Alternative Interpretation of the Adequate Traffic Levels of Crumb Rubber-Modified Binders on Superpave®

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ABSTRACT

The present study aims at proposing an alternative interpretation for the choice of modified asphalt binders on Superpave®, according to which heavier traffic levels described in the standardized binder classifications must comply with one additional requirement for the material to be graded as H, V or E. Here, one 50/70-penetration grade original binder (PG 64S-xx) was modified with crumb rubber, either with or without polyphosphoric acid – PPA (AC+rubber and AC+rubber+PPA). Both formulations are graded as PG 76-xx and were subjected to MSCR tests at five high pavement temperatures (52, 58, 64, 70 and 76°C) and four pairs of creep-recovery times (1/9, 2/9, 4/9 and 8/9 s). Decreases in the percent recoveries from 18 to 90% and increases in J_{nr} from 5 to 187% could be seen when moving from the AC+rubber to the AC+rubber+PPA. Interestingly, the AC+rubber+PPA showed a decrease by one grade in the traffic level (from E to V) at 58°C. This is an indication that the AC+rubber+PPA may be highly susceptible to rutting on pavements with too busy traffic and vehicles traveling at low speeds. Therefore, its use on such pavements must be made with caution in order to avoid the occurrence of premature failure by rutting.

Keywords: Crumb rubber, MSCR test, Superpave, creep time, traffic level.

1. INTRODUCTION

Rutting (or permanent deformation) is a critical distress mechanism that affects safety, comfort and the durability of flexible asphalt pavements. It can be described as depressions in the wheelpath, and mixture shearing – or pavement uplift – may also be observed on the sides of such depressions depending on the level of severity. In general, ruts lower than 0.33 in (or 0.84 cm) can be left untreated because they are not expected to seriously compromise the service life of the pavement and safety. On the other hand, deeper ruts demand levelling or overlaying services in the pavement structure [1].

It is known that the appearance of rutting in a pavement is due to the contributions of the asphalt binder and the aggregates after each loading-unloading cycle. Laboratory studies carried out by Bahia and co-workers [2] describe these contributions in terms of the accumulation of permanent deformation in the asphalt mixture. As cited by the authors, the binder seems to play a key role in the accumulation of rutting in the first few loading-unloading cycles, whereas the aggregates would play this major role in a region where the rate of accumulation of permanent strain in the mixture approaches a constant value. The same opinion is shared by Wasage and co-workers [3], who also suggested that the majority of rutting occurs during the initial stages of loading. Since the rheological behavior of asphalt binders are strongly dependent on the loading time and temperature, it can be said that the study of the rheological parameters of the materials in a great variety of temperatures and loading times is important. In other words, one may have a more precise estimation of the amount of rutting by studying the binder properties in the laboratory under testing conditions that closely approach those of the real pavement.

Several binder tests and parameters have been proposed over the years to estimate the susceptibility of the material to rutting, which include empirical-based tests such as penetration and softening point, oscillatory shear tests in the dynamic shear rheometer (DSR) and parameters derived from this test protocol such as $G^*/\sin\delta$ (complex modulus G^* divided by the sine of the phase angle δ) and, more recently, repeated creep tests at one and more stress levels [4]. There seems to be a consensus in the literature that these repeated creep tests closely simulate the actual loading-unloading conditions experienced by the binder in the pavement, since the association of binder testing results with mixture testing data yields good correlations in many cases [2, 5, 6]. The most recent version of such tests – namely, multiple stress creep and recovery (MSCR) – is standardized by ASTM and AASHTO under the designations D7405 and T350, respectively.

Together with the development of MSCR, researchers updated the Superpave® specification by replacing the original binder rutting parameter $G^*/\sin\delta$ by the nonrecoverable (creep) compliance J_{nr}, which is derived from MSCR. The AASHTO M320 specification (Superpave®) first incorporated J_{nr} in 2009 and, since then, traffic levels have been proposed to the binder as a function of J_{nr} at the highest standardized stress level (3.2 kPa). It is believed that such classification was derived from the ones proposed by researchers according to the repeated creep and recovery test data, which is the forerunner of MSCR [7]. According to this proposed criterion, the binder receives a traffic designation that is associated with a number of equivalent single-axle loads (ESAL's) and an average traffic speed. Four categories of levels can be found, namely, standard traffic – S (less than 10 million ESAL's and speeds greater than 70 km/h), heavy traffic – H (between 10 and 30 million ESAL's or traffic speeds between 20 and 70 km/h), very heavy – V (more than 30 million ESAL's or traffic speeds lower than 20 km/h) and extremely heavy – E (more than 30 million ESAL's and traffic speeds lower than 20 km/h) [8].

Despite the fact that such procedures and classifications are closer to the actual conditions experienced by the binder in the field pavement, it cannot be stated that such criteria are enough to address rutting on pavements. This is especially critical when one observes that the Superpave® specification takes into account heavier traffic levels for the binder by consecutively decreasing the maximum J_{nr} value by half and keeping the test temperature unchanged, as based on the publication by D'Angelo [9]. However, it can be said that this is still not enough to fully understand the behavior of the material under more critical loading conditions, since the relationship between the traffic speed and the strain in the binder is nonlinear [10]. Therefore, it is important to study the role of the loading time on the creep-recovery response of the binder, as well as to how this role will affect its traffic designation on Superpave®.

The present study evaluated the responses of unmodified and crumb rubber-modified asphalt binders in the MSCR tests at very long loading times, with values ranging from 1.0 to 8.0 s. Such values are expected to represent the passage of slow-moving vehicles on the surface of the pavement, which in turn would lead to a nonlinear increase in the accumulated strain of the binder and could change its traffic designation. Lastly, a refined version of the binder classification according to its traffic level is proposed and tested, as based on the reference values for J_{nr} set by the AASHTO M320-09 standard in its Table 3 (4.0 kPa^{-1} for standard traffic, 2.0 kPa^{-1} for heavy traffic, 1.0 kPa^{-1} for very heavy traffic and 0.5 kPa^{-1} for extremely heavy traffic).

2. MATERIALS AND METHODS

The selected binders and formulations were prepared by utilizing the following materials: (a) a 50/70-penetration grade base binder, which came from the Lubnor-Petrobras refinery (Fortaleza, Ceará, Brazil) and graded as PG 64S-xx according to Superpave®; (b) reclaimed tire rubber, with 100% of the particles passing through the #30 mesh (particle size of 0.60 mm); and (c) polyphosphoric acid (PPA) provided by the Innophos Inc. company and designated as Innovalt® E200. A similar high-temperature performance grade of 76-xx was targeted in the study, and the continuous grades of the prepared materials were kept between 76.0 and 78.0°C to control their actual degrees of stiffness. A Silverson L5M-A high-shear mixer was used in the preparation of the two formulations. The modifier contents and classifications of the formulations with crumb rubber alone (designated hereafter as AC+rubber) and crumb rubber combined with PPA (designated hereafter as AC+rubber+PPA) are shown in Table 1.

TABLE 1 Modifier Contents and Processing Variables

designation of the variable and unit	AC+rubber	AC+rubber+PPA
PG grade (according to AASHTO M320-09, Table 3)	76-xx	76-xx
continuous grade (°C)	77.8	77.8
binder content (percentage by mass)	85.0	87.4
crumb rubber content (percentage by mass)	15.0	12.0
polyphosphoric acid content (percentage by mass)	not applicable	0.6
mixing temperature (°C)	190	190
mixing time (min)	90	120[a]
rotation speed (rpm)	4,000	4,000

[a] The polyphosphoric acid was added to the formulation after 90 min of mixing time.

To carry out the MSCR tests, an AR-2000ex DSR provided by TA Instruments was used. Standardized parallel plates with diameter of 25 mm were selected, and the gap was fixed at 1.0 mm. Prior to the beginning of the tests, the binders were short-term aged according to the ASTM D2872-04 standard. Five high pavement temperatures ranging from 52 to 76°C and equally spaced by 6°C (52, 58, 64, 70 and 76°C) were chosen, and only the stress levels of 0.1 and 3.2 kPa – as established by the AASHTO T350-14 standard – were used. At least two replicates were tested for each formulation, and the following parameters were calculated: (a) percent recovery R; and (b) nonrecoverable compliance J_{nr}. Four loading-unloading conditions (1/9, 2/9, 4/9 and 8/9 s) were chosen in the MSCR tests, and the binders were graded according to the standardized traffic level criteria and the one evaluated in the present study. The outcomes of the base binder are not shown here for brevity, but they may be found elsewhere [11].

As shown in Table 2 (reference values obtained from the AASHTO M320-09 standard), two requirements for J_{nr} must be complied by the binder for a specific traffic level to be assigned to it, namely, one at the standardized loading-unloading times of 1/9 s and the other at longer creep times. A previous study reported by the authors [11] already indicated that some modified binders may depict differences in their traffic designations, depending on their modifier contents and types. Therefore, the use of such refined criteria may avoid the occurrence of premature failure by rutting in the pavement, since binders with substantial increases in J_{nr} at longer creep times will be identified and excluded before their use in the field.

TABLE 2 Draft of the Proposed Traffic Criteria as Based on the AASHTO M320-09 Standard

rolling thin-film oven (RTFO) aged residue, 163°C, 85 min	
70S – "standard" traffic (S), $J_{nr}3200 \leq 4.0$ kPa^{-1} for loading time = 1.0 s, tested at environmental temperature (°C)	70
70H – "heavy" traffic (H), $J_{nr}3200 \leq 2.0$ kPa^{-1} for loading time = 1.0 s **and $J_{nr}3200 \leq 4.0$ kPa^{-1} for loading time = 2.0 s**, tested at environmental temperature (°C)	70
70V – "very heavy" traffic (V), $J_{nr}3200 \leq 1.0$ kPa^{-1} for loading time = 1.0 s **and $J_{nr}3200 \leq 3.5$ kPa^{-1} for loading time = 4.0 s**, tested at environmental temperature (°C)	70
70E – "extremely heavy" traffic (E), $J_{nr}3200 \leq 0.5$ kPa^{-1} for loading time = 1.0 s **and $J_{nr}3200 \leq 3.5$ kPa^{-1} for loading time = 8.0 s**, tested at environmental temperature (°C)	70

3. RESULTS AND ANALYSES

Table 3 reports the R values at 0.1 and 3.2 kPa for all the studied formulations. As expected, higher temperatures and longer creep times decrease the amount of recovered strain in the asphalt binder, regardless of the modifier type and content. In general, the AC+rubber shows higher elastic responses (i. e., higher R values) than the AC+rubber+PPA. This may be explained by the fact that PPA is not a polymer, and therefore its ability to stiffen the base asphalt binder does not include substantial elastic responses at high temperatures when the major modifier does not react with it. These comments and discussions are in alignment with the data reported by Fee et al. [12] and D'Angelo [13], amongst others. The results vary from 5.0 to 76% at 0.1 kPa and do not overcome 44% at 3.2 kPa for the AC+rubber. In terms of the AC+rubber+PPA, such results are all lower than 47% at 0.1 kPa and do not exceed 36% at 3.2 kPa, i. e., decreases from 18 to 90% when moving from one formulation to the other.

With respect to the recovery values by themselves, one may see that they are typically null at the temperatures of 70 and 76°C. Brazilian pavements commonly require PG-graded asphalt binders of 64-xx and 70-xx [14] and, based on this, one may see that both crumb rubber-modified materials barely show recovery at such temperatures ($R \leq 12\%$) and the highest stress level. Even though a minimum value for R is not an official requirement on Superpave®, studies indicated that elasticity may give some contribution to the reduction in the amount of permanent strain in the asphalt mixture [10]. In other words, it is important for the binder to show at least a reasonable degree of elasticity at high pavement temperatures, especially because other distress mechanisms must also be minimized. In this aspect, the AC+rubber may be taken as the best formulation due to its greater level of elasticity at the studied temperatures.

Table 4 shows the nonrecoverable compliances at the same pavement temperatures. As can be seen, the results of the AC+rubber+PPA are greater than those of the AC+rubber and increase with increasing loading time and temperature. This is a clear indication that the AC+rubber+PPA is more prone to rutting than the AC+rubber, as well as that the rubber particles play a major role in such rutting resistance. Another indication is that the rubber particles do not react with PPA to improve stiffness and elasticity in the formulation, differently from what can be seen in other cases such as the styrene-butadiene-styrene (SBS) copolymer and Elvaloy® [9, 11, 12]. Finally, one particular case for the AC+rubber (70°C and 2.0 s) can be highlighted with respect to the maximum value for J_{nr} at 3.2 kPa in the 2009 and later versions of Superpave®, namely, 4.0 and 4.5 kPa^{-1}. In this case, the formulation would not be appropriate for standard traffic according to M320-09 ($J_{nr} >$ 4.0 kPa^{-1}); however, its use could be possible if the newer versions were considered ($J_{nr} <$ 4.5 kPa^{-1}).

TABLE 3 Percent Recovery Values of the Asphalt Binders

asphalt binder	stress level (kPa)	creep time (seconds)	results at each temperature (%)[a]				
			52	*58*	*64*	*70*	*76*
AC+rubber	0.1	1	75.5	67.6	60.5	51.3	41.6
		2	62.5	56.7	48.9	37.9	27.3
		4	55.1	47.9	39.8	29.3	19.1
		8	36.6	29.2	19.7	11.2	5.0
	3.2	1	44.0	27.0	12.0	3.1	0.0
		2	29.4	13.7	3.8	0.0	0.0
		4	19.1	6.8	0.4	0.0	0.0
		8	4.9	0.0	0.0	0.0	0.0
AC+rubber+PPA	0.1	1	46.9	39.2	29.5	21.1	13.4
		2	37.4	29.4	21.0	12.9	6.6
		4	24.9	16.6	8.7	3.0	0.0
		8	15.5	8.2	3.0	0.0	0.0
	3.2	1	35.9	20.6	7.2	0.0	0.0
		2	22.9	9.0	0.7	0.0	0.0
		4	9.7	1.1	0.0	0.0	0.0
		8	2.3	0.0	0.0	0.0	0.0

[a] The gray-shaded boxes highlight the null values for R and for each formulation.

TABLE 4 Nonrecoverable Compliance Values of the Asphalt Binders

asphalt binder	stress level (kPa)	creep time (seconds)	results at each temperature (kPa^{-1})[a, b]				
			52	*58*	*64*	*70*	*76*
AC+rubber	0.1	1	0.051	0.146	0.364	0.875	1.940
		2	0.125	0.317	0.782	1.874	**4.179**
		4	0.207	0.530	1.268	2.983	6.591
		8	0.596	1.497	3.685	8.641	19.127
	3.2	1	0.124	0.356	0.948	2.237	4.695
		2	0.261	0.750	1.934	**4.418**	9.161
		4	0.452	1.276	3.202	7.228	15.325
		8	1.279	3.435	8.429	19.354	41.972
AC+rubber+PPA	0.1	1	0.110	0.283	0.729	1.738	3.888
		2	0.220	0.576	1.464	3.519	7.799
		4	0.503	1.358	3.544	8.541	18.791
		8	0.981	2.665	6.804	16.079	34.454
	3.2	1	0.136	0.390	1.069	2.624	5.645
		2	0.285	0.832	2.209	5.154	11.146
		4	0.672	1.924	4.883	11.510	25.359
		8	1.352	3.755	9.680	23.216	50.648

[a] The gray-shaded boxes highlight the temperatures and creep-recovery times in which J_{nr} exceeds 4.0 kPa^{-1}.

[b] The numbers in bold indicate the temperatures and loading times at which J_{nr} is greater than 4.0 kPa^{-1} (maximum allowed value according to AASHTO M320-09) but lower than 4.5 kPa^{-1} (maximum allowed value in more recent versions of Superpave®).

In terms of J_{nr}, the Superpave® specification M320-09 sets a maximum value of 4.0 kPa^{-1} (4.5 kPa^{-1} in more recent versions) for the asphalt binder to be used for paving applications, as mentioned earlier. Based on this, one may infer that none of the studied formulations may be used on pavements with high PG grades of 70°C and higher and loading times longer than 1.0 s, since J_{nr} is typically higher than 4.0 kPa^{-1} in such testing conditions. This could possibly create a restriction for the use of both formulations on pavements with greater severity of loading, e. g., highways and roads/streets with channelized traffic. In addition, the results of J_{nr} are from 5 to 187% higher for the AC+rubber+PPA when compared with the AC+rubber, which again places the AC+rubber as the best formulation among those studied in the present paper.

As can be seen in Table 5, the traffic levels are similar in both criteria at all temperatures, with exception of the AC+rubber+PPA at 58°C – extremely heavy in the M320-09 criteria and very heavy in the proposed ones (Table 2). Similar findings were also observed for other modifier types in a previous article [11], e. g., PPA, Elvaloy® and SBS. This points out that the AC+rubber+PPA may not be recommended for some particular cases in which the traffic conditions result in the application of too severe loads in the pavement, even for rutting temperatures lower than 64°C. In a more general context, one must choose the most appropriate formulation for a specific pavement condition based not only on the rheological parameters in loading conditions established by standards, but also the ones actually expected in the field pavement. If this is not done, then premature failure by rutting might be observed due to the differences between the loading times used in the laboratory and those actually seen in the pavement.

TABLE 5 Traffic Levels in the M320-09 and Proposed J_{nr} Criteria

temperature (°C)	traffic levels, AC+rubber		traffic levels, AC+rubber+PPA	
	M320-09 criteria	proposed criteria	M320-09 criteria	proposed criteria
52	52E-xx	52E-xx	52E-xx	52E-xx
58	58E-xx	58E-xx	58E-xx	58V-xx
64	64V-xx	64V-xx	64H-xx	64H-xx
70	70S-xx	70S-xx	70S-xx	70S-xx
76	76-xx	76-xx	76-xx	76-xx

4. CONCLUSIONS

The following conclusions can be drawn from the present study:

- asphalt binder modification with crumb rubber (AC+rubber) and a combination of crumb rubber with PPA (AC+rubber+PPA) result in formulations with percent recoveries and nonrecoverable compliances that recommend their use at pavement temperatures no greater than 64°C when the loading time is expected to be longer than 1.0 s;
- the AC+rubber shows percent recoveries from 18 to 90% higher and nonrecoverable compliances from 5 to 187% lower than the corresponding ones of the AC+rubber+PPA, which indicates that the rubber particles play a major role in the degrees of improvement in the MSCR parameters when compared with PPA;
- the use of the refined criteria for determining the adequate traffic levels of the binders identified decreases in such traffics for the AC+rubber+PPA at particular pavement temperatures (in this case, 58°C); this implies that the binder may not be appropriate for all types of heavier traffic levels observed on roads and highways worldwide; and

- the proposal of a new method for selecting even more appropriate binders for a specific traffic (i. e., two maximum J_{nr} values to be observed rather than only one) is a complementary attempt to deal with several vehicles traveling at small speeds in the pavements – and thus applying loads for much longer times; in addition, the main motivation behind such proposal is to offer a procedure that is not time-consuming and feasible for users.

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