Effects of filler/bitumen ratio and bitumen grade on rutting and fatigue characteristics of bituminous mastics

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ABSTRACT

Bituminous mastics are a blend of bitumen and the finest mineral particles which have the role of filling the voids created by the coarse mineral aggregates. The rheological properties of the mastic phase have a determinant effect on the mechanical behavior of the whole asphalt and can be evaluated in the light of tests recently developed for pure and modified bitumens. The objective of this research is to evaluate the effects of different filler/bitumen ratios and two bitumens grades (50/70 and 30/45) on rheological properties of bituminous mastics associated with permanent deformation and fatigue cracking. The original samples were subjected to short- and long-term ageing according to standard procedures using a rolling thin film oven and a pressure ageing vessel. The short-term aged samples were submitted to the MSCR test and the long-term aged samples were submitted to the LAS test. The MSCR test was performed at 52, 58, 64, 70 and 76°C in order to cover a wide range of temperatures where permanent deformation can occur. The LAS test was run at 25°C, which is a typical temperature where fatigue cracking appears in the asphalt. The overall conclusions are: (i) the filler/bitumen ratio are responsible for an expressive increase in the resistance of the asphalt to the accumulation of plastic deformations and these positive effects are more expressive when a harder bitumen is used; (ii) in the light of the af parameter, obtained from the fracture mechanics, the harder the bitumen and the higher the f/b ratio, the higher the tolerance to fatigue damage of the mastics, but, on the other hand, the fatigue life curves, obtained from the continuum mechanics, indicated the opposite, i.e., the harder the bitumen and the higher the f/b ratio, the lower the fatigue life of the mastics. The analysis based on the fatigue parameter of the Superpave specification (G.sin□) is in tune with the results obtained from the analysis of the fatigue life curves.*

Keywords: Asphalt, Fatigue Cracking, Mineral filler, Permanent Deformation, Rheology

1. INTRODUCTION

Asphalt mixtures are complex composite materials consisting basically of mineral aggregates, bitumen, mineral fillers and voids filled with air. Additives can also be added to either asphalts or bitumens, in order to enhance their performance. Understanding the effect of individual components of this blend is essential to correctly design asphalt mixtures in order to meet desirable structural and surface requirements (Delgadilho and Bahia, 2008; Yildirim et al., 2000; Bennert et al., 2010; Gudimettla et al., 2004; Tayebali et al., 1998). It is well known that mineral fillers considerably influence the mechanical properties of asphalt mixtures, affecting the rheological properties of the mastic phase (blend of bitumen and filer particles inferior to 75 micra). Researches have reported that the physical properties and chemical constituents of mineral fillers affect the rheological and mechanical properties of bitumen-filler mastics, depending on the type, grading and shape, and concentration of the mineral filler in the asphalt (Ishai and Craus, 1977; Heukelom, 1965; Huschek and Angst, 1980; Tunnicliff, 1967; Kavussi, and Hicks, 1997).

Specifications that drive the design of asphalts currently restrict the amount of mineral filler in order to avoid the production of excessively stiff asphalts. Some specifications do that recommending low proportions of fines in the aggregate gradation and others do that recommending low filler/bitumen (f/b) ratios. High amounts of mineral fillers are always desired when the target is to obtain very stable asphalts, which are able to resist very heavy traffic loading without accumulating high levels of plastic deformation on the wheel track. On the other hand, excessively hard asphalts become more fragile and consequently more susceptible to crack under fatigue and low temperatures. Due to these antagonic effects on performance, the selection of the right amount of mineral filler to compound asphalt is a task of great importance. With the advent of new scientifically sound rheological tools, the challenge of finding the equilibrium point in terms of filler/bitumen ratio in an asphalt can be more efficiently addressed. In order to achieve this aim, the multiple-stress creep and recovery test (MSCR) and the linear amplitude sweep test (LAS), currently used to characterize bitumens, were applied here to characterize bituminous mastics with different filler/bitumen ratios. The global effects of the type of bitumen on the flow and fatigue properties of bituminous mastics were also investigated.

2. MATERIAL AND TESTING PROGRAM

2.1 Materials

The following variables were chosen to outline this experiment: (i) one mineral filler: basalt; (ii) two base bitumens: a 30/45 and a 50/70 penetration grade bitumen; and (iii) three filler/bitumen ratios (by mass): 15%, 30% and 45%. A total of six bituminous mastics were prepared using the two bitumens and the three f/b ratios. The mastics prepared with the 50/70 pen-grade bitumen were mixed within the temperature range of 150 to 154 ºC. The mastics prepared with the 30/45 pen-grade bitumen were mixed within the temperature range of 156 to 162ºC.

2.2 Test protocols

Ageing of bitumens-filler mastics was performed using a rolling thin film oven (RTFO), following the ASTM D2872 – 2012, and a pressuring aging vessel (PAV), and according to the ASTM D6521 – 2013. The MSCR test was carried out using the DSR TA Instruments model AR2000ex with parallel plates of 25 mm in diameter and 1 mm in high between plates with only short-term aged samples. The creep and recovery times, the stress levels and the number of loading-unloading cycles were the ones established by the ASTM D7405-10a standard procedure. The LAS test was also conducted on the DSR, using parallel plates of 8 mm in diameter with 2 mm in high between plates, at the fixed temperatures of 25 ºC with both short- and long-term aged samples. The test was run in two stages: (a) a frequency sweep with the application of a constant strain of 0.1% and frequencies ranging from 0.2 to 30 Hz; and (b) a linear amplitude sweep with linear strain increments from 0% to 30% within a time interval of 300 s and at constant frequency of 10 Hz.

3. RESULTS AND DISCUSSION

3.1 Multiple Stress Creep and Recovery (MSCR) Test

The percent recoveries (R) of the 30/45 and 50/70 bitumens at different temperatures are shown in Table 1. The addition of mineral filler in different f/b ratios led to a slight increase in the elastic response of the mastics, i.e., the presence of filler was responsible for the reduction in the amount of unrecovered strain of the bitumens at typical high pavement temperatures. This effect loses intensity as temperature increases, i.e., the temperature increase is responsible for an expressive reduction in the elasticity provided by the filler addition. The same effect is observed when the stress level increases, i.e., the application of higher stresses is also responsible for an expressive decrease in the elastic recovery of the mastics and this is valid for both bitumens. These results are also useful to see that the increase in percent recoveries is also dependent on bitumen type – mastics prepared with the 30/45 bitumen present percent recoveries slightly higher than those prepared with the 50/70 bitumen. At the most critical rutting temperatures, i.e., 64 and 70°C, the increase in percent recovery is obtained only when relatively high f/b ratios are used and the stress level is low. At higher stresses, the effect of filler addition is practically null. The highest level of elastic recovery is obtained for the f/b ratio of 45% for both bitumens. As a matter of comparison, tests with modified asphalt binders graded as PG 76-xx have indicated that percent recoveries around 15% at 100 Pa and 2% at 3.2 kPa at 64°C were obtained when 6.0% of low-density polyethylene was added to a PG 64-xx bitumen (Domingos, 2011; Domingos and Faxina, 2015).

Table 1: Percent recoveries of the mastics – 100 Pa and 3.200 Pa

f/b ratio (%)	%R – 100 Pa (%)				%R – 3.200 Pa (%)			
	52°C	58°C	64°C	70°C	52°C	58°C	64°C	70°C
50/70 base bitumen								
0	4.72	0.34	0	0	1.57	0	0	0
15	7.96	3.38	0	0	5.90	0	0	0
30	11.51	6.65	1.44	0	8.70	1.79	0	0
45	13.39	10.70	6.02	2.11	9.09	2.72	0	0
30/45 base bitumen								
0	1.74	0	0	0	1.55	0	0	0
15	7.09	2.05	0	0	6.44	1.05	0	0
30	6.14	2.41	0.07	0	5.95	0.85	0	0
45	15.05	10.95	9.39	3.31	13.48	5.93	0.76	0

The non-recoverable compliances of the 30/45 and 50/70 bitumens in respect to temperature are shown in Table 2. The addition of filler in different f/b ratios led to the reduction of the J_{nr} values, especially at the highest f/b ratios, for both bitumens. Since the non-recoverable compliance is an indicator of the susceptibility of the bitumen to rutting, it can be said that the mastics are less prone to the accumulation of unrecovered strain under creep and recovery loading than the base bitumen. Similarly to what was observed in terms of percent recovery, the increase of temperature and stress level also affected the J_{nr} values expressively, increasing them in this case. Results are also useful to see that the increase in non-recoverable values is also dependent on the bitumen type – mastics prepared with the 30/45 base bitumen present J_{nr} values expressively lower than those prepared with the 50/70 base bitumen. At the most critical rutting conditions, i.e., temperatures of 64 and 70°C and a high stress level, an expressive reduction in J_{nr} values is obtained only when relatively high f/b ratios are used. As a matter of comparison, tests with modified asphalt binders graded as PG 76-xx have indicated that non-recoverable compliances around 0.7 at 100 Pa and 0.9 at 3.2 kPa at 64°C were obtained when 6.0% of low-density polyethylene was added to a PG 64-xx bitumen (Domingos, 2011; Domingos and Faxina, 2015).

Table 2: Non-recoverable compliance of the mastics – 100 Pa and 3.200 Pa

f/b ratio (%)	J_{nr} – 100 Pa (kPa^{-1})				J_{nr} – 3.200 Pa (kPa^{-1})			
	52°C	58°C	64°C	70°C	52°C	58°C	64°C	70°C
50/70 Bitumen								
0	0.58	1.50	3.69	8.29	0.61	1.62	4.04	9.09
15	0.22	0.58	1.52	3.67	0.22	0.64	1.66	4.09
30	0.09	0.23	0.58	1.42	0.09	0.24	0.64	1.58
45	0.05	0.10	0.24	0.55	0.04	0.11	0.27	0.66
30/45 Bitumen								
0	0.19	0.55	1.52	3.72	0.19	0.58	1.56	3.82
15	0.05	0.13	0.37	0.93	0.05	0.13	0.38	0.96
30	0.03	0.09	0.23	0.56	0.03	0.09	0.24	0.59
45	0.01	0.02	0.05	0.13	0.01	0.02	0.06	0.14

The results presented in Tables 1 and 2 are useful to understand how the presence of mineral filler and its concentration is the asphalt are responsible for an expressive increase in the resistance of the asphalt to the accumulation of plastic deformations. The addition of increasing f/b ratios results in a slight increase in elastic recovery and has a more expressive effect on the non-recoverable compliance, reducing it. Either in terms of percent recovery or non-recoverable

compliance values, the pure bitumen presents the lowest resistance to permanent deformation – this fact highlights the positive effect of the addition of mineral filler in high concentrations. These results are also valuable to differentiate the effect of bitumens of different performance grades or consistencies. In summary, from the bitumen point of view, the mix of high f/b ratios (around 45%) and a harder base bitumen (30/45) is the best solution to enhance the resistance to permanent deformation, in the light of the results obtained from the MSCR tests conducted in standard conditions.
The percent differences in non-recoverable compliances ($J_{nr,diff}$) values of the mastics in respect to temperature are shown in Table 3. None of mastics exceeded the maximum value of 75% at high pavement temperatures, recommended for modified bitumens. This indicates that none of the mastics are overly stress sensitive. As an example, a bitumen modified with 6.0% of low-density polyethylene at 64°C presents a $J_{nr,diff}$ value of about 27% (Domingos, 2011; Domingos and Faxina, 2015). In the light of the $J_{nr,diff}$ values, the mastics prepared with the 30/45 bitumen are less stress sensitive than those prepared with the 50/70 bitumen, highlighting the positive effect of using a harder bitumen as far as the resistance to permanent deformation is concerned.

Table 3: Percent differences in non-recoverable compliances ($J_{nr,diff}$,%) of the mastics

f/b ratio	50/70 base bitumen				30/45 base bitumen			
	52°C	58°C	64°C	70°C	52°C	58°C	64°C	70°C
0	6.0	7.2	8.8	9.3	0.5	5.5	2.4	2.8
15	0.8	8.6	8.7	10.7	0.3	1.3	3.3	3.2
30	5.7	7.1	9.9	10.2	4.2	1.9	4.6	6.3
45	18.7	2.5	11.9	18.0	3.6	4.7	5.2	8.6

The new version of the Superpave specification contains a complementary specification for bitumens ascribing a certain traffic level based on the J_{nr} values of the bitumen at the highest pavement temperature: S (Standard), H (Heavy), V (Very heavy) and E (Extremely heavy). Although these traffic levels have been set for pure and modified bitumen, they can be used illustratively to show how the f/b ratio can improve the traffic class that a pavement can support. The traffic levels for the mastics at different temperatures are shown in Table 4. At 64°C, the 50/70 bitumen would not be recommended even for a standard traffic. On the other hand, the 30/45 would be recommended for a heavy traffic at 64°C. At 70°C, the 30/45 would be recommended only for a standard traffic. These results indicate that both bitumens would be recommended only for pavements with low traffic levels (H or S, depending on pavement temperature) and that they would not be recommended for pavements with high traffic levels, like V and E, both at 64 or 70°C.

Table 4: Traffic level classification based on J_{nr} values according to the FHWA

Base bitumen	f/b ratio (%)	52°C	58°C	64°C	70°C
50/70	0	V	H	-	-
	15	E	V	H	-
	30	E	E	V	H
	45	E	E	E	V
30/45	0	E	E	H	S
	15	E	E	E	V
	30	E	E	E	V
	45	E	E	E	E

The results in Table 4 highlight the positive effect of adding high concentrations of mineral fillers in asphalts once that higher traffic levels can be served. At 64°C, the E class can be obtained with a f/b ratio of 15% when the 30/45 bitumen is used while the same traffic level could be reached only with a f/b ratio of 45% when the 50/70 bitumen is used. At 70°C, only the class V can be obtained with the 50/70 bitumen while the class E can be obtained with a f/b ratio of 45% when the 30/45 is used. These results clearly show that a harder base bitumen is essential when high levels of resistance to permanent deformation are desired. At 70°C, for instance, the use of a 30/45 bitumen is capable of increasing the traffic level from H to V, for a f/b ratio of 30%, and from V to E, when a f/b ratio of 45% is used, compared to the adoption of a 50/70 bitumen.

3.2 Linear amplitude sweep (LAS) Test

The fatigue behavior of the mastics in the LAS test was evaluated with basis on two approaches: (i) the viscoelastic continuum damage (VECD) approach and (ii) the fracture mechanics approach. In the VECD analysis, the parameter

A_{35} represents the integrity of the material without damage and it is expressed in terms of the intercept of the curve *number of cycles to failure (N_f) versus strain amplitude* with the ordinate, i.e., when the strain level is zero (Johnson, 2010). The *B* value is associated to the sensitivity of the bitumen to an increase in the strain level and it is expressed in terms of the slope of the curve *N_f versus strain amplitude*. Higher slopes (higher absolute *B* values) indicate that the fatigue life of the material decreases at a higher rate when the strain amplitude increases. Likewise, smaller slopes (lower absolute B value) indicate that the fatigue life of the bitumen decreases at a lower rate (Hintz, 2012). In the analysis based on the fracture mechanics, the parameter a_f corresponds to the minimum local point of the relationship between *da/dN* (variation rate of crack length *a* with the number of cycles *N*) and *a* (the crack length). In other words, the a_f values indicate the point where a rapid increase in the fracture growth rate is observed in the curve *da/dN* versus *a* (Hintz, 2012). The numerical values of the parameters A_{35} and *B* of the fatigue model and the damage tolerance index a_f are presented in Table 5. As can be seen, the mastics prepared with the 30/45 base bitumen presented a_f values at 25ºC superior to those presented by the mastics prepared with the 50/70 base bitumen, in the long-term aged condition. The a_f values also increased with the increase of the f/b ratio for both base bitumens. The mastic prepared with the 30/45 base bitumen with a f/b ratio equal to 45% is the most tolerant to fatigue damage, in the light of the parameter a_f at 25°C after long-term ageing.

Table 5: Parameters A_{35} and *B* and the damage tolerance index a_f – LAS test at 25ºC

f/b ratios	50/70 base bitumen			30/45 base bitumen		
	A_{35}	B	a_f (mm)	A_{35}	B	a_f (mm)
0.00	1.06E+05	-3.060	0.733	3.08E+04	-2.942	1.959
0.15	6.34E+04	-3.223	0.909	4.12E+03	-3.136	2.596
0.30	1.56E+04	-3.240	2.636	3.47E+03	-3.341	2.925
0.45	3.03E+03	-3.570	2.809	3.04E+02	-4.166	3.116

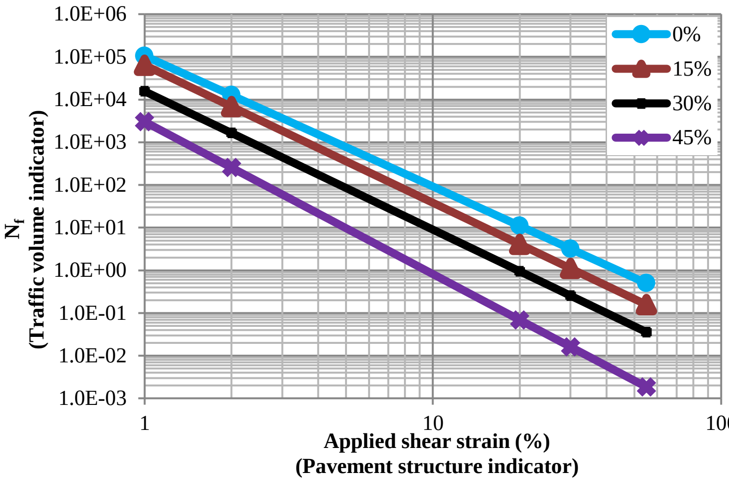
The fatigue life curves at 25°C for the long-term aged mastics obtained from the VECD approach are depicted in Figure 2. These graphs clearly show that the increase of the f/b ratio reduces the fatigue resistance of the asphalt and being more expressive for the f/b ratio of 45%. The comparison depicted in Figure 3 of the N_f values obtained at 3% strain and 25°C for both bitumens shows clearly that the mastics prepared with the 50/70 base bitumen present a higher number of load repetitions to failure at low and intermediate f/b ratios, whereas at high f/b ratios both bitumen present the same number of load repetitions to failure. These results clearly show that at high f/b ratios, the consistency of the base bitumen is not a determinant factor on the resistance of the mastics to fatigue cracking.
The mastics were also subjected to oscillatory tests to measure complex modulus (G*) phase angle (δ) in order to evaluate the effect of the f/b ratio and the bitumen type on the fatigue performance of the mastics, in the light of the fatigue parameter G*.sinδ of the Superpave specification. These results are presented in Figure 4 for the temperature of 25°C. The fatigue parameter increases with the increase of the f/b ratio for both bitumens but the values obtained for the mastics prepared with the 30/45 bitumen are higher than the ones obtained for the mastics prepared with the 50/70 bitumen. According to the rationale of this parameter, the stiffer the material the lower its fatigue resistance. In this sense, the mastics prepared with the 30/45 base bitumen at high f/b ratios are more prone to fatigue cracking. These results are in tune with those obtained from the analysis of the fatigue life curves.

4. CONCLUSIONS

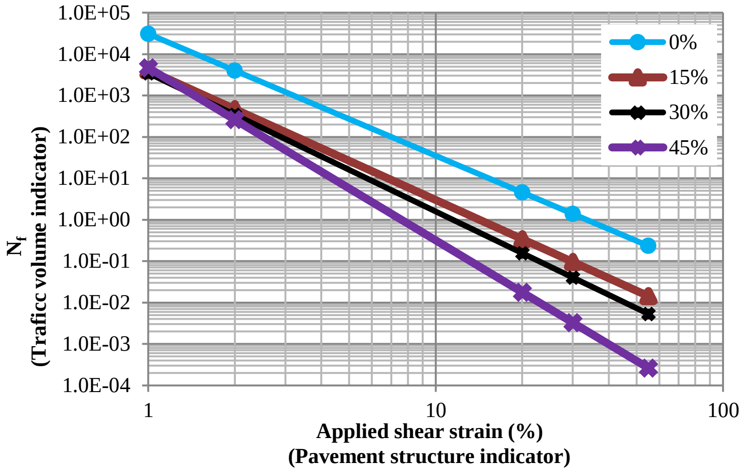
In this paper, the effect of the filler/bitumen ratio and the bitumen type on rheological properties of bituminous mastics associated with permanent deformation and fatigue were evaluated by means of the multiple-stress creep-recovery (MSCR) test and the linear amplitude sweep (LAS) test. The main conclusions are presented below:

- the addition of mineral filler in different f/b ratios led to a slight increase in the elastic response of the mastics, but this effect loses intensity with the increase of test temperature and stress level; at the most critical rutting temperatures, i.e., 64 and 70°C, the increase in percent recovery is obtained only when relatively high f/b ratios are used and the stress level is low, and at higher stress levels, the effect of filler addition is practically null;
- the addition of mineral filler in different f/a ratios led to the reduction of the J_{nr} values, especially at the highest f/a ratios, for both bitumens; the increase in temperature and stress level increased the J_{nr} values expressively; at the most critical rutting conditions, i.e., temperatures of 64 and 70°C and a high stress level, an expressive reduction in non-recoverable compliance values is obtained only when relatively high f/b ratios are used;
- none of mastics exceeded the maximum value of 75% for the $J_{nr,diff}$ parameter at high pavement temperatures, indicating that none of the mastics are overly stress sensitive; the mastics prepared with the 30/45 bitumen are less stress sensitive than those prepared with the 50/70 bitumen, highlighting the positive effect of using a harder bitumen as far as the resistance to permanent deformation is concerned;
- the analysis of the traffic levels based on the J_{nr} values indicated that both the 50/70 and the 30/45 bitumen would be recommended only for pavements with low traffic levels (H or S, depending on pavement temperature), but the results showed that the traffic level can be improved in the extent that more mineral filler

is added: at 64°C, for instance, the E class can be obtained with a f/b ratio of 15% for the 30/45 bitumen while the same traffic level could be reached only with a f/b ratio of 45% when the 50/70 bitumen is used;



(a)



(b)

Figure 2. Fatigue life curves at 25ºC: (a) PAV-aged 50/70 mastics and (b) PAV-aged 30/45 mastics

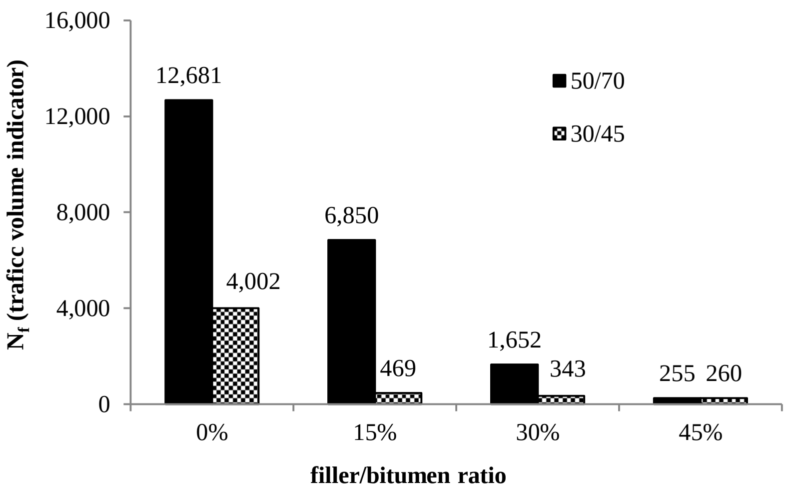


Figure 3. Fatigue lives of mastics prepared with the 30/45 and the 50/70 bitumens at 3% strain

- the mastics prepared with the 30/45 base bitumen presented a_f values at 25ºC superior to those presented by the mastics prepared with the 50/70 base bitumen and the a_f values also increased with the increase of the f/b ratio for both base bitumens; this means that the harder the bitumen and the higher the f/b ratio, the higher the tolerance to fatigue damage of the mastics;

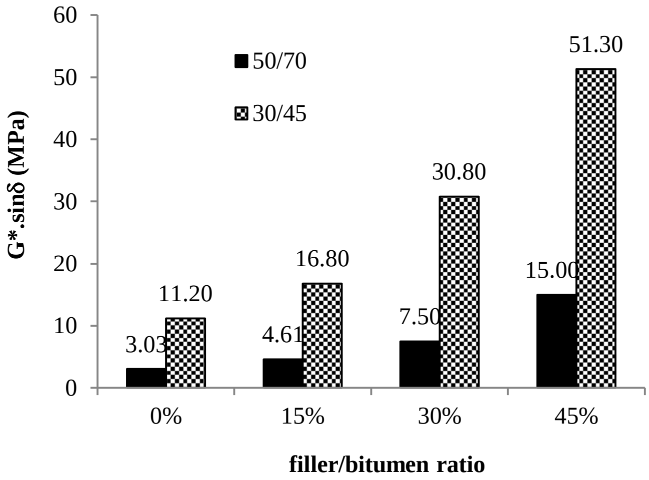


Figure 4. Fatigue parameter of the Superpave specification at 25ºC

- the fatigue life curves showed that the increase of the f/b ratio reduces the fatigue resistance of the asphalt and that this reduction is more expressive for the f/b ratio of 45%; the mastics prepared with the 50/70 base bitumen presented a higher number of load repetitions to failure at low and intermediate f/b ratios, whereas at high f/b ratios both bitumen present the same number of load repetitions to failure, showing that at high f/b ratios, the consistency of the base bitumen is not a determinant factor on the resistance of the mastics to fatigue cracking.

The overall conclusions are: (i) the presence of mineral filler and its concentration are responsible for an expressive increase in the resistance of the asphalt to the accumulation of plastic deformations and these positive effects are more expressive when a harder bitumen is used; (ii) in the light of the a_f parameter, obtained from the fracture mechanics, the harder the bitumen and the higher the f/b ratio, the higher the tolerance to fatigue damage of the mastics, but, on the other hand, the fatigue life curves, obtained from the continuum mechanics, indicated the opposite, i.e., the harder the bitumen and the higher the f/b ratio, the lower the fatigue life. The analysis based on the fatigue parameter of the Superpave specification (G*.sinδ) showed results similar to those obtained from the analysis based on the fatigue life curves. Interestingly, at higher f/b ratios, the consistency of the bitumen does not interfere on the resistance of the mastics to fatigue cracking. Results like these reinforce the importance of being careful with the amount of filler to be added to the asphalt, once that excessive filler contents can seriously harm the fatigue performance of the asphalt when the fatigue phenomenon is addressed by means of the continuum mechanics theory.

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REFERENCES

Bennert, T., Reinke, G., Mogawer, W., Mooney, K. (2010). Assessment of Workability and Compaction of Warm-Mix Asphalt. *Transportation Research Record* 2180, 36-47.

Delgadilho, R., Bahia, H. (2008). Effects of Temperature and Pressure on Hot Mixed Asphalt Compaction: field and laboratory study. *Journal of Materials in Civil Engineering* 20 (6) 440-448.

Domingos, M.D.I., Faxina, A.L. (2015). Rheological Behaviour of Bitumens Modified with PE and PPA at Different MSCR Creep-recovery Times. *International Journal of Pavement Engineering* 16(9), 771-783.

Domingos, M.D.I. (2011). Caracterização do Comportamento Fluência-recuperação de Ligantes Asfálticos Modificados Virgens e Envelhecidos. Dissertação (Mestrado). Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos (in portuguese).

Gudimettla, J., Cooley, L., Brown, E. (2004). Workability of Hot-Mix Asphalt. *Transportation Research Record* 1891, 229-237.

Heukelom, W. (1965) The Role of Filler in Bitumen Mixes. *Journal of the Association of Asphalt Paving Technologists*, 34, 396-429.

Hintz C. (2012). Understanding Mechanisms Leading to Asphalt Binder Fatigue. [PhD dissertation]. Madison (WI). University of WIscosin-Madison.

Huschek, S. and Angst, C.H. (1980) Mechanical Properties of Filler-Bitumen Mixes at High and Low Service Temperatures. *Journal of the Association of Asphalt Paving Technologists*, 49, 440-475.

Ishai, I. and Craus, J. (1977) Effect of the Filler on Aggregate-Bitumen Adhesion Properties in Bituminous Mixtures. *Journal of the Association of Asphalt Paving Technologists*, 46, 228-258.

Johnson C.M. (2010). Estimating Asphalt Binder Fatigue Resistance Using an Accelerated Test Method (PhD Dissertation]. Madison (WI). University of Wisconsin-Madison.
Kavussi, A. and Hicks, R.G. (1997) Properties of Bituminous Mixtures Containing Different Fillers. *Journal of the Association of Asphalt Paving Technologists*, 66, 153-186.
Tayebali, A., Malpass, G., Klhosla, N. (1998). Effect of Mineral Filler Type and amount Design and Performance of Asphalt Concrete Mixtures. *Transportation Research Record* 1609, 36-4.
Tunnicliff, D.G. (1967) Binding Effects of Mineral Filler. *Journal of the Association of Asphalt Paving Technologies*, 36, 14-156.
Yildirim, Y., Solaimanian, M., Keunedy, T. (2000). Mixing and Compaction Temperatures for Hot Mix Asphalt Concrete. Research Report Number 1250-5, 99p.