Influence of Bitumen and Filler on the Selection of Appropriate Mixing and Compaction Temperatures

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Abstract: This paper presents a rheological evaluation, based on viscosity variation with temperature and shear rate, of several mastics combining six bitumens (two neat and four SBS polymer modified) and three fillers (two limestone and one lime). Filler content (filler-to-bitumen ratio) was defined according to two methods (fixed mass ratio and fixed volume ratio as a function of the Rigden voids and the increase of the softening point). The Superpave method and two other alternative methods (High Shear Rate Viscosity and Zero Shear Rate Viscosity), which were proposed in literature to select appropriate mixing and compaction temperatures of hot-mix asphalt, were implemented to assess the effect of the bitumen-filler combination on construction procedures. Results have shown that the mastic behaviour is highly dependent on the filler-to-bitumen ratio and that the filler type has a relevant and similar influence on mixing and compaction temperatures. Natural hydraulic lime showed a very high stiffening power, while the gradation differences of the limestone fillers showed a very limited effect. The temperature variation with the bitumen type, the SBS content, and the filler type and content differs with the method used for the selection of working temperatures. Nevertheless, working temperatures are more dependent on SBS modification (25-35°C) than on the filler (< 10°C).

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Key words: Bituminous mastic; Filler; Mixing and compaction temperatures; SBS; Viscosity.

Introduction

Mixing and paving/compaction are the two main tasks of the asphalt production process, which together determine the quality of material and, ultimately, the pavement performance. In the hot-mixing method, these processes are highly influenced by the viscosity of the bitumen, which depends on the temperature and the type of bitumen, as, during mixing, the aggregate coating quality is determined and, during compaction, the ability of aggregate particles to form a compact, resistant, durable, and cohesive structure with designed air void content [1-4] is determined. However, bitumen behavior variability does not explain all variability in asphalt workability. One of the suggested explanations is that the bituminous mastic is the true lubricant of the aggregate matrix [5, 6].

This study integrates an ongoing research project on hot-mix asphalt mixing and compaction operations. The main objective is to evaluate the rheological behavior differences at the working temperature range in mastics composed of different bitumens, including SBS (styrene-butadiene-styrene) polymer modification, and fillers. Moreover, two filler specifications, one being a fixed filler-to-bitumen mass ratio and the other a volume ratio determined as a function of the filler physical properties, were implemented to evaluate if the new method, which takes into account filler properties, leads to less variability in mastic behaviour when incorporating different fillers. Bitumen and mastic viscosity measurements were used to quantify the effect of the different components in the mastic behaviour, and three methods were adopted to define adequate mixing and compaction temperatures.

Problem Statement

Bituminous Mastic

The bituminous mastic is a composite material combining bitumen and fine aggregate. When integrated in a bituminous mixture with coarse aggregate, the mastic has a recognized influence on the mixture behaviour [7-11]. The cohesion and adhesion properties of the mastic are of utmost importance to bind the coarse aggregate particles [12, 13]. Adding mineral particles to the bitumen matrix leads to a stiffening of the mastic, primarily related to the volume concentration of the filler. Despite admitting that the mastic may comprise particles of up to 2 mm [8, 14], the properties and content added of the very fine aggregate (filler) are the most influential. Previous literature has reported the importance of the physicochemical nature, the particle size and shape, the surface energy, etc. [9].

NCHRP Project 9-45 "Test Methods and Specification Criteria for Mineral Filler Used in HMA" [10] identified the Rigden voids, the size distribution (fineness modulus), the calcium content, and the methylene blue value as critical filler properties for asphalt performance. It was found that the viscosity of the mastic relates well to the workability of the asphalt, as measured by the number of gyrations to attain 92% of the asphalt maximum density in the gyratory compactor. It was concluded that the mastic viscosity depends on the Rigden voids and the bitumen viscosity, and the following equation was developed from data:

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	8 1 8 1 9
	a) Baghouse Dust
Material	b) Commercial Filler (Limestone Dust; Portland
	cement; Fly Ash; Hydraulic Lime)
	- Mass f/b Ratio ^c : 1.1-1.5 or 1.3-1.5 Depending on
	Mixture Type
JAE ^a	- if Aggregate is Granite, 3% Minimum
	Commercial Filler Content or 2% Hydraulic Lime
	- Sieve Gradation (mm): 0.475 (100%); 0.180
	(95-100%); 0.075 (75-100%)
	- Volume <i>f/b</i> Ratio: Average of <i>f/b</i> Values
EP^{b}	Determined with $\Delta T_{R\&B}$ of 12 and 16°C – Eq. (1)
	- Sieve Gradation (mm): 2 (100%); 0.125
	(85-100%); 0.063 (70-100%)

 Table 1. Paving Material Specifications in Portugal: Filler [15, 16].

^a JAE – *Junta Autónoma de Estradas* (former road network administration institution); ^b EP – *Estradas de Portugal* (current institution); ^c filer particles < 0.075 mm

$$\eta_{\rm M} = -8244 + 4.68 \times \eta_{\rm b} + 205 \times \nu \tag{1}$$

where η_M is the mastic viscosity (f/b = 1.0) (cP); η_b is the bitumen viscosity (T = 135°C; $\dot{\gamma} = 6.8 \text{ s}^{-1}$) (cP); v is the filler Rigden voids (%). A maximum value of 5.0 to the mastic-to-bitumen relative viscosity was recommended for good workability.

Currently, most construction specifications still in use worldwide only define the material type and a broad sieve gradation for the filler, and general limits for the filler-to-bitumen ratio (f/b). In the latest revision of the specifications for paving materials, the main concessionaire of the Portuguese road network, *Estradas de Portugal S.A.*, changed the criterion for recommending the filler content [15, 16]. Table 1 compares the previous criterion, based on a mass f/b interval as a function of the asphalt type, with the current one based on the volume f/b determined from:

$$f'b = \frac{(100-v) \times \Delta T_{R\&B}}{1021.2 - \Delta T_{R\&B} \times v}$$
(2)

where v is the filler Rigden voids (%); $\Delta T_{R\&B}$ is the softening point increase (from bitumen to mastic) (°C). This equation was developed at the Belgium Road Research Centre to predict the stiffening effect of the filler on the mastic [17].

Working Temperatures

Adequate asphalt mixing and compaction temperatures (hot-mixing method) are currently selected based on the equiviscous concept. The temperatures are calculated from bitumen viscosity testing at various temperatures, considering "optimum" viscosity values for mixing and compaction. These viscosity values (see Table 2) were defined a long time ago, when only neat bitumens were in use [18], and field experience showed that reasonable results could in general be obtained. The Superpave method [19] uses the same viscosity values are adopted in many specifications and standards all over the world [20]. The Shell method [3] proposes a broader viscosity range for compaction considering other conditions like the influence of aggregate properties.

Table 2. Methodologies for the Determination of Mixing and Compaction Temperatures (Neat Bitumens).

	Metho	d	Superpave [19]	Shell [3]
]	Femperatur	e [°C]	135 & 165	-
	Shear Rate	$e[s^{-1}]$	6.8	-
Visc	cosity	Mixing	0.17±0.02	0.20
[Pa	[Pa·s] Compaction		0.28±0.03	2.00 to 20.00

This issue becomes more complex with modified bitumens, which are being used increasingly [21], aiming to improve bitumen properties over different temperature ranges [3, 22]. The above described methods often recommend very high temperatures, which causes concerns about the degradation of the bitumen and greater atmospheric emissions. Field experience has proved that such an increase of mixing and compaction temperatures is not needed [18]. Mostly, the specifications rely on the recommendations from the binder suppliers [19, 23].

While neat bitumens show Newtonian behaviour at high temperatures, which in a simplistic form is defined as the shear viscosity not varying with the shear rate, modified bitumens show non-Newtonian behaviour, of the shear-thinning type [3, 24-26]. A pseudoplastic (shear-thinning) material presents a reduction of the viscosity with increasing shear rate. The viscosity is constant for both very low and very high shear rates, with the corresponding values being occasionally named as "first" and "second" Newtonian regions [24]. The flow curve (viscosity variation with shear rate) is usually modelled with one of the following models: Cross model; power-law; Sisko model; or Bingham model. The Cross model describes the flow curve over the entire shear rate range, and can be defined with the following four parameter equation:

$$\frac{\eta - \eta_{\infty}}{\eta_0 - \eta_{\infty}} = \frac{1}{1 + k \times \dot{\gamma}^m} \tag{3}$$

where η is the shear viscosity (Pa.s) at shear rate $\dot{\gamma}$ (s⁻¹); η_{∞} is the infinite shear viscosity (Pa.s); η_0 is the zero shear viscosity (Pa.s); k and *m* are constants. Constant *m* indicates shear rate dependency (0 for Newtonian fluids) and *k* has dimensions of time and defines the onset to shear-thinning behaviour [27]. The other models only partially describe the flow curve.

Considering the differences in neat and modified bitumens rheology, and the stated problems with the implementation of the traditional methods, some research effort has been focussed on this issue. Table 3 describes briefly four different methods for the determination of adequate mixing and compaction temperatures proposed in literature for modified bitumens, comprising: the High Shear Rate Viscosity (HSRV) [4, 18, 25, 28], the Zero Shear Rate Viscosity (ZSRV) [26, 29-30], the Steady Shear Flow (SSF) test [18], and the Phase Angle (PA) [18]. In the first two methods, viscosity characterization is performed with a rotational viscometer (RV), though considering different experimental conditions (temperature and shear rate), while in the other two methods a dynamic shear rheometer (DSR) is used. The HSRV and ZSRV methods are criticized for the extrapolation of the viscosity for the very high or very low shear rate conditions. Likewise, the SSF and PA methods are based on testing at much lower temperatures than used for mixing and compaction operations.

	High Shear Rate Viscosity [4, 18, 25, 28]		Zero Shear [26,	Rate Viscosity 29-30]	Steady Shear Flow Test	Phase Angle	
	Original	Evolution	Original Simplification		[18]	[18]	
			Te	sting			
Apparatus	F	RV		RV	DSR	DSR	
T [°C]	135	& 165	120, 1	35 & 165	76, 82 & 88	50, 60, 70 & 80	
Ϋ́ [s ⁻¹]	Var	riable	Variable 6.8		-	-	
τ [Pa]	-	-	-	-	500	-	
w [rad s^{-1}]	-	-	-	-	-	0.001 - 100	
			Recommende	d Temperatures			
	Т @	η (γ΄)	Τ (ά	ψη(γ΄)	Τ @ η (τ)	$T = f[w(\delta)]$	
	$\dot{\gamma} = 500 \text{ s}^{-1}$	$\dot{\gamma} = 500 \text{ s}^{-1}$	$\dot{\gamma} = 500 \text{ s}^{-1}$	$\dot{\gamma} = 500 \text{ s}^{-1}$	$\tau = 500 \text{ Pa}$	$\delta = 86^{\circ}$	
	0.17	0.275				$[325 \times w(\delta)^{-0.0135} - 32]$	
Mix	± 0.020	±0.020	3.000	0.750 ± 0.050	0.170±0.020	1.8	
C	0.28	0.55	< 000	1.400±0.100 or	0.250+0.020	$\left[300 \times w(\delta)^{-0.0120} - 32 \right]$	
Comp	±0.030	±0.030	0.000	1.100 ± 0.200	0.550±0.030	1.8	

Table 3. Methodologies for the Determination of Mixing and Compaction Temperatures (PMBs).

Micaelo *et al.* [31] analysed the implementation of the different versions of HSRV and LSRV methods with several SBS polymer modified bitumens from Iberian refineries. The High Shear Rate Viscosity (evolution version) (HSRV-E) and Zero Shear Rate Viscosity (simplification version) (ZSRV-S) methods were considered the most promising methods as the resulting temperatures were closer to the suppliers' recommendations.

Laboratory Testing

Two different paving grade bitumens, from Galp-Porto refinery, in Portugal, were modified with SBS and blended with three different fillers (using two different filler-to-bitumen ratios) for the evaluation of SBS and filler influence on the rheological behaviour of the bituminous mastic at high temperatures.

Two fillers were obtained from crushed limestone (RC 480 and RC 590 commercial references) and the other was a natural hydraulic lime (NHL5). All three fillers met the requirements in NP EN 13042:2002 "Aggregates for Bituminous Mixtures and Surface Treatments for Roads, Airfields and Other Trafficked Areas". Table 4 presents the physical properties of the fillers. RC 590 and RC 480 are obtained from the same quarry, but RC 590 has a finer gradation. The type of material and the particles gradation are the two filler variables under analysis. No Rigden voids information was provided by the producer for RC 590, and the range for lime is rather broad.

The bitumens were modified at the NIDIN lab (Probigalp) with SBS polymer (2% and 4% of final mass). The bitumen, the polymer and the aromatic extract type NF 100 were mixed at $165-175^{\circ}$ C

within 150 minutes, including preparation and final storage tasks. SBS polymer, a thermoplastic elastomer polymer, is one of the most commonly used additives for bitumen modification [32]. It causes a decrease of the needle penetration test value and an increase of the softening point test value. There is an improvement of the flexibility and ductility of the bitumen at low temperatures. Asphalts with SBS modified bitumen have higher resistance to rutting [3, 33]. The aromatic extract type NF 100 is used to aid the stabilization of the mixing process.

The bitumens were characterized with the following tests: needle penetration (NP EN 1426:2010); softening point - Ring and Ball method (NP EN 1427:2010); polymer dispersion (EN 13632:2003); dynamic viscosity using a rotating spindle apparatus (EN 13302:2010). From this point on, the bitumens are designated by the paving grade (35/50 or 50/70) and when modified, the letter "P", polymer, is added followed by the polymer content. For example, "35/50 P2" corresponds to a paving grade 35/50 modified with 2% of SBS polymer.

The mastic samples were produced by mixing the bitumen with the predefined filler content at 150-165 °C for 30-45 min. All mastic combinations were fabricated with two different filler-to-bitumen ratios in accordance to the two filler specifications described in the previous section. For JAE, the f/b (mass) of 1.2, next to the lower limit, was selected. For EP, the f/b (volume) was determined with Eq. (2), considering that both limestone based fillers have equal Rigden voids and for the lime, the middle value of given voids interval. Table 5 presents the f/b values used in the production of the mastics. The samples were first taken using the needle penetration

Table 4. Characteristics of the Fillers (Eurocalcio and Secil Product Data Sheets).

	Gradation ((% Mass Passing) EN 933-10	- Finanasa Plaina Mathad	Partiala Dansity	Diadan Voida EN 1007 4	
Filler	2	0.125	0.063	EN 106 6 $[am^2/a]$	Fallicle Defisity EN 1007 7 $[M_{\alpha}/m^3]$		
	[mm]	[mm]	[mm]	EN 190-0 [CIII /g]	EN 1907-/[Wig/iii]	[%0]	
RC 480	100-100	100-98	88.5-78.5	3680	2.71	32	
RC 590	100-100	99-98	95-85	4190	2.68	-	
NHL5	100-100	100-90	75-85	5000-6400	2.70-2.90	28/45	

	RC	C 480	R	C 590	NHL5		
Method	f/b			f/b	f/b		
	Mass	Volume	Mass	Volume	Mass	Volume	
JAE	1.20		1.20		1.20		
EP	1.68	0.65	1.70	0.65	1.57	0.58	

Table 5. Filler-to-bitumen Ratios Used in the Mastics.

and softening point tests and then with dynamic viscosity measurements, using a coaxial viscometer (rotating spindle apparatus) under varied test conditions (temperature and shear rate). The viscosity was measured at 120, 135, 150, 165, and 180°C. The viscosity was measured at 3 to 5 different shear rate values for each temperature value, depending on the spindle torque working range defined by the manufacturer. The viscosity measurement limits of each spindle are as follows: 0.025-500 Pa.s for n° 21; 0.125-2500 Pa.s for n° 27; 0.250-5000 Pa.s for n° 28.

Results and Discussion

Bitumen Characterization

Table 6 lists the results of the needle penetration (Pen) and softening

 Table 6. Bitumen Testing: Penetration and Softening Point Tests.

point ($T_{R\&B}$) tests. With the exception to 35/50 P2, modified bitumens have lower penetration and higher softening point values than original neat bitumens. Often, hard grade bitumens present extra difficulties with polymer dissolution and homogenization, particularly with low polymer content values [34]. Fig. 1 shows polymer dispersion in the modified bitumens, obtained with fluorescent microscopy. 35/50 PMBs show larger polymer particles (medium size), with shape differences between P2 and P4, while for the 50/70 there is a very fine dispersion of the polymer. The aromatic extract that was added and the processing time also affect the polymer particle size, but the modification process was kept the same for all bitumens. According to the list of PMBs established for use in Portugal (NP EN 14023:2010), P4 bitumens are classified as 25/55-65 type, and 50/70 P2 as 45/80-55 type, while 35/50 P2 does not comply with any PMB class.

Fig. 2 illustrates the variation of the dynamic viscosity with shear rate (2.8 to 74.4 s⁻¹) and temperature (120, 135, and 165 °C), and the Cross model curves that were fitted to measurements. As expected, the viscosity increases with the polymer content for both bitumens. For the same polymer content, the viscosity of 35/50 PMBs is in most situations similar or minor than the equivalent 50/70. These results corroborate that the two bitumens reacted differently to the

Table 0. Bituilleli	Testing. Felletiation	i and Softening	Fount Tests.				
Droparty	Test Standard -	Ne	eat		Mod	lified	
Property	Test Standard	35/50	50/70	35/50 P2	35/50 P4	50/70 P2	50/70 P4
Pen [0.1 mm]	EN 1426	41.5	62.5	42.3	39.9	52.9	42.7
T _{R&B} [°C]	EN 1427	51.8	48.5	56.9	70.2	57.6	78.3
PI	EN 1426	-1.2	-1.1				



50/70 P2



35/50 P4



Fig. 1. Polymer Dispersion in Modified Bitumen (Fluorescent Microscopy).



Fig. 2. Viscosity Variation with Shear Rate and Temperature.

SBS polymer, as concluded before from the microscopy analysis. Regarding shear rate dependency, the measurements show non-Newtonian behaviour for the modified bitumens with increasing dependency at lower temperatures and higher polymer contents. Table 7 presents the computed parameters of the Cross model for all combinations. Results and conclusions are limited by the restricted number of data points and the narrow shear rate range. Shenoy et al. [35] proposed, after testing numerous bitumens, minimum values of viscosity variation (η/η_0) to determine the critical shear rate from which there is a significant change from the "first" Newtonian region (η_0). For $\eta_0 \dot{\gamma} < 500$ Pa is defined $\eta/\eta_0 = 0.962$. Only 3 of the situations listed in Table 7 do not comply with the minimum variation.

Table 8 lists the mixing and compaction temperatures recommended by the suppliers and calculated by using several methods presented in the previous section (neat bitumens with Superpave and modified bitumens with Superpave, HSRV-E and

 Table 7. Bitumen Rheological Behaviour: Cross Model Parameters.

Ditumon	Variable		r	Tempera	ture (°C)	
ыципен	variable	100	120	135	150	165	180
35/50	η	6.25	1.55	0.64	0.31	0.15	0.10
50/70	η	4.40	1.10	0.46	0.23	0.13	0.07
25/50	η_0		5.89	1.20	0.67	0.39	0.23
35/50 D2	η_{∞}		2.74	1.09	0.61	0.34	0.21
P2	m		0.75	2.01	0.15	0.18	0.21
	η_0		5.30	2.12		0.77	0.43
35/50 D4	η_∞		4.47	1.88		0.66	0.42
14	m		3.30	2.07		0.52	3.09
50/70	η_0	11.47	2.88	1.32	0.64	0.44	0.28
50/70 D2	η_{∞}	8.80	2.41	1.29	0.63	0.27	0.12
F2	m	0.62	2.61	4.44	7.54	0.27	0.21
50/70	η_0		6.38	2.58	2.15	0.71	0.59
50/70 P4	η_∞		5.90	2.49	1.26	0.69	0.39
14	m		0.87	2.64	1.89	5.42	1.33

LSRV-S). The viscosity variation with temperature at constant shear rate conditions, as required by each method, was computed from fitting to data at 120, 135, 150, 165, and 180℃. The temperatures obtained for the neat bitumens fall in the intervals recommended by the suppliers, while for the PMBs, the Superpave temperatures are very high as expected (up to 26℃ above the top limit), HSRV-E leads to values above recommended temperatures for P4 PMBs (up to 16℃ above the top limit) and ZSRV-S to values below recommended for P2 PMBs (up to 15℃ bellow the bottom limit).

Mastic Characterization

Tables 9 and 10 present the needle penetration and softening point test values for the mastics designed according to the JAE and EP specifications, respectively. As expected, there is a decrease in the needle penetration values and an increase in the softening point values as compared with bitumen test values. Hence, Δ Pen and $\Delta T_{R\&B}$ values are higher for the EP formulation due to the increased filler content, which stiffens the mastic. Despite the gradation differences, the two limestone fillers cause a similar stiffening effect. Both limestone fillers showed a significantly lower stiffening effect than NHL5. Moreover, the NHL5 relative stiffening effect increases with the filler content and, though the EP specification determines a lower *f/b* ratio for NHL5 than for the limestone fillers, the

Table 8. Determined and Recommended Mixing and Compaction Temperatures
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		Ν	eat		Modified				
Method			35/50	50/70	35/50 P2	35/50 P4	50/70 P2	50/70 P4	
г		mix	150	150-165		-175	155-170		
Recommended		comp	140	-150	155-	-165	150-165		
	0	mix	165	159	184	201	181	199	
ed	Superpave	comp	155	149	172	189	170	187	
nin		mix	-	-	172	189	168	186	
ten	HSKV-E	comp	-	-	155	171	154	171	
De	ZEDV C	mix	-	-	148	164	150	165	
ZS	ZSKV-S	comp	-	-	140	155	142	157	

	J				0					
D (35/50			35/50 P2			35/50 P4		
Properties	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	
Pen (0.1 mm)	28	31	22	24	24	20	22	21	18	
$\Delta Pen(0.1 \text{ mm})$	-14	-11	-20	-20	-20	-23	-17	-18	-21	
$T_{R\&B}$ (°C)	57.9	56.9	61.4	60.4	61.4	71.6	94.6	95.4	94.4	
$\Delta T_{R\&B}$ (°C)	+6.1	+5.1	+9.6	+3.5	+4.5	+14.7	+24.4	+25.2	+24.2	
		50/70			50/70 P2			50/70 P4		
	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	
Pen (0.1 mm)	40	40	33	31	33	27	33	30	28	
$\Delta Pen(0.1 \text{ mm})$	-22	-23	-29	-22	-20	-26	-10	-13	-15	
$T_{R\&B}$ (°C)	52.9	53.6	56.7	58.4	59.1	61.6	81.1	82.7	85.8	
$\Delta T_{R\&B}$ (°C)	+4.5	+5.2	+8.3	+0.8	+1.5	+4.0	+2.8	+4.4	+7.5	

Table 9. Mastics (JAE f/b Ratio) Properties: Needle Penetration and Softening Point Tests.

Table 10. Mastics (EP f/b Ratio) Properties: Needle Penetration and Softening Point Tests.

Dropartias		35/50			35/50 P2			35/50 P4	
Properties	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5
Pen (0.1 mm)	21	22	19	21	21	18	16	16	14
$\Delta Pen(0.1 \text{ mm})$	21	20	23	22	23	26	23	23	25
$T_{R\&B}$ (°C)	61.1	62.6	66.6	66	72.7	97.7	101.7	102	126.4
$\Delta T_{R\&B}$ (°C)	+9.3	+10.8	+14.8	+9.1	+15.8	+40.8	+31.5	+31.8	+56.2
		50/70			50/70 P2			50/70 P4	
	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5	RC 480	RC 590	NHL5
Pen (0.1 mm)	34	33	26	28	27	24	27	25	22
$\Delta Pen(0.1 \text{ mm})$	-29	-30	-36	-25	-26	-29	-16	-18	-21
$T_{R\&B}$ (°C)	56.6	57.5	62.2	60.7	62	73.1	84.8	87	90.1
$\Delta T_{R\&B}$ (°C)	+8.2	+9.1	+13.8	+3.1	+4.4	+15.5	+6.5	+8.7	+11.8

differences on ΔPen and $\Delta T_{R\&B}$ values become larger. The f/b ratio calculation in EP specifications is based on a $\Delta T_{R\&B}$ value between 12 and 16°C, which is intended to optimize the mastic behaviour. Only 4 out of 24 cases fall within this range, with extreme values of 3°C (50/70 P2 + RC480) and 56°C (35/50 P4 + NHL5).

The viscosity testing conducted on the different mastics showed significant shear rate dependency, which is an indication of non-Newtonian behaviour, as concluded before in other research studies [10, 36]. The Cross model was used to express the viscosity variation with shear rate, at constant temperature, for the different mastics. Fig. 3 plots the relative viscosity (mastic-to-bitumen ratio) with f/b (mass) content, at the temperature of 135 °C and the shear rate of 6.8 s⁻¹, for the comparison with the workability limit proposed by Bahia *et al.* [10]. The values plotted for f/b=1 were obtained from Eq. (1) and not directly from the experimental program. It can be seen that the mastic behaviour is highly dependent on the filler/bitumen combination. The mastics with 35/50 PMBs show higher relative viscosity values than the mastics with 50/70 PMBs, but all mastics with 35/50 bitumens (neat and PMBs) exhibit steeper slopes of the relative viscosity variation with f/b (average 11.0 compares to 6.8). Hence, the filler effect on 35/50PMBs is likely to be related with the polymer dispersion characteristics previously mentioned, where the polymer and the filler particles may have interacted to create thicker layers of adsorbed (fixated) bitumen around filler particles that contribute to the (higher) viscosity in the hydrodynamic regime [6].

Both limestone fillers, despite differences in gradation, have a similar stiffening effect on the mastics when the same bitumen is

used. In opposition, the lime (NHL5) has a high stiffening effect that is maximized with 35/50 bitumens. Furthermore, it was not possible to measure the viscosity of 35/50P4+NHL5 at 135 °C. Surprisingly, the results for the mastics formulated according to the EP specification are not closer among mastics with different fillers (and the same bitumen). For the mastics with PMBs, the higher stiffening effect of NHL5 as compared with the other fillers is very similar despite the f/b ratio differences (EP/JAE formulation).

The relative viscosity values predicted for f/b=1 of the mastics with 50/70 PMBs are substantially higher than the measured values with f/b=1.2, while the opposite happens with the 50/70 (neat) bitumen (relative viscosity near 1.0). Nevertheless, though no measurements were taken for f/b=1.0, the values for f/b=1.2 and the trend lines allow us to conclude that all mastics, including the ones with NHL5, would not reach the relative viscosity limit of 5.0 proposed by Bahia *et al.* [10].

Mixing and Compaction Temperatures

The evaluation of the influence of the filler type and SBS content on construction operations based on the viscosity variation, either with plots or with the Cross model parameters, is rather difficult/limited. For that reason, a new method was developed based on paving and compaction temperatures. The variable used for the analysis is the required temperature increase of harsh mastics such that all mastics (same bitumen and different fillers) have the same viscosity of the softer mastic. The temperature increase is measured from the



Fig. 3. Mastics' Relative Viscosity (T = 135° C; $\dot{\gamma} = 6.8 \text{ s}^{-1}$).

working (mixing and compaction) temperatures evaluated for the bitumen. Fig. 4 illustrates the method used to determine the required temperature increase, with the steps numbered from (1) to (5). The steps are summarized below:

- (η_{Mb}; η_{Cb}) bitumen viscosities for adequate mixing (η_{Mb}) and compaction (η_{Cb}) are defined for each method (see Tables 2 and 3);
- (T_{Mb}; T_{Cb}) bitumen mixing and compaction temperatures corresponding to viscosity η_{Mb} and η_{Cb} are determined from bitumen viscosity testing;
- (3) $(\eta_{Mm}; \eta_{Cm})$ mastic mixing and compaction viscosities are evaluated from viscosity tests on the softer mastic assuming T_{Mb} and T_{Cb} values;
- (4) $(T_{Cm2}; T_{Mm2b})$ mixing and compaction temperatures for the other mastic are evaluated assuming η_{Mm} and η_{Cm} values;
- (5) $(\Delta T_{C1,2}; \Delta T_{M1,2})$ required temperature increase between the two mastics for mixing and compaction operations is calculated as the difference between T_{Cm2} , or T_{Mm2b} , and T_{Cb} , or T_{Mb} values.

For all bitumens, the mastics incorporating RC 480 have the lowest viscosity values. Therefore, RC480 was defined as the reference for ΔT calculation. Figs. 5 and 6 show ΔT results for the mastics with RC 590 and NHL5 (bars/left axis), measured from the bitumen mixing (M) and compaction (C) temperatures (dots/right axis), as determined with the three methods (Superpave, HSRV-E, ZSRV-S). For the mastics with neat bitumens, only the Superpave



Fig. 4. Method for Determination of Increase of Working Temperatures for Bitumen-mastic.

method was used. The results show similar ΔT values for mixing and compaction purposes in each individual situation. The maximum value of ΔT is 19°C for 50/70 P2+NHL5 (HSRV-E/mixing) while the minimum value is -1°C for 35/50 P4+RC590 (Superpave/compaction). On average, the mastics with RC 590 require an extra 2°C (JAE) or 4°C (EP) while the mastics with NHL5 require an extra 10°C in comparison with the mastics with RC480.

When the same f/b ratio is used (JAE formulation), the results show a ΔT decrease with SBS content for 35/50 bitumens while with 50/70 bitumens, ΔT is nearly constant. In contrast, for the EP formulation, the ΔT variation with the bitumen, the SBS and the filler type show different trends depending on the method used to determine the temperatures. For the RC 590 filler, the Superpave and ZSRV-S methods show a ΔT decrease with an increase of SBS content but HSRV-E shows similar ΔT values. For the NHL5, the Superpave method led to a ΔT decrease with an increase of SBS for 35/50 bitumen while the opposite situation occurred for ZSRV-S.

Regarding the ability of the new formulation method (EP) to reduce, if not eliminate, behaviour differences among mastics with different fillers, the results show higher ΔT values for RC 590 and similar values for NHL5, when compared to RC 480 mastics. However, ΔT values differences between RC 590 and NHL5 are lower than when equal f/b content is used. Therefore, despite the limited number of fillers included in the study, it can be concluded that Eq. (2) should be re-analyzed considering the in-service performance and the material workability. A new model should not only include the filler properties but also the bitumen properties as proposed by Faheem [9], considering the mastic to bitumen relative complex modulus.



Fig. 5. Filler and Bitumen Influence on Working Temperatures (JAE Specification).

Conclusions

Current specifications for paving materials do not set a method for the definition of adequate mixing and compaction temperatures when using modified bitumens, where the filler effect should also be considered. This paper presents a rheological study of mastics fabricated with six bitumens (neat and SBS modified) and three fillers, using two filler-to-bitumen ratios according to EP and JAE specifications.

The results have shown that the mastic behaviour is highly specific to the filler-bitumen combination. Although the paving grade 50/70 was shown to be more reactive with SBS than 35/50 (50/70 PMBs exhibited in general higher viscosity values), after mixing with the filler, the mastics with 35/50 bitumens (neat and PMBs) presented higher viscosity values than the mastics with 50/70 bitumens. Hydraulic lime (NHL5) showed a very high stiffening power while the gradation of the limestone fillers had a minor effect. Also, the effect of f/b on the relative viscosity increase is highly dependent on the filler-bitumen combination. The mastics with NHL5 show steeper slopes (relative viscosity to f/b) for all



Fig. 6. Filler and Bitumen Influence on Working Temperatures (EP Specification).

bitumens with the extreme values of 3.2 (50/70 P2+RC480) and 18.8 (35/50 P2+NHL5).

Mixing and compaction temperatures are influenced up to 18 °C by the filler type, though more often by less than 10 °C, while the SBS modification can reach 25 to 35 °C of temperature variation, depending on the considered method for the working temperatures' determination.

New filler specifications, considering a filler physical property (Rigden voids), can be considered an improvement, though this needs more testing as the mastics behaviour depends on other factors.

The study presented in this paper is part of an on-going research project on the evaluation of the effect of mixing and compaction conditions on asphalt properties. We intend to assess in the near future the influence of mixing and compaction temperatures on the volumetric and mechanical properties of asphalts with SBS modified PMBs.

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