Effect of Different Creep and Recovery Times on the MSCR Test for Highly Modified Asphalt Binder

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ABSTRACT

The development of the multiple stress creep and recovery (MSCR) test represented an improvement in the evaluation of rutting susceptibility of asphalt binders. However, the creep and recovery times of the current test protocol (1 and 9 seconds, respectively) may not be adequate to predict performance under extremely heavy and slow traffic conditions or to allow full recovery of polymer modified binders. Highly modified asphalt binders have been increasingly used in pavements under severe traffic and weather conditions, and, because of the higher polymer content in these materials, they can be more sensitive to variations in loading times and stresses. However, the influence of different loading times has not been investigated in detail for these materials yet. In this paper, the effect of longer creep and recovery times on the MSCR test was evaluated for a highly modified asphalt binder, and the results were compared with those obtained for a neat asphalt binder and a regular SBS modified binder. Tests were carried out at the high PG temperature of each binder and three situations were analyzed: (i) the increase of creep time to 2,

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4 and 8 s; (ii) the increase of recovery time to 240 and 500 s; and (iii) the increase of both times simultaneously, to 2/18 s and 3/27 s. The highly modified binder analyzed was more susceptible to variation in creep and recovery times than the other binders and showed considerable increase in compliance due to nonlinear behavior, although there is no evidence that this was caused by the high polymer amount in this material. The results support the need of further investigation in this subject for future refinements in the MSCR test protocol and the specification criteria for slow or standing traffic, so that the susceptibility to longer loading times can be properly considered.

Keywords

highly modified asphalt, MSCR, loading times, rheology, performance grade

Introduction and Background

Although the major factors that influence rutting resistance of an asphalt mixture are related to the stability of the aggregate skeleton, the asphalt binder plays an important role as it can take part of the stresses away from the particle contacts and inhibit irreversible slips between aggregates. However, this ability depends on factors that include binder properties, air voids in the mixture, temperature and traffic conditions [1,2]. For this reason, the selection of an adequate binder for each situation is of great importance. Until the development of the Superpave mix design method in the 1990s, in the United States, and the adoption of the performance grading (PG) system, empirical parameters such as penetration, softening point, Saybolt-Furol viscosity and ductility were used for binder selection and characterization. After that, specifications began to adopt rheological parameters, which consider effects of the viscoelastic behavior that is typical of asphalt materials, and that had previously been ignored [3]. One of the goals of the Superpave method was to identify rheological properties of binders that could be directly related with their field performance [4]. As a result, the parameter $|G^*|/\sin\delta$ (where $|G^*|$ is the complex modulus and δ is the phase angle, both at a frequency of 10 rad/s) was adopted as a means to characterize the rut potential of binders and to determine their high temperature PG. The concept behind this parameter is the work dissipated during each loading cycle, which is related to the accumulation of permanent deformation and is affected by the total resistance to deformation (represented by $|G^*|$) and the relative elasticity of the binder (reflected by δ) [3]. Despite the great improvement brought by the use of rheological parameters to the characterization of asphalt binders, the parameter $|G^*|/\sin\delta$ has not established itself as a reliable indicator of rut resistance, especially for modified asphalt binders [4–11]. That led to a search for improvements on the specification, resulting in the development of the multiple stress creep and recovery (MSCR) test.

THE MSCR TEST

The MSCR test was developed with the aim of being a simple and easy-to-use procedure to determine the high PG temperature of asphalt binders, based on their performance in the field and suitable for characterization of modified materials [7]. According to D'Angelo et al. [8], the MSCR is based on the RCRT (repeated creep and recovery test), in which a constant shear stress is applied on the binder sample for 1 s and then removed, letting the sample rest for 9 s before a new creep stress is applied. By applying successive cycles of creep and recovery, the test tries to reproduce the type of loading that occurs in the field. The RCRT, however, was carried out using one single stress level, and it came to light that the behavior of some asphalt binders was sensitive to the applied level of stress and strain [6]. Therefore, the test protocol was adapted to apply 11 levels of stress, ranging from 0.025 to 25.6 kPa, with 10 cycles for each of them, and became known as the MSCR test. Later on, the test protocol was standardized and only two stress levels were kept: 0.1 kPa and 3.2 kPa [12].

The current test procedure, ASTM D7405-15, *Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer* [13], includes 10 additional conditioning cycles at 0.1 kPa. Domingos and Faxina [14] verified that this change in relation to the previous versions of the test significantly affects the results in a positive way, especially for the characterization of polymer modified binders. As established in AASHTO M332-14, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test* [15], the non-recoverable compliance (J_{nr}) obtained through the

MSCR test can now be used for determining the high temperature PG of binders, since this parameter has shown good correlations with rutting results for asphalt mixtures in laboratory and field [7]. Another parameter that results from the MSCR test is the percent recovery ($R_{\%}$), which is very sensitive to binder modification [9,12]. An important feature of the MSCR test is its ability to characterize the response of asphalt binders outside of the linear viscoelastic region, since modified binders may show nonlinear behavior at much lower stress levels [7,8].

Despite the advantages and benefits of the MSCR test, there are still some concerns regarding the current test protocol and the criteria adopted in the specifications. For example, it is not known for sure to what extent the stress levels of 0.1 kPa and 3.2 kPa represent adequately the stresses that reach the binder inside the asphalt mixture. Indeed, Gardel, Planche and Dreessen [9] have found stronger correlations between binder MSCR results and mixture rutting performance when stresses higher than 6.4 kPa were used. There are also doubts regarding the number of cycles, which may be too low for reaching a steady-state response of the binder or for characterizing long-term permanent deformation [6,16,17].

One especially important debate is about the creep and recovery times applied in the MSCR test. The times of 1 s for creep and 9 s for the recovery portion of each cycle were initially established based on the results obtained by Bahia et al. [5] for repeated creep tests that preceded the MSCR [12]. However, one of the existing concerns is that this recovery time may be too short to capture the delayed elastic response of some modified binders [8,16]. On the other hand, some researchers believe that creep times longer than 1 second might be necessary for an adequate characterization of binder response under heavy and slow traffic situations [18].

The standard MSCR test, with 1 s creep and 9 s recovery cycles, was validated by correlating the results of J_{nr} with field and laboratory rutting experiments. The stress level of 3.2 kPa provided the best correlation for a typical traffic situation in the I-55 Mississipi Field Study [7]. However, as described by D'Angelo [7], for results obtained with the FHWA's accelerated loading facility (ALF) and the Hamburg Wheel Tracking test, good correlations were not obtained and better ones were achieved by increasing stress levels to 25.6 and 12.8 kPa, respectively. In both situations, the asphalt mixtures were subjected to high loads with slow speed and high constant temperature, and it is possible that improved correlations might be obtained by changing the creep and recovery times, to account for the reduced load speeds.

In a typical traffic situation, as the one observed in the I-55 Mississipi test sections, there is a mix of different loadings, speeds and temperatures, but for unusual situations with extremely heavy and slow or standing traffic, combined with high temperatures, it is possible that the standard MSCR test does not correlate so well to what happens in the field. Al-Qadi et al. [19] observed in the Virginia Smart Road project that the duration of the loading pulse in an actual pavement is mostly affected by the vehicle speed and the depth beneath the pavement surface, and it can vary from 0.02 s for a vehicle speed of 70 km/h and a depth of 40 mm to 1.0 s for a vehicle speed of 10 km/h at a depth of 597 mm. For a constant depth, the reduction of vehicle speed from 72 to 8 km/h can result in a loading pulse up to 15 times longer [19]. Therefore, an adjustment of the creep and recovery times of the MSCR test might improve the correlation between field rutting and the J_{nr} parameter in such situations. The authors also concluded that vehicle speed does not affect the magnitude of the vertical stress under the asphalt layer, hence an increase in stress have not the same effect as an increase in the loading time.

As a result of these uncertainties, a number of studies in the literature investigated the influence of variations in the creep time, in the recovery time, and in both times simultaneously, on the results of the MSCR test.

INCREASE OF CREEP TIME

Kataware and Singh [20] investigated the effect of increasing creep time from 1 to 2 s, maintaining the original recovery time of 9 s. Three asphalt binders were evaluated (one unmodified, one SBS modified and one crumb rubber modified binder) and, as the creep time was increased, an increase on J_{nr} and a reduction on $R_{\%}$ were observed. However, the magnitude of these changes depended on the binder type and the testing temperature.

The same was observed by Domingos [12], who tested 12 modified binders, all of them PG 76-xx, using creep times of 1, 2, 4 and 8 s, with 9 s of recovery on each cycle. Each binder responded differently to the increase in loading time, what was related to their elasticity, the reaching of the steady state condition and the rearrangement of polymer chains within the material. This led to the conclusion that, since binders that show similar results in the standard test protocol can behave differently when creep time is increased, it is important to consider this behavior when selecting binders that will be subjected to very low or standing traffic. From this same perspective, Domingos and Faxina [18] recommended that the current specifications were refined and the MSCR test with longer creep times was used for selecting binders for slower traffic situations.

INCREASE OF RECOVERY TIME

The existing concerns about the recovery time of the MSCR test come from the fact that modified binders may take different time periods to recover from the application of a creep stress [8]. This was verified by Delgadillo, Bahia and Lakes [16], who observed that some binders may take more than 1,000 s for a full recovery of the delayed elastic strain, even for lower levels of stress. Domingos [12] applied longer recovery times to analyze their effects on the MSCR test results. A recovery time of 500 s was used for binders considered highly elastic and 240 s was used for the others, all of them polymer-modified with PG 76-xx, and it was observed that these increased recovery times were able to minimize the influence of delayed elasticity on the results. Kataware and Singh [20] showed that recovery times two or three times longer than the standard one (18 and 27 s) are already high enough to impact the test results, depending on the asphalt binder.

INCREASE OF CREEP AND RECOVERY TIMES

Another possibility that has been approached in the literature is the increase of both creep and recovery times simultaneously, while maintaining the same ratio between them (1:9). What was observed by Kataware and Singh [20] and Domingos and Faxina [21] is that when this is done, the result is an increase in J_{nr} and a reduction in $R_{\%}$, showing that the increase in creep time has a more pronounced effect than the increase in recovery time. Therefore, increasing both times together can also be an option to represent more severe traffic conditions.

HIGHLY MODIFIED ASPHALT BINDERS

Although the mentioned studies have analyzed several types of asphalt binders, none of them studied the effect of longer creep and recovery times on the behavior of a highly modified asphalt binder (HiMA). This type of binder contains a different type of SBS polymer, which can be incorporated in asphalt materials in higher amounts without showing compatibility or workability issues. While most of the SBS-modified binders contain from 2% to 3% of polymer in their composition, polymer content in HiMA binders can range between 7% and 8% [22,23]. Because of the ability of the SBS to absorb some of the asphalt components and swell, the material goes through a phase inversion and the polymer becomes a fully continuous phase, what leads to significant improvements on the binder properties [24]. This way, these binders behave more like a bitumen-modified polymer than like a polymer-modified bitumen [25].

Such level of modification can increase resistance against fatigue, rutting, thermal cracking and reflective cracking, what makes this material suitable for several applications, such as perpetual asphalt pavements, thinner pavement structures and stress relief asphalt mixtures for mitigating reflective cracking [26–31]. Despite these advantages, the high amounts of polymer may result in behaviors that are not usual for other asphalt binders, since the material response is more affected by the polymeric phase.

Objectives

Bearing in mind that time can strongly influence the results of the MSCR test and rutting behavior, and that this influence may be different for each type of material, it is important to understand how this variable affects the response of a HiMA binder, which is a relatively new type of material and which behavior is more linked to the polymer in its composition. Therefore, the present study aims to evaluate how the response of a HiMA binder changes when different creep and recovery times are used in the MSCR test, by analyzing the variation of J_{nr} and $R_{\%}$ in relation to the standard test protocol. The same effect is assessed for a neat binder and a regular SBS modified binder.

The findings of this study will provide evidence that polymer-modified asphalt binders can have their behavior greatly affected by changes in load time, and the adjustment of creep and recovery times in the MSCR test might be a useful tool to predict more accurately their performance in the field, for unusual traffic situations with extremely heavy and slow vehicles. In the current specification, these situations require lower values of $J_{nr3.2}$, but it will be demonstrated that binders with low compliance levels can be affected in different ways by different creep and recovery times, therefore considering the effect of load duration can be more effective than limiting J_{nr}., to obtain an insight of how proper consideration of loading time may be important for a more precise characterization of asphalt materials, especially for those that will be used in very slow or standing traffic situations.

Materials and Methods

RHEOLOGICAL CHARACTERIZATION OF ASPHALT BINDERS

In the present study, three asphalt binders were analyzed: one HiMA binder, one standard SBS-modified binder (classified as 60/85 in the Brazilian grading specification), and one neat binder (penetration grade 30/45). All of them were commercial binders, and modification was performed by the suppliers. The exact content of polymer in each of the modified binders is not known.

Characterization of linear viscoelastic properties of the asphalt binders was performed using the dynamic shear rheometer (DSR), with the 25 mm parallel plate geometry and 1 mm gap setting. Tests were conducted following the guidelines in ASTM D7175-15, *Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer* [32]. Prior to evaluation, short-term aging simulation was carried out for all binders by means of the rolling thin film oven (RTFO) procedure according to ASTM D2872-12e1, *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)* [33]. Frequency sweep oscillatory tests were performed from 0.2 to 30 Hz, in temperatures from 40 to 76°C, at 0.1% strain. $|G^*|$ and δ were obtained and time-temperature superposition was applied to construct the master curves at a reference temperature of 40°C, which are presented in Figs. 1a and 1b.

The slopes of the $|G^*|$ master curves show how both modified binders are less sensitive to time and temperature variations than the neat binder 30/45, within the linear viscoelastic region. The SBS 60/85 and HiMA binders showed very similar values for $|G^*|$, except for lower frequencies (which are equivalent to higher temperatures), where HiMA was slightly stiffer. Regarding δ, the difference between the unmodified and the modified binders was even more pronounced. While δ values were approximately the same for high frequencies, for lower frequencies δ was higher for the 30/45 binder and lower for SBS 60/85 and HiMA binders, which approached a more elastic behavior. Lower values of δ were observed for HiMA, when compared to the SBS 60/85, indicating higher elasticity even for lower frequencies.

The high temperature PG of each binder was determined following the AASHTO M332-14 specification, which uses results of the MSCR test for grading the materials. This method allows an asphalt binder to be graded at different temperatures depending on the traffic loading condition [34]. PG was determined assuming all binders would be used in a situation of extremely heavy traffic (designation "E", for 30 million ESALs and traffic speed lower than 20 km/h), limiting $J_{nr3.2}$ to the maximum of 0.5 kPa^{-1}. This was done to obtain the temperatures at which the three binders show similar values of $J_{nr3.2}$, so that the variation of this parameter could be evenly compared for all binders. Results of PG determination are presented in Table 1, where $J_{nr,diff}$ is the stress sensitivity parameter.

Results obtained for the standard MSCR tests at the selected temperatures put in evidence the high recovery of the modified binders, especially for HiMA, which showed more than 88% of recovery even at a temperature higher than SBS 60/85. It is interesting to observe that the 30/45 binder was classified with a low PG temperature, of 52°C, even though it is a relatively stiff binder. In fact, if this binder is graded following the standard AASHTO M320-16, without using the MSCR test, the high PG temperature obtained is 70ºC, as presented in Table 1. However, its poor recovery and the low threshold established for J_{nr} (for traffic designation "E") leaded to a lower PG.

For the HiMA binder, $J_{nr,diff}$ exceeded the limit of 75% established in the PG specification. This parameter indicates the stress sensitivity, and is calculated from the percent difference between $J_{nr0.1}$ and $J_{nr3.2}$. The limitation of $J_{nr,diff}$ aims to ensure that the performance is not abruptly compromised when stresses or temperatures higher than expected experienced by the pavement, and U.S. agencies and suppliers have reported challenges with attending to the 75% limit, especially for modified binders with very low J_{nr} [35]. White [36] reported the same issues with highly modified binders in Australia, and related them to the extremely low values of $J_{nr0.1}$ of these materials, pointing out that the properties of the base binder can contribute to elevate $J_{nr,diff}$. Due to the lack of documented correlations between $J_{nr,diff}$ and changes in field performance, and since many binders have shown good performance without attending to the 75% limit, this requirement has been questioned by many researchers [35]. Given this background, it was decided to maintain the 82E-xx grading for HiMA in the present study, even with the $J_{nr,diff}$ requirement being exceeded.

One curious result regarding $J_{nr,diff}$ was the negative value of -16.2% obtained for the SBS 60/85 binder, which indicates that J_{nr} was reduced when stress was increased from 0.1 to 3.2 kPa. Results of this type are not commonly found in the literature, and in some cases are attributed to test variability, as in Domingos and Faxina [37]. For the case observed in the present study, negative $J_{nr,diff}$ values were obtained for different samples of the SBS 60/85 binder, even for different temperatures and for some of the tests with different loading times that are presented further, what weakens the hypothesis that it was caused by test variability.

EXPERIMENTAL PLAN

After the characterization and grading of the asphalt binders, MSCR tests with different creep and recovery times were conducted. These tests were conducted at the high PG temperature of each binder (for traffic designation “E”), which was previously determined, in order to obtain similar $J_{nr3.2}$ values for all binders in the standard test (1/9 s test) and allow comparisons of the percent variation of this parameter due to changes in creep and recovery times. Therefore, the 30/45 binder was tested at 52°C, SBS 60/85 was tested at 76°C and HiMA was tested at 82°C.

The selection of different testing ~~these~~ temperatures ~~also~~ has allowed the evaluation of the binders at the maximum temperatures they may experience in the field, according to the specification, which would be critical for rutting distresses (although situations where the pavement temperature reaches 82°C, for example, are not often seen). The idea was to evaluate the materials at the temperatures they would probably be applied in real world situations, having in mind that they are considerably different materials, and would not be considered for the same situation. It is important to emphasize that this choice of test temperatures aims to identify different trends of behavior, and does not allow performance comparisons between binders, as it gives advantage to 30/45 (lowest temperature) and disadvantage to HiMA (highest temperature). Additional tests with increased creep time were conducted at the same temperature for all binders (76°C), in order to identify the real influence of temperature over the results.

In addition to the standard MSCR test (1/9 s), tests were conducted with longer creep times of 2, 4 and 8 s (2/9 s, 4/9 s and 8/9 s, respectively), longer recovery times of 240 s and 500 s (1/240 s and 1/500 s) and longer creep and recovery times combined, of 2 s creep and 18 s recovery (2/18 s) and 3 s creep and 27 s recovery (3/27 s). These combinations of creep and recovery times were the same used in previous studies found in the literature, from ~~selected in order to allow comparisons with results from~~ Domingos [12], Kataware and Singh [20] and Domingos and Faxina [21], and were chosen to allow comparisons between the results for different types of asphalt binder, including those found by other researchers. These times are not based on actual field conditions, but were chosen aiming to simulate increases of creep and recovery times in different levels. Mimicking field conditions is extremely complex, and the goal was to understand the effect of longer creep and recovery times over different types of asphalt binder. All the results presented below are the average of two samples.

Results and Discussion

EFFECT OF INCREASED CREEP TIMES

Results obtained for the tests with increased creep times are presented in Table 2. The percent increases of J_{nr} in relation to the standard 1/9 s test were also calculated and are shown in Fig. 2a. In order to eliminate the influence of temperature in the comparison between the three binders, ~~HiMA and SBS 60/85,~~ additional 1/9 s and 8/9 s tests were conducted for 30/45 and HiMA at 76°C, and the results are also presented in Fig. 2b. In a first comparison between the unmodified binder and modified ones, it is interesting to notice that for the 30/45 binder $J_{nr0.1}$ and $J_{nr3.2}$ were affected in a very similar way, even at 76°C, so $J_{nr,diff}$ was not greatly affected. On the other hand, the modified binders showed considerable changes in $J_{nr,diff}$ as creep time was increased. For SBS 60/85, the initial negative $J_{nr,diff}$ became increasingly higher reaching positive values on the 4/9 s and 8/9 s tests, but those were still very low when compared to the stress sensitivity levels achieved for HiMA at 82°C, which reached 2012.1%.

Not only stress sensitivity was strongly affected by the increase of creep time for HiMA at 82°C, but also $J_{nr3.2}$, that went from 0.22 to 15.31 kPa^{-1}, and $R_{\%3.2}$, that decreased from 88.4% to only 7.4%. Interestingly, such extreme changes were observed only for 3.2 kPa. At 0.1 kPa, percent increases in J_{nr} were very close for all binders, and HiMA showed much lower compliances than the others did. ~~Although different levels of sensitivity to creep time were observed for each binder, this fact can be partially attributed to the different temperatures at which they were tested.~~ At 76°C, HiMA presents lower levels of compliance than SBS 60/85, even with 8 seconds of creep in each cycle. The percent increase in $J_{nr3.2}$, however, was more than twice as high as that obtained for SBS 60/85, even though this can be at least partially explained by the extremely low values of $J_{nr3.2}$ at the 1/9 s test.

Even though 76°C is a very high temperature for the 30/45 binder, resulting in extremely high values of $J_{nr3.2}$, the percent increase of this parameter when creep time was increased to 8 s was still lower than that observed for the polymer modified binders at the same temperature, confirming that the effect of increased creep times observed is related to the type of material, and was not a result of the different testing temperatures adopted. The different testing temperatures affected the results of J_{nr}, but even at the same testing temperature HiMA was the most affected by the increase in creep time (at 3.2 kPa), and 30/45 was the less affected binder.

A deeper understanding of how creep time affected the MSCR results for these materials is possible by analyzing the cycle-to-cycle variations of J_{nr} in the different situations tested. The values of J_{nr} in each cycle are presented in Figs. 3a-d. For the tests conducted at 76°C, the results are shown in Figs. 4a-d. The initial 10 conditioning cycles at 0.1 kPa are not represented.

From these data, it is evident that the behavior of HiMA at 3.2 kPa was affected by creep time differently from the other binders and from HiMA itself at 0.1 kPa. For the three binders at 0.1 kPa and for 30/45 and SBS 60/85 at 3.2 kPa, J_{nr} is approximately constant throughout the 10 cycles, with small variations only in the first cycles at 3.2 kPa. For HiMA, however, $J_{nr3.2}$ gets higher at each cycle, and such increases are intensified as creep time in increased. In the standard 1/9 s test, the trend of increasing J_{nr} is slight but perceptible, while in the tests with longer creep times it becomes more evident. The same could be observed for the 8/9 s test with HiMA at 76ºC, as shown in Figs. 4a and 4b, confirming that this behavior is not a result of higher temperature only. In the 1/9 s test at 76ºC, however, the increase of J_{nr} in each cycle was not observed, even for 3.2 kPa. For the 30/45 binder at 76°C, an increase of $J_{nr3.2}$ at each cycle could be observed as well, but it was a much lower variation in relation to the initial $J_{nr3.2}$.

The fact that this deviant behavior seen for HiMA happened only when the stress level was 3.2 kPa indicates that it is not an effect of time only, but is also related to a nonlinear behavior induced by a high level of shear stress. As stated by Macosko [38], deviations from linear viscoelasticity occur when both strain and strain rate are not small during flow, and these two conditions can be achieved through the application of a high enough stress, for a long enough time. Delgadillo and Bahia [39] showed that, as stress is increased, the time needed for the transition between linear viscoelastic response and nonlinear viscoelastic response is reduced, and different asphalt binders may exhibit different levels of nonlinearity that become more pronounced with higher stress level and longer loading time. According to them, binder nonlinearity is directly related to permanent deformation in asphalt mixtures.

One nonlinear phenomenon that is especially pronounced in polymer melts, according to Macosko [38] is a shear-thinning effect (a reduction in viscosity with the increase in shear rate) related to the disentanglement of polymer chains. As it was observed by Kluttz and Stephens [40], very high strains can cause yield behavior in polymer-modified binders, as the material morphology changes. By analyzing how viscosity was affected during the creep portions of the tests, it was found that HiMA suffered a higher reduction in viscosity through each cycle, what could be related to the behavior observed. These data are presented in Figs. 5a-cd, where it is possible to see the viscosity overshoots and the viscosity drops that are characteristic of nonlinear viscoelastic behavior [38,41]. During creep flow, the variation in viscosity results from effects of time dependency and from the increase in shear rate, which interact in a complex way. In order to analyze these effects independently, constant shear rate experiments and steady shear flow curves would be necessary, which are out of the scope of this paper. However, those effects can be explained by changes in the organization of polymer molecules during stress application. When a constant stress is applied, the polymer network initially deforms within the mechanical limits of the network, due to the stretching of the molecules. Continuous strains lead to disentanglement of such molecules and to the dismantling of the network, and the polymer starts to flow [42]. Although nonlinear behavior was already expected for modified binders, it seems that HiMA was more distant from linearity than SBS 60/85 was, probably because of a more active dismantling of the polymer network, and that was determinant to the phenomena observed. As for the conventional 30/45 binder, viscosity did not change throughout the test cycles, and the behavior was closer to linearity. It is also important to remember that, although rutting behavior is related to the viscosity observed during creep cycles, it is also highly dependent on what happens during the recovery portion of each cycle, and that helps to explain why polymer-modified binders can show better performance without reaching higher viscosity values.

It is possible to conclude that the polymer network in HiMA binder formed a structure with lower compliance and higher elastic recovery, but the 3.2 kPa stress was high enough to dismantle it when applied for long enough times, at the considered temperatures. This caused extreme increases in J_{nr}, decreases in $R_{\%}$ and reduction in viscosity during time. The SBS 60/85 binder, on the other hand, was not affected in the same way by the increase in creep time, suggesting that its structure could resist to higher stresses without such extreme changes in behavior. Nevertheless, several factors were involved in the results obtained, such as properties of the base asphalt binders, properties of the polymers used for modification, polymer content in each material and temperature. Therefore, the behavior observed for HiMA cannot be attributed to the level of modification only without further experiments. However, it sustains the fact that different materials can respond in very different ways to the increase in loading time, depending on the stress level and temperature, and this is not being considered in the current specifications for very slow or standing traffic.

EFFECT OF INCREASED RECOVERY TIMES

In Table 3 the results of the MSCR tests with longer recovery times (1/240 and 1/500 s) are presented and compared to the 1/9 s test results. The percent decreases of J_{nr} in relation to the 1/9 s test are shown in Fig. 6. Results show that the increase of recovery time resulted in lower J_{nr} for all binders, including the unmodified one. This effect was higher for the modified materials, what is probably related to delayed elasticity in their behavior. An interesting trend was observed for the $J_{nr,diff}$ parameter, which was the opposite of that observed when creep times were increased. As the recovery time was increased, $J_{nr,diff}$ was reduced for both modified binders, reaching a negative value of -10% for HiMA and an even lower value of -35.5% for SBS in the 1/500 s test.

Another noticeable result was the increase in $R_{\%}$, which was also present for all binders tested. For the 30/45 binder, this increase was not high enough to bring $R_{\%}$ to significant levels.

For the polymer modified binders, the increase was higher at 3.2 kPa than at 0.1 kPa, reaching more than 90% of recovery. For HiMA, 500 s of recovery were enough for an almost full recovery of the samples.

In polymer materials, the microstructure is rebuilt during the recovery portions of each cycle and the entanglements between polymer chains are reformed. This way, the balance between structure dismantling during creep and the restructuration during the recovery period determines the new steady state behavior. This process is characteristic of time dependent behavior, and can involve both viscoelastic and thixotropic mechanisms [43]. Therefore, it is possible that the higher polymer loading in HiMA was responsible for the more pronounced effects of increasing recovery time, but, as stated in the previous section, several factors are involved in these results, which should be better investigated.

EFFECT OF INCREASED CREEP AND RECOVERY TIMES IN THE SAME PROPORTION

Finally, the results of MSCR tests with creep and recovery times increased in the same proportion are presented in Table 4, and the percent increases of J_{nr} are presented in Figs. 7a and 7b. The results showed a trend very similar to that observed when only the creep time was increased. For all binders, J_{nr} was higher and $R_{\%}$ was lower, indicating that the effect of increasing creep time is more pronounced than the effect of increasing recovery time, when the ratio between them is constant. HiMA was once again more sensitive to the changes in creep and recovery times, confirming the behavior that was observed in previous tests, but only at 3.2 kPa. At 0.1 kPa, the 30/45 binder was the most affected and HiMA suffered the lowest increase in J_{nr}, especially in the

3/27 s test. The SBS 60/85 binder, in turn, was less affected in terms of J_{nr} than the 30/45, for all tests. Regarding percent recovery, values were reduced as times were increased for all binders. As it can be observed in Figs. 8a and 8b, $J_{nr3.2}$ values for HiMA also sequentially increased in each creep-recovery cycle.

Summary and Conclusions

This paper describes a laboratory experiment in which a highly modified asphalt binder (HiMA), a regular SBS modified binder (SBS 60/85) and a neat binder (pen 30/45) were subjected to MSCR tests with different creep and recovery times. The effects of the increase in creep time to 2, 4 and 8 s, the increase in recovery time to 240 and 500 s, and the increase of both times simultaneously to 2 s creep and 18 s recovery, and 3 s creep and 27 s recovery, were evaluated. Tests were conducted at the high PG temperature of each binder (for traffic designation "E"), which was determined during the characterization of the materials, in order to obtain similar Jnr values for all binders in the standard 1/9 s test and allow comparisons of the percent variation of this parameter due to changes in creep and recovery times. Based on the results obtained, the following conclusions could be drawn:

- From the three asphalt binders tested, HiMA was the most affected by the changes in creep and recovery times, in terms of the MSCR test parameters used in current specifications ($J_{nr3.2}$, $J_{nr,diff}$ and $R_{3.2}$), for the conditions tested. For longer creep times, this binder presented higher increase in $J_{nr3.2}$and reduction in $R_{3.2}$ than the others, and for longer recovery times it experienced higher drop in compliance levels and higher gains in percent recovery. Such behavior might be related to the higher polymer content, although further experiments are necessary to confirm that, since other factors (like the properties of the base binder, the properties of the polymers used in modification, and the temperature) can influence as well.

- Results suggest that the sensitivity to time in the MSCR tests is closely related to the stress level applied. When 0.1 kPa was applied, the percent increase in J_{nr} was very similar for all binders, when creep time was increased. For 3.2 kPa, however, a clearer difference was observed between them, especially for HiMA, which could not reach the steady state after 10 cycles and suffered a considerable drop in viscosity throughout the test. HiMA binder presented more nonlinear viscoelastic behavior compared to the SBS 60/85 for this level of stress. The 3.2 kPa stress might be high enough for a more active dismantling of the polymer structure and lead to increased changes in overall behavior. Therefore, the determination of the stress levels that better relate to pavement behavior in the field is also important to characterize accurately the sensitivity of modified binders to different loading times.

- This paper provides evidence that ~~D~~different materials with similar levels of non-recoverable compliance in the standard MSCR test can behave in very different ways when subjected to longer loading times. However, this possibility is not taken into account by current specifications for very slow or standing traffic situations. The consideration of susceptibility to longer loading times may serve as a tool for selecting adequate binders for these situations more efficiently, and should be regarded as a possible refinement in future PG specifications. It is suggested that future studies try to correlate MSCR test results with different loading times and field rutting in extremely heavy and slow traffic situations.

- Based on the findings of this study, it is recommended that researchers consider the effect of loading time when dealing with rutting in extremely heavy and slow or standing traffic, and that adjustments in the creep and recovery times of the MSCR test be considered as tools to better predict the behavior of modified binders in such extreme situations.

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TABLE 1 Performance grade determination results for the asphalt binders.

Parameter		30/45	SBS 60/85	HiMA	Requirements (AASHTO M332-14)
Temperature, °C		52	76	82	-
$\lvert G^{*}\rvert / \sin\delta$, kPa (non-aged binder)		14.41	1.49	1.36	≥ 1.00
MSCR test (RTFO aged binder)	$J_{nr3.2}$, kPa^{-1}	0.23	0.30	0.22	< 0.50
	$R_{\%3.2}$, %	7.02	81.68	88.43	-
	$J_{nr,diff}$, %	2.1	-16.2	109.4	< 75.0
PG (AASHTO M332-14)		52E-xx	76E-xx	82E-xx	-
True PG grade, °C		55.9	79.7	84.0	-
PG (AASHTO M320-16)		70-XX	76-XX	82-XX	-

TABLE 2 Results of MSCR tests with increased creep times.

Binder	Test	$J_{nr0.1}$, kPa^{-1}	$J_{nr3.2}$, kPa^{-1}	$J_{nr,diff}$, %	$R_{\%0.1}$, %	$R_{\%3.2}$, %
30/45 (52°C)	1/9 s	0.230	0.235	2.2	8.7	7.0
	2/9 s	0.428	0.436	1.9	4.4	2.5
	4/9 s	0.828	0.847	2.4	1.2	0.0
	8/9 s	1.708	1.766	3.4	0.0	0.0
SBS 60/85 (76°C)	1/9 s	0.358	0.300	-16.0	83.2	81.7
	2/9 s	0.627	0.546	-12.8	80.0	75.0
	4/9 s	1.234	1.281	3.8	71.9	57.6
	8/9 s	2.665	3.511	31.7	58.8	31.7
HiMA (82°C)	1/9 s	0.103	0.216	109.4	95.0	88.4
	2/9 s	0.189	0.863	355.6	93.5	70.9
	4/9 s	0.396	4.353	999.6	90.0	32.2
	8/9 s	0.795	15.308	2012.1	84.8	7.4
30/45 (76°C)	1/9 s	8.441	8.890	5.3	0.0	0.0
	8/9 s	68.536	75.098	9.6	0.0	0.0
HiMA (76°C)	1/9 s	0.040	0.071	78.2	97.0	94.4
	8/9 s	0.332	1.662	400.8	89.6	55.0

TABLE 3 Results of MSCR tests with increased recovery times.

Binder	Test	$J_{nr0.1}$, kPa^{-1}	$J_{nr3.2}$, kPa^{-1}	$J_{nr,diff}$, %	$R_{\%0.1}$, %	$R_{\%3.2}$, %
30/45 (52°C)	1/9 s	0.230	0.235	2.2	8.7	7.0
	1/240 s	0.197	0.205	4.1	12.1	8.4
	1/500 s	0.188	0.203	7.8	15.9	8.7
SBS 60/85 (76°C)	1/9 s	0.358	0.300	-16.0	83.2	81.7
	1/240 s	0.240	0.158	-34.3	88.7	89.8
	1/500 s	0.197	0.127	-35.5	90.4	91.4
HiMA (82°C)	1/9 s	0.103	0.216	109.4	95.0	88.4
	1/240 s	0.056	0.061	10.2	97.4	96.5
	1/500 s	0.048	0.043	-10.0	97.8	97.5

TABLE 4 Results of MSCR tests with increased creep and recovery times.

Binder	Test	$J_{nr0.1}$, kPa^{-1}	$J_{nr3.2}$, kPa^{-1}	$J_{nr,diff}$, %	$R_{\%0.1}$, %	$R_{\%3.2}$, %
30/45 (52°C)	1/9 s	0.230	0.235	2.2	8.7	7.0
	2/18 s	0.427	0.434	1.6	4.7	2.9
	3/27 s	0.637	0.657	3.0	3.1	0.6
SBS 60/85 (76°C)	1/9 s	0.358	0.300	-16.0	83.2	81.7
	2/18 s	0.589	0.464	-21.3	81.6	78.9
	3/27 s	0.881	0.730	-17.1	78.3	72.8
HiMA (82°C)	1/9 s	0.103	0.216	109.4	95.0	88.4
	2/18 s	0.166	0.662	297.9	94.5	77.5
	3/27 s	0.207	1.178	468.4	93.9	67.1

List of Figure Captions

FIG. 1 Master curves of (a) dynamic modulus ($|G^*|$) and (b) phase angle (δ) of asphalt binders at 40°C after RTFO aging.

FIG. 2 Percent increases of J_{nr} in 2/9, 4/9 and 8/9 s tests, in relation to the standard 1/9 s test, for (a) binders at their PG temperature and (b) at 76°C.

FIG. 3 Values of J_{nr} for each creep-recovery cycle in (a) 1/9 s, (b) 2/9 s, (c) 4/9 s, and (d) 8/9 s tests.

FIG. 4 Values of J_{nr} for each creep-recovery cycle at 76°C in (a) 1/9 s for HiMA and SBS 60/85, (b) 8/9 s tests for HiMA and SBS 60/85, (c) 1/9 s tests for 30/45 and (d) 8/9 s tests for 30/45.

FIG. 5 Variation of viscosity during creep cycles on 8/9 s tests, at 3.2 kPa, for (a) HiMA at 76°C, (b) HiMA at 82°C, (c) SBS 60/85 at 76°C, and (d) 30/45 at 52°C and (e) 30/45 at 76°C.

FIG. 6 Percent decreases of J_{nr} in 1/240 and 1/500 s tests, in relation to the standard 1/9 s test.

FIG. 7 Percent increases of J_{nr} in 2/18 and 3/27 s tests, in relation to the standard 1/9 s test.

FIG. 8 Values of J_{nr} for each creep-recovery cycle in (a) 2/18 s and (b) 3/27 s tests.