rut resistant formulation at the mixture scale. According to the criteria developed by Bastos *et al.* (2017a), the three asphalt mixtures would be suitable for extremely heavy traffic on pavements at 60ºC because their F_N values are all greater than 1,000 cycles. These classifications are similar to those obtained for the AC+PPA and the AC+Elvaloy+PPA at 64ºC, as well as the AC+Elvaloy+PPA at 70ºC (see Table 3).

Table 5: Mixture rutting parameters and rankings of binders and mixtures

description (parameter or ranking)	results for each formulation[b]		
	base binder (AC)	AC+PPA	AC+Elvaloy+PPA
flow number F_N @ 60ºC (cycles)	2,167	2,533	7,050
assigned traffic level (Bastos *et al.*, 2017a)[c]	E	E	E
coefficient of variation (%)	4.49	8.22	24.82
ranking of mixtures (F_N)[a]	3	2	1
ranking of binders ($G^*/sin\delta$ @ 64ºC)[a]	**3**	1	2
ranking of binders ($G^*/sin\delta$ @ 70ºC)[a]	**3**	1	2
ranking of binders ($J_{nr}3200$ @ 64ºC)[a]	**3**	**2**	**1**
ranking of binders ($J_{nr}3200$ @ 70ºC)[a]	**3**	**2**	**1**

[a] 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 $J_{nr}3200$ values) received the first positions.
[b] The ranking of mixtures was used as reference to all rankings of binders. Similar positions are highlighted in bold.
[c] Traffic levels recommended to the mixtures according to their F_N values and the approach proposed by Bastos *et al.* (2017a). E = extremely heavy traffic ($F_N > 1{,}000$ and $N > 3\times10^7$).

Similarly to the conclusions drawn by Bahia *et al.* (2001) and Domingos *et al.* (2017), the outcomes of the parameter $G^*/sin\delta$ were found unsuitable to estimate the rutting resistance of the mixture according to F_N. The rankings based on $G^*/sin\delta$ and F_N were totally reversed for the two studied formulations, which clearly 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 $J_{nr}3200$ yielded rankings similar to those of the mixtures both 64 and at 70ºC, which is in close agreement with opinions expressed by several researchers (Bessa *et al.*, 2019; Domingos *et al.*, 2017; Klinsky *et al.*, 2020; Saboo e Kumar, 2016). In other words, the nonrecoverable compliance at 3.2 kPa and derived from the MSCR test finds support in this study to be used as a performance-related parameter in the estimation of rutting in the asphalt mixture at typical high pavement temperatures. However, caution must be taken when considering particular modification types such as PPA alone: despite the promising results of

$J_{nr}3200$ (binder data), the F_N values of this formulation were only 17% higher than the corresponding ones of the base material (mixture data). As highlighted by Lv *et al.* (2019), this may be explained by the ordinary elastic properties of the PPA-modified binder, and not specifically its improved degree of stiffness as suggested by $J_{nr}3200$.

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 at high pavement temperatures typically observed on Brazilian pavements (64 and 70ºC);
- Modification of a 50/70 base binder with PPA and Elvaloy+PPA not only increased its stiffness (lower nonrecoverable compliances), but also improved its elastic responses (higher percent recoveries). The best outcomes obtained for the AC+Elvaloy+PPA at 64 and 70ºC – and confirmed by mixture data and the verification of the degree of elasticity of the material according to AASHTO TP 70-13 – suggest that several polymer networks were developed in the binder phase, as well as a strong polymer structure (which could not be seen for the AC+PPA);
- Neither the AC+PPA nor the AC+Elvaloy+PPA were found to be overly stress sensitive according to the Superpave® specification, since the 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 this new parameter does not penalize formulations with very small compliances – especially the polymer-modified ones;
- The data obtained by fitting the raw strains to 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 asphalt mixtures according to their flow number values at 60ºC were similar to those based on the nonrecoverable compliances of the binders at 64 and 70ºC. On the other hand, the rankings based on oscillatory shear data showed fully 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 those prepared with PPA), the nonrecoverable compliance calculated at 3.2 kPa finds great support in the study to be used as a performance-related rutting parameter for asphalt binders.

Acknowledgments

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

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