MIXING AND COMPACTION TEMPERATURES OF ASPHALT MIXTURES WITH MODIFIED BITUMEN

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ABSTRACT

In opposition to neat bitumens, modified ones have non-Newtonian rheological behaviour, shear-thinning type. Viscosity varies not only with temperature but also with shear rate and modifying agent (type and content). Traditional equiviscous methodology based on dynamic viscosity values of 0.17±0.02 Pa.s and 0.28±0.02 Pa.s determine extremely high temperatures, which increases energy consumption and may cause bitumen-polymer bond degradation. Field experience indicates that lower temperatures can be used without compromising aggregate evolving with bitumen and on-site compaction.

This paper presents a rheological study of several paving grade bitumens, from different suppliers and base crudes, before and after lab modification with SBS (2 to 4%), aiming to compare mixing and compaction temperatures determined with different methodologies (traditional equiviscous/Superpave, zero shear rate viscosity and high shear rate viscosity) and recommended by the suppliers.

The rheology of bitumen was assessed by measuring the dynamic viscosity with a rotational viscometer for different temperature and shear rate conditions. Viscosity – shear rate dependency was modeled with Cross and Power models for each test temperature.

The results have shown that the same paving grade bitumen, produced from different crudes, have very different rheological behaviours. The high shear rate viscosity (evolution) method determines the nearest mixing and compaction temperatures to the ones indicated by the suppliers. The Superpave and the high shear rate viscosity (original) methods determine very high temperatures, often above 180ºC for mixing condition, while with zero and low shear rate viscosity methods the temperatures are much lower than the ones recommended by the suppliers.

Keywords: polymer modified bitumen, mixing and compaction temperatures, viscosity

1. INTRODUCTION

Asphalt binders, where bitumen is included, have a high contribution to road pavement's life despite being present in smaller quantities than any other component of asphalt mixtures. Together with fine aggregate (< 2 mm) constitutes the bituminous mastic that is responsible for the adhesion between coarse aggregate particles (> 2 mm) and provides asphalt required characteristics such as the stability, the flexibility, the durability, the fatigue resistance, the impermeability, the workability, the compactability and the adherence [1, 2]. Therefore, it is very important to study binder's behaviour and try to predict the performance of asphalt mixtures in-service.

Modified bitumens are obtained with addition of one or more additives to neat bitumen, obtained directly from oil refining. Additives are selected with the goal of improving neat bitumen properties, and different additives influence different properties of the bitumen and over different temperatures range [2-4]. Additives can be combined to modify the performance at low, intermediate and high in-service temperatures and at production temperatures.

Modified bitumens were introduced in early 70's in most industrialized countries, while in Portugal just in the 90's, with the increase of functional and structural pavement requirements. Hence, modified bitumens consumption has been growing in road construction industry. It is mainly used in asphalt mixtures with discontinuous aggregate gradation for surface layers.

The mechanical behaviour of bitumen is dependent on temperature and loading (time and magnitude), from which broad mechanical responses to loading can be obtained. At low temperatures and short loading periods the bitumen has elastic behaviour. At intermediate and high service temperatures and increasing loading periods the bitumen has viscoelastic behaviour. At mixing and compaction (high) temperatures bitumen has viscous behaviour [3, 5].

The asphalt layers construction process has two phases, mixing and compaction, which together determine asphalt end quality and pavement performance. The mixing and compaction processes are influenced by the viscosity of the bitumen, dependent of the type of bitumen and the temperature, as during mixing it determines aggregates coating quality and during compaction the ability to aggregate particles constitute a compact, resistance, durable, and cohesive structure with designed air void content [1, 3, 5].

Neat bitumens have Newtonian behaviour at high temperatures, i.e. the viscosity is independent of shear rate, as presented in Figure 1a. In opposition, the viscosity of modified bitumens decreases with shear rate (Figure 1b), for a constant temperature, i.e. modified bitumens are non-Newtonian (shear-thinning type), [1, 5].

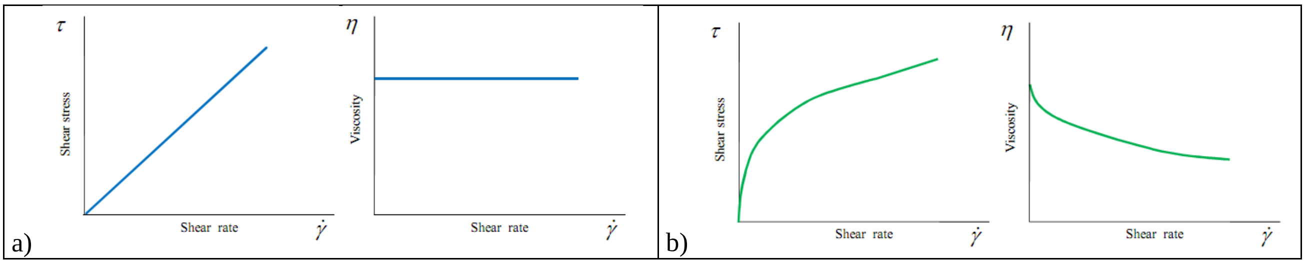


Figure 1: Newtonian and shear-thinning non-Newtonian rheological behaviours (modified from [5])

The variation of viscosity with shear rate (decreasing) is also dependent on temperature and modifier additive (type and content). Often, modified bitumens have lower viscosity dependency on shear rate with increasing temperatures and greater dependency with increasing additive content [6].

2. MIXING AND COMPACTION TEMPERATURES

During asphalt production in plant aggregates are first heated and dried, and then the bitumen, at the predefined temperature, is added to coat the aggregates. In a continuous plant both tasks take place in the drum while in a batch plant aggregates heating is separated from mixing. At this stage it is required that bitumen coat aggregates properly. If the bitumen temperature is too high, low viscosity, bitumen can drain off the asphalt mixture during transport. On the other hand, if bitumen temperature is too low, high viscosity, not all aggregate particles will be coated [2, 3].

After the mixing process, asphalt is transported to field; it is spread and compacted at a predefined temperature, the compaction temperature, aiming at achieving design air voids content. The temperature determines asphalt workability and compactability during paving and compaction operations, which influences the final aggregate structure and the performance of asphalt layers in service [5, 7]. Compaction temperature should be the one that makes bitumen act as a lubricant, in order to easy aggregate particles movement and create a compact and durable structure, and to provide cohesion to asphalt. Cohesion between aggregate particles depends on the bitumen film thickness, which is function of the quantity and the viscosity of the bitumen. It is desired that asphalt can be compacted without excessive deformations (proper initial cohesion) and in service can support loading as design predicted (in-service cohesion). If the temperature is too high, low viscosity, the bitumen is too fluid; asphalt does not have enough cohesion and just can't resist roller loading, resulting in successive compaction and discompaction events. In opposition, if the temperature is too low, high viscosity, the compactability is significantly reduced by the increase of aggregates particles movement difficulty, becoming almost impossible to achieve desired air voids content [1, 3, 5]. The optimum compaction temperature is the one that leads to low shear resistance of aggregates particles so that rollers can reduce asphalt volume and do not cause excessive shear deformations [1].

2.1 Methodologies for mixing and compaction temperatures determination

Currently used methodologies are based on the equiviscous concept, i.e. each bitumen mixing and compaction temperatures are established by determining the viscosity variation with temperature, using viscometers, and finding out the temperatures such that the bitumen has the defined mixing and compaction viscosities.

The viscosity ranges that are used for determining mixing and compaction temperatures were defined long ago, when just neat bitumens were used [8]. Field experience tells that this methodology (testing and viscosity ranges) provide reasonable results for neat bitumens. The viscosity ranges were defined to lab conditions and are commonly used as an estimation of the adequate temperatures to carry out mixing (in plant) and compaction (in field). Compaction occurs during a broader temperature range due to asphalt cooling.
Table 1 presents the specifications of two methods, Superpave [5] and Shell [3]. In the Superpave method, it is defined that viscosity is measured with a rotational viscometer at two temperatures (135ºC and 165ºC) and with a shear rate of 6.8 s^{-1}. Shell proposes a broad viscosity range for compaction as it considers that asphalt field compactability depends not only on the bitumen but also on the other conditions like the aggregate (gradation, shape and fiction properties, etc.).

Table 1: Methodology for mixing and compaction temperatures determination (non-modified bitumen)

Method		Superpave [5]	Shell [3]
Temperature [°C]		135 e 165	-
Shear rate [s^{-1}]		6.8	-
Viscosity range [Pa·s]	Mixing	0.17±0.02	0.20
	Compaction	0.28±0.03	2.0 a 20

With the increasing use of modified bitumens it was found that with the application of the Superpave method often resulted unreasonable mixing and compaction temperatures. The temperatures were too high, often above 180°C, because of the high viscosity exhibited by modified bitumens. Several studies concluded that as production temperature rises excessive aging, degradation and toxic fumes release may occur to the bitumen, and that mixing and compaction temperatures can be lowered without compromising the quality of mixing and compaction [5, 7, 9].

Hence, road administrations usually define in road construction specifications mixing and compaction temperatures proposed by the bitumen suppliers despite some times being based on non-confirmed predictions because there is not much experience using that bitumen [7].

With the aim of finding new methodologies to determine adequate mixing and compaction temperatures for asphalt production with modified bitumens, several researchers have carried out studies during the last decade on viscosity variation with test conditions (temperature, shear rate) and influence of the production temperature on volumetric and mechanical properties. In some cases, researchers have tried to estimate the shear rate during mixing and compaction processes.

Table 2 presents four methodologies proposed during the last decade, the High Shear Rate Viscosity (HSRV), the Zero Shear Rate Viscosity, the Low Shear Rate Viscosity and the Steady Shear Flow test. In the first three methods, it is used the rotational viscometer for the viscosity characterization though considering different experimental conditions (temperature and shear rate). For the first two methods, two different proposed versions are presented.

Yildirim *et. al.* [5] calculated the shear rate inside the Superpave Gyratory Compactor of 487 s^{-1}, which was rounded to 490 s^{-1}, and defined that mixing and compaction temperatures should be determined by considering 490 s^{-1} instead of 6.8 s^{-1} with the same viscosity ranges (0.17±0.02 Pa.s and 0.28±0.03 Pa.s). This method is designated as the High Shear Rate Viscosity (original), HSRV-O. In a more recent study, [9], the same authors state that current viscosity ranges fail to meet equiviscous assumption and should be increased to 0.275±0.03 Pa.s and 0.550±0.06 Pa.s. This method is designated as the High Shear Rate Viscosity (evolution), HSRV-E.

Khatri *et. al.* [6] introduced the concept of zero shear rate viscosity after concluding that the critical compaction stage in the gyratory compactor is more dependent on the low shear rate viscosity, and recommended it for determining mixing and compaction temperatures of modified bitumens. Viscosity target ranges for mixing and compaction were changed to 3.0±0.3 Pa.s and 6.0±0.6 Pa.s (0 s^{-1}). This method is designated as Zero Shear Rate Viscosity (original), ZSRV-O. In an attempt to simplify the process, i.e. to avoid prediction of viscosity at 0 s^{-1} with curve-fitting models, new viscosity target ranges were determined at 6.8 s^{-1}, 0.750±0.05 Pa.s and 1.40±0.10 Pa.s (Zero Shear Rate Viscosity (simplification), ZSRV-S). Stuart [10] investigated the application of ZSRV-O and concluded that the compaction viscosity range should be reduced to 1.10±0.20 Pa.s.

Bahia *et al.* [11] state that asphalt experts considered the term "zero shear" a theoretical concept difficult to understand and should be substituted by the term "low shear", which eventually originated defining the shear rate of 0.001 s^{-1}. This method is designated as Low Shear Rate Viscosity (LSRV).

Reinke [8] presented a new method based not on viscosity measurements with a rotational viscometer, at high temperatures, but on measurements with a dynamic shear rheometer at warm temperatures (76 ºC to 94 ºC), which was called the Steady Shear Flow test (SSF). The determined temperatures, obtained with a procedure that involve viscosity measurements extrapolation out to high temperatures condition, matched well with the temperatures ranges used in practice. The viscosity target ranges are 0.17±0.02 Pa.s and 0.35±0.03 Pa.s. This method was not implemented in this study.

Table 2: Different methodologies for mixing and compaction temperatures determination (modified bitumen)

Methodology		**High Shear Rate Viscosity [5, 8, 9, 12]**		**Zero Shear Rate Viscosity [6, 10, 11]**		**Low Shear Rate Viscosity [6, 11]**	**Steady Shear Flow Test [8]**
		Original	**Evolution**	**Original**	**Simplification**		
Temperature [°C]		135 e 165		120, 135 e 165			76, 82 e 88
Shear rate [s-1]		500	500	0.000	6.8	0.001	-
Shear stress [Pa]		-	-	-	-	-	500
Viscosity range [Pa·s]	Mixing	0.17±0.02	0.275±0.03	3.0	0.750±0.05	3.0±0.3	0.17±0.02
	Compaction	0.28±0.03	0.550±0.06	6.0	1.40±0.10 or 1.10±0.20	6.0±0.6	0.35±0.03

In order to express the variation of viscosity with shear rate, at constant temperature, two models can be used, the Cross model (1) and the power-law model (2). The first model covers any range of shear rate while the second is adequate for shear rate values between 1 and 10^3 s^{-1} [13]. In the ZSRV and LSRV methods was used the Cross model and for the other methods the model with better adjustment to data.

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{1 + (K\dot{\gamma})^m} \tag{1}$$

$$\eta = k\dot{\gamma}^{n-1} \tag{2}$$

Where η is the viscosity (Pa.s); η_∞ is the viscosity for infinite shear rate (Pa.s); η_0 is the viscosity at zero shear rate (Pa.s); $\dot{\gamma}$ is the shear rate (s^{-1}); *k*, *m* and *n* are constants of the model.

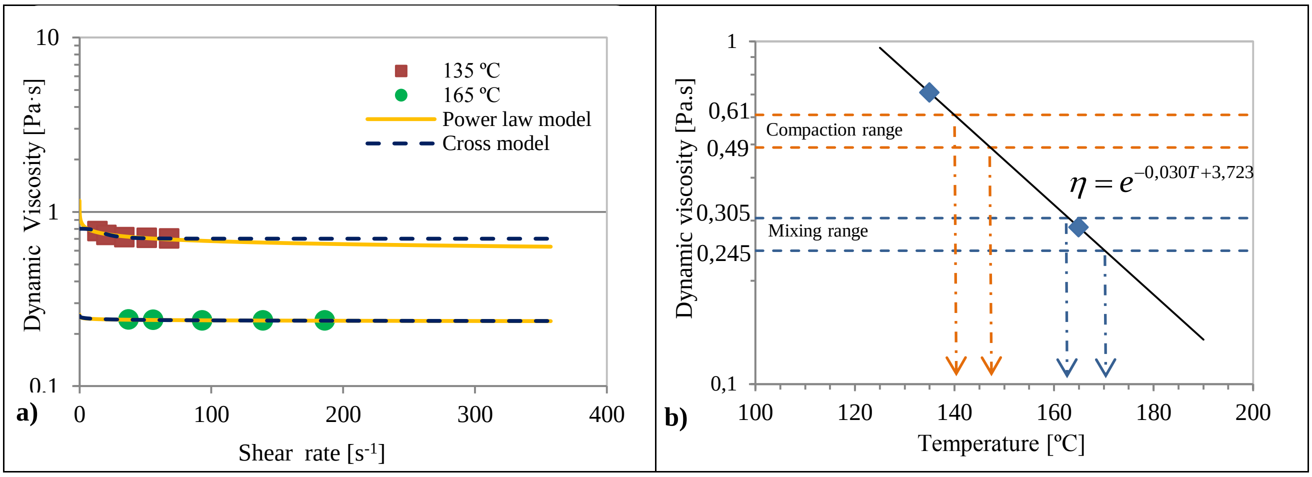


Figure 2: Determination of mixing and compaction temperatures

First, the Cross or the Power-law model are used to express viscosity variation with shear rate, for each test temperature (Figure 2a). Then, an exponential model is used to define viscosity variation with temperature, for a constant shear rate (method dependent) (Figure 2b). Finally, mixing and compaction temperatures are determined based on the method defined viscosity ranges.

3. EXPERIMENTAL PROGRAM

In this study five samples of neat bitumen were selected from two suppliers (Galp e Cepsa) and three refineries (Sines and Porto – Galp and Huelva – Cepsa). The bitumens are classified in two paving grades, 35/50 for the bitumen from Sines and Porto, and 50/70 for the bitumen from Sines, Porto and Huelva. These bitumens were characterized according to the European standards (needle penetration – EN 1426, softening point - Ring and Ball method – EN 1427 and viscosity using a rotating spindle apparatus – EN 13302:2003).

The bitumens samples were modified at NIDIN lab (Probigalp) with SBS polymer (2%, 3% and 4% of final mass). After modification the modified bitumens were characterized according to the European standards. From this point forward, bitumens are designated by a code composed by the supplier initial letter (G or C), the refinery (S, P or H) and the paving grade (35/50 or 50/70). For the modified bitumens, it is added the letter "P", polymer, followed by the polymer content. For example, GS 35/50 P2 corresponds to the bitumen supplied by Galp, from Sines refinery, paving grade 35/50 and modified with 2% of SBS polymer.

For the modification of the bitumen it was used the NIDIN modification procedure, i.e. initially it was defined the total mass of modified bitumen to prepare and then the mass of all reagents used in the modification (bitumen, SBS polymer and aromatic extract type NF 100). The polymer and bitumen were mixed during 150 minutes. The modification of bitumen with styrene-butadiene-styrene (SBS), a thermoplastic elastomer polymer, causes the decrease of the needle penetration test result and the increase of the softening point test result. There is also an improvement of flexibility and ductility of the bitumen at low temperatures. Asphalt mixtures with SBS modified bitumen have higher resistance to rutting [2, 3]. The aromatic extract, type NF 100, is used to help stabilizing the mixing process. Complete description on modification procedure and results can be found in [14].

The modified bitumens samples were first characterized with regular tests and then dynamic viscosity was measured with the rotational viscometer (EN 13302:2003) at varied test conditions (temperature and shear rate). Viscosity was measured at 120, 135, 150, 165 and 180 ºC. For each temperature, viscosity was measured at 3 to 5 different shear rate values. The number of tested shear rates values depended on maximum allowed spindle torque (simples 21and 27).

4. RESULTS

4.1 Bitumen characterization

Table 3 presents the neat bitumens characteristics. All bitumens are in agreement with Portuguese specifications [15]. For paving grade 50/70, the bitumen from Huelva has highest viscosity and the bitumen from Porto the lowest (about half), while for paving grade 35/50, the bitumen from Porto exhibits more viscosity than the one from Sines.

Table 3: Neat bitumen characteristics

Property	European Standard	Neat bitumen CH 50/70	GS 50/70	GP 50/70	GS 35/50	GP 35/50
Needle penetration (0.1 mm)	EN 1426	51.2	51.3	66.1	48.3	42.1
Softening point (Ring and ball method) (°C)	EN 1427	52.1	50.3	46.5	50.6	52.1
Kinematic viscosity (mm2/s)	EN 13302	648.86	417.79	362.95	476.55	564.33
Penetration index	-	-0.64	-1.07	-1.48	-1.13	-1.08

Figure 3 shows the variation of the dynamic viscosity with the temperature and the shear rate of two bitumens (before modification) of the same paving grade (50/70) from two different refineries (Huelva and Sines). As expected the viscosity, at constant temperature, does not vary significantly (or nothing) with the rate shear, i.e. both bitumens exhibit Newtonian behaviour. For constant shear rate conditions the viscosity decreases with temperature, showing both bitumens the same temperature susceptibility (decreasing rate approximately -0.044). In opposition, if the penetration indexes (IP) of the two bitumens are compared a different conclusion is taken (-0.64 vs. -1.07).

Table 4 and 5 presents, respectively, SBS modified bitumen characteristics (150 minutes of mixing operation) and modified bitumen specifications defined by the National Road Infrastructures Institute (INIR) [16]. Bitumens modified from 50/70 paving grade bitumens are compared with PMB 45/80-55 and bitumens from 35/50 paving grade bitumens are compared with PMB 25/55-65. Modified bitumens do not comply with all properties specifications which may have resulted from the lab modification procedure.

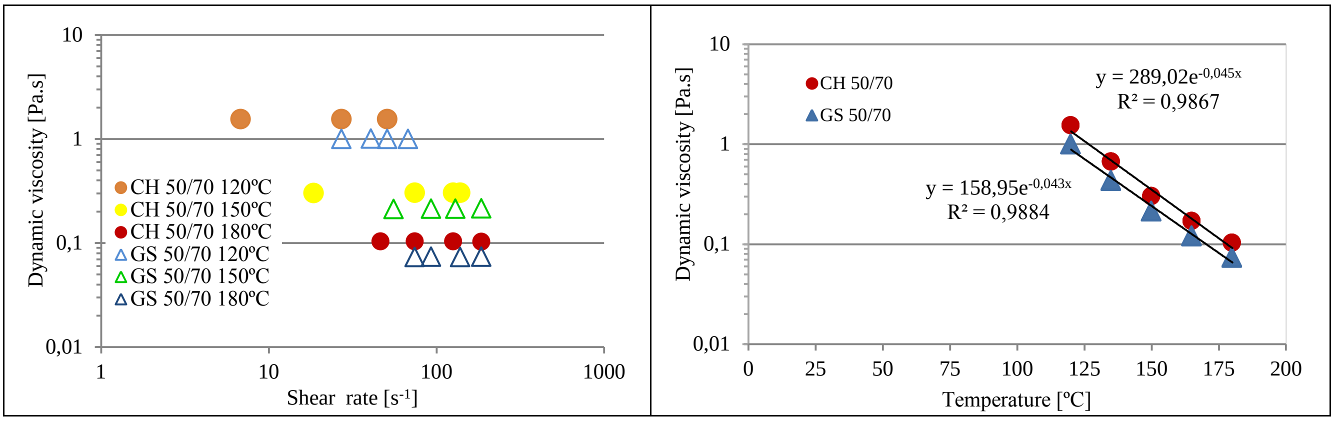


Figure 3: Viscosity variation with shear rate and temperature of GS 50/70 and CH 50/70 bitumens

Table 4: Modified bitumens characteristics (150 minutes of mixing)

Properties		**CH 50/70 P2**	**CH 50/70 P3**	**CH 50/70 P4**	**GS 50/70 P2**	**GS 50/70 P3**	**GS 50/70 P4**	**GP 50/70 P2**	**GP 50/70 P3**	**GP 50/70 P4**	**GS 35/50 P2**	**GS 35/50 P3**	**GS 35/50 P4**	**GP 35/50 P2**	**GP 35/50 P3**	**GP 35/50 P4**
Needle penetration (0.1 mm)		37.1	36.6	33.6	42.3	35.8	36.7	58.8	57.1	55.7	43.4	37.3	31.7	43.8	39.5	30.5
Softening point (°C)		57.8	60.0	62.2	55.7	59.1	66.7	49.6	52.8	85.7	53.8	61.5	71.7	53.9	56.7	74.9
Resistance to hardening under the influence of heat and air - RTFOT method	Δ mass (%)	0.09	0.04	-0.06	-0.04	-0.04	-0.06	0.20	0.17	-	-	-	0.07	-	-	-
	Retained penetration (%)	74.7	68.7	74.6	57.4	74.2	60.4	75.1	67.7	-	-	-	57.7	-	-	-
	Softening point increase (°C)	6.8	7.6	6.4	7.6	6.3	1.5	5.6	3.9	-	-	-	4.3	-	-	-
Elastic recovery (%)		45.5	74.6	72.0	63.3	76.1	81.0	53.3	75.0	97.5	69.0	86.3	94.5	77.5	81.5	87.5
Storage stability	Δ needle penetration (0.1 mm)	17.8	8.9	33.4	2.4	21.5	26.4	6.1	6.6	1.3	1.6	9.5	17.6	1.6	4.8	7.9
	Δ softening point (°C)	21	25.9	45.2	6.05	34.4	40.6	0.7	4.45	27.9	18.6	31.4	31.5	3.6	28.9	41.7
Penetration index		-0.12	0.28	0.51	-0.28	0.06	1.52	-0.93	-0.21	5.36	-0.62	0.61	2.00	-0.58	-0.20	2.39

Table 5: Polymer modified bitumens specifications [16]

Properties		**PMB 25/55-65**	**PMB 45/80-55**
Needle penetration (0,1 mm)		25-55	45-80
Softening point (°C)		≥65	≥55
Resistance to hardening under the influence of heat and air (RTFOT method)	Δ of mass (%)	≤0,3	≤0,3
	Retained penetration (%)	≥50	≥50
	Increase of the softening point (°C)	≤8	≤8

Elastic recovery (%)		≥70	≥70
Storage stability	Δ of needle penetration (0,1 mm)	≤9	≤9
	Δ of softening point (°C)	≤5	≤5

The penetration index (IP) was determined though it is not usually considered for modified bitumens characterization (non-Newtonian behaviour). For each bitumen, IP increases with polymer content (e.g., for GS 50/70 IP varies from -1.07 (0%) to +1.52 (4%). Results confirm expectations, the more polymer content is added, the lower the thermal susceptibility of bitumens is.

Figure 4 illustrates the viscosity variation with shear rate and temperature (120, 135 and 165 °C) of four modified bitumens (CH 50/70 P2, CH 50/70 P4, GP 35/50 P2 and GP 35/50 P4). The Cross and power law models were fitted to data and are represented in Figure 4. It is possible to clearly identify the decrease of viscosity with shear rate for constant temperature conditions, and that the variation magnitude increases with bitumen's polymer content. In opposition, as the polymer content increases the viscosity variation amount with temperature decreases. Modified bitumens obtained from Huelva bitumen are more influenced by polymer content variation. Both models fit well to data for the shear rate range tested.

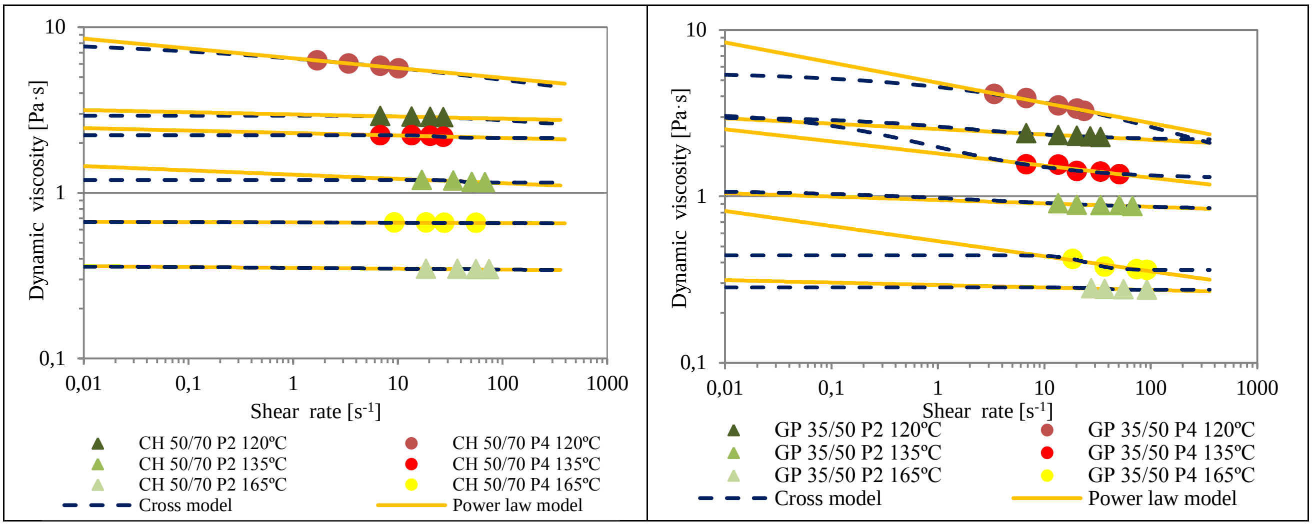


Figure 4: Viscosity variation with shear rate and temperature of some polymer modified bitumens

4.2 Mixing and compaction temperatures

The Superpave method was used to determine mixing and compaction temperatures of neat bitumens and the above presented methodologies (listed in Table 2) were used for polymer modified bitumens. The steady shear flow method was not implemented as it requires viscosity measurements with Dynamic Shear Rheometer, which was not available. Table 6 and 7 present respectively, mixing and compaction temperatures that were determined for paving grade bitumens and temperatures recommended by suppliers for the paving grade bitumens and polymer modified bitumens.

Table 6: Mixing and compaction temperature of neat bitumens (Superpave method)

Bitumen	Mixing temperature	Compaction temperature
CH 50/70	159 ºC – 164 ºC	150 ºC – 154 ºC
GS 50/70	152 ºC – 157 ºC	143 ºC – 147 ºC
GP 50/70	149 ºC – 154 ºC	140 ºC – 144 ºC
GS 35/50	154 ºC – 159 ºC	144 ºC – 148 ºC
GP 35/50	157 ºC – 161 ºC	148 ºC – 152 ºC

Table 7: Production temperatures recommended by suppliers

	Neat bitumen		Modified bitumen	
	35/50	35/50	35/50	50/70
Mixing temperature	150°C – 160°C		160°C – 175°C	155°C – 170°C
Compaction temperature	140°C – 150°C		155°C – 165°C	150°C – 165°C

The temperatures obtained for the non-modified bitumens are in general agreement with the temperature range proposed by suppliers for mixing and compaction tasks. Mixing temperatures are lower than 160°C, with the single exception of CH 50/70, and above 150°C. Compaction temperatures are lower than 150°C, with the single exception of CH 50/70, and above 140°C. As expected, Superpave method provides rational results when applied to paving grades bitumens.

The temperatures obtained with the selected methods for the modified bitumens are illustrated in Figure 5. Each plot refers to a method (identified on title) and to each bitumen it is represented the determined mixing and compaction temperatures, considering mean viscosity target values proposed by each method. Additionally, temperatures ranges recommended by suppliers (Table 7) are represented with a coloured horizontal band.

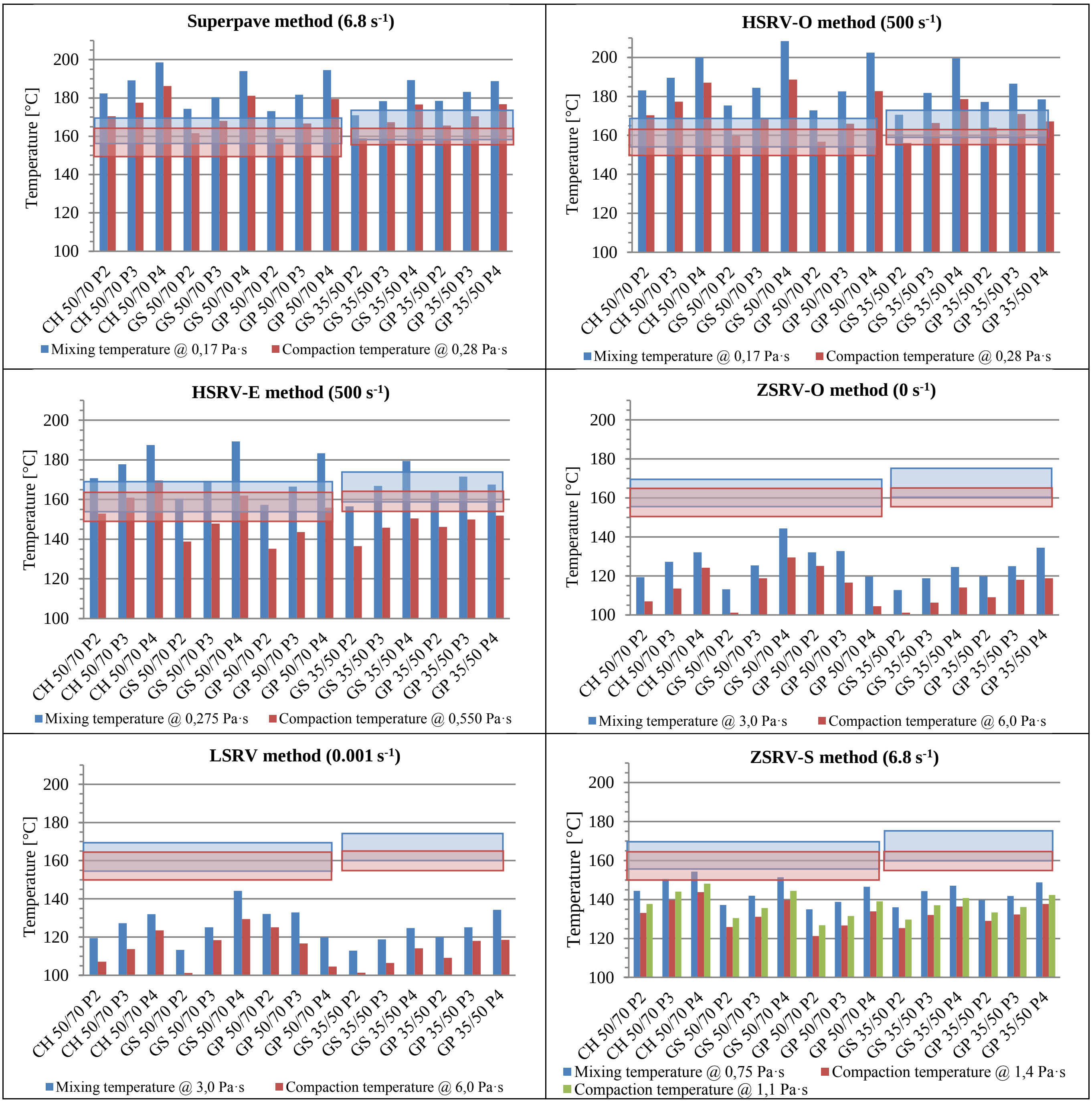


Figure 5: Mixing and compaction temperatures determined with the following methods: a) Superpave; b) HSRV-O; c) HSRV-E; d) ZSRV-O; e) LSRV; f) ZSRV-S

- **Superpave method**

It is observed that mixing and compaction temperatures increase proportionally to the SBS polymer content and that, in general terms, are higher than recommended by suppliers, with the exceptions to mixing temperature of GS 35/50 P2 and to compaction temperature of GS 50/70 P2, GP 50/70 P2 and GS 35/50 P2, which are in agreement to the specifications. Mixing temperatures are very high, above 180°C, which can cause degradation of SBS polymer and has environmental and health risks. Regarding compaction temperatures, this method determines high temperatures as well, above 165 ºC, which can originate successively compaction and discompaction phenomena due to very low asphalt bearing capacity (roller loading). As expected this method is considered unsatisfactory.

- **High Shear Rate Viscosity (original) method**

The determined temperatures increase as more as SBS the modified bitumen has, being in general the highest obtained by the different tested methods. Using this method some bitumens have recommended mixing temperatures around 200 ºC. The mixing temperature of GS 35/50 P2 and the compaction temperature of GS 50/70 P2, GP 50/70 P2, GS 35/50 P2 and GP 35/50 P2 are within suppliers recommended temperatures ranges. This method is considered also not adequate.

- **High Shear Rate Viscosity (evolution) method**

In general, this method determines mixing temperatures near or within suppliers recommended temperature range. Only 50/70 paving grade bitumens modified with 4% SBS have predicted mixing temperatures above 180 ºC. Regarding compaction, the obtained temperatures are mostly below the minimum temperature recommended for compaction realization.

- **Zero Shear Rate Viscosity (original) method**

All bitumens have temperatures lower than minimum recommended temperatures for carrying out asphalt mixing (at least 11 ºC) and compaction (at least 20 ºC). This method was developed aiming at determining mixing and compaction temperatures below, respectively, 150 ºC and 160 ºC. However, the determined temperatures are much lower than these targets, being within temperatures ranges considered not reasonable by construction industry (120-140 ºC for mixing and 100-120 ºC for compaction).

- **Low Shear Rate Viscosity method**

The results obtained are very similar to the previous method and the same conclusions can be taken. There are not differences between determining the temperatures at 0 s^{-1} or 0.001 s^{-1} shear rates.

- **Zero Shear Rate Viscosity (simplification) method**

All determined mixing and compaction temperatures are below minimum recommended temperatures. As this method has evolved from other method (ZSRV-O) the same target temperatures apply, and though temperatures have increased, at determined temperatures conditions it is considered to be almost impossible to achieve desired aggregate coating and asphalt air voids content in field. The viscosity variation proposed by [10], from 1.4 Pa·s to 1.1 Pa·s, implies necessarily higher compaction temperatures, and in this situation closer to supplier specifications.

- **Comparison between methods**

Table 8 shows the minimum, the average and the maximum mixing and compaction temperatures determined by each method. Figure 6 and 7 illustrate the variation of the maximum, the average and the minimum temperatures with used determination method, for the studied bitumens grouped according to the bitumens paving grade used for modification (Figure 6) and the modified bitumens grade (Figure 7). It is possible to take the following conclusions:

a. The Superpave and the HSRV methods determine, for the modified bitumens, close temperatures; and higher average temperatures than Superpave method for the non-modified bitumens;
b. The HSRV-E method determines lower average mixing and compaction temperatures than Superpave and HSRV-O methods;
c. The ZSRV (O and S versions) and the LSRV methods determine the lowest temperatures (mixing and compaction) and below industry recommended temperatures;
d. In opposition to what would be expected, the ZSRV methods (original and simplification) determine different mixing and compaction temperatures despite having one evolved from the other, aiming the simplification of the calculus procedure and obtaining similar results; determined compaction temperatures difference increases if it is used the 1.1 Pa·s target.

All tested methods determine mixing and compaction temperatures that are not totally in agreement with the temperatures ranges specified by construction guides and suppliers. As expected, temperatures obtained with Superpave method are very high. In opposition, the HSRV-O method determines even higher temperatures than Superpave.

The ZSRV (O and S versions) and the LSRV methods determine very low temperatures, and lower than specified by the suppliers. The only method with results close to suppliers recommended temperatures is HSRV-S. This method determines temperatures ranges that may be used in modified asphalt mixtures mixing and compaction processes.

Table 8: Mixing (M) and compaction (C) temperatures of polymer modified bitumens

	Superpave		**HSRV-O (500 s^{-1})**		**HSRV-E (500 s^{-1})**		**ZSRV-O (0 s^{-1})**		**LSRV (0.001 s^{-1})**		**ZSRV-S (6.8 s^{-1})**		
	M	**C**	**M**	**C**	**M**	**C**	**M**	**C**	**M**	**C**	**M**	**C 1.4 Pa.s**	**C 1.1 Pa.s**
Minimum temperature	171	159	171	156	157	135	113	101	113	101	135	121	127
Average temperature	184	171	186	171	171	150	125	114	126	114	144	133	137
Maximum temperature	199	186	208	189	189	170	144	130	144	129	154	144	148

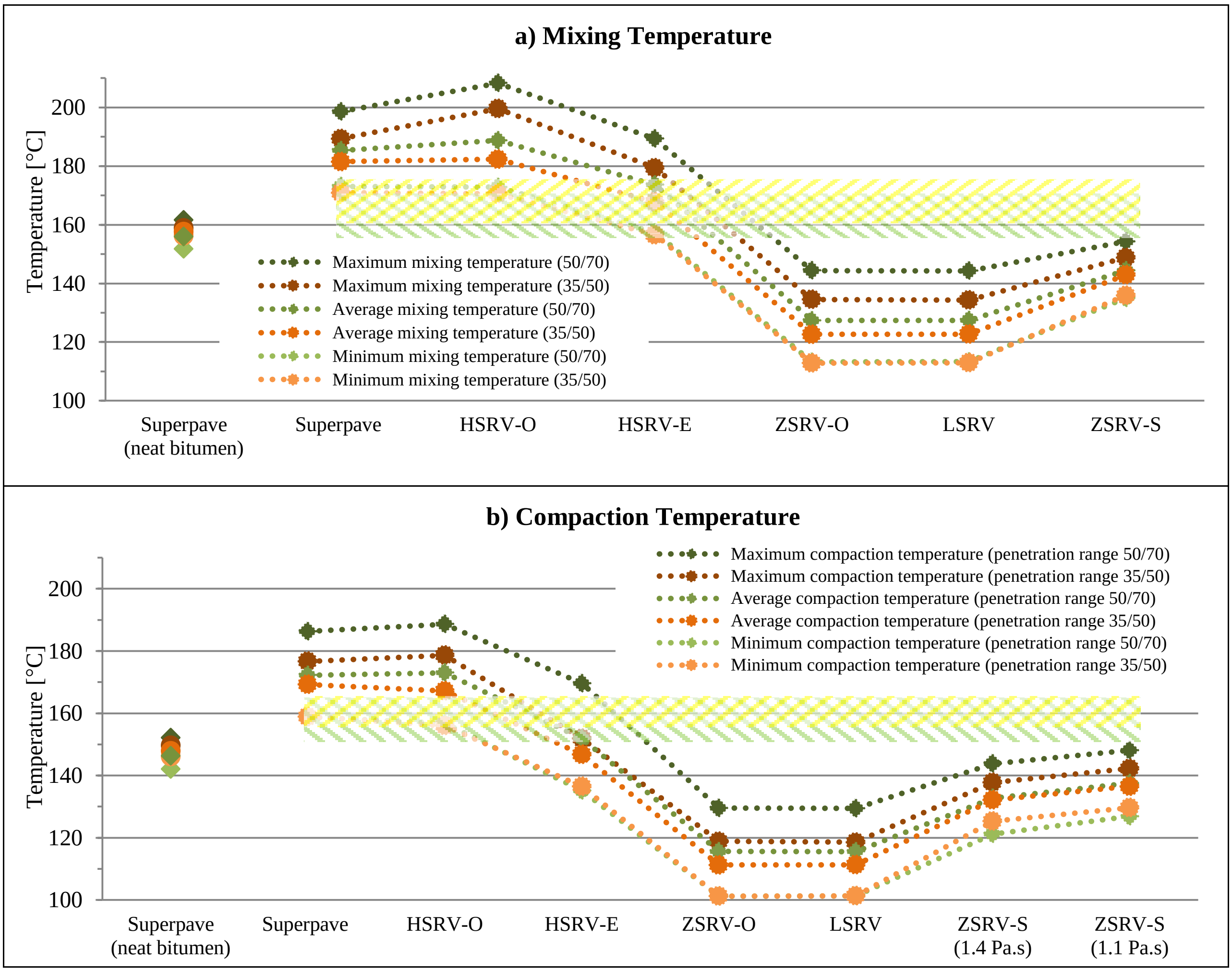
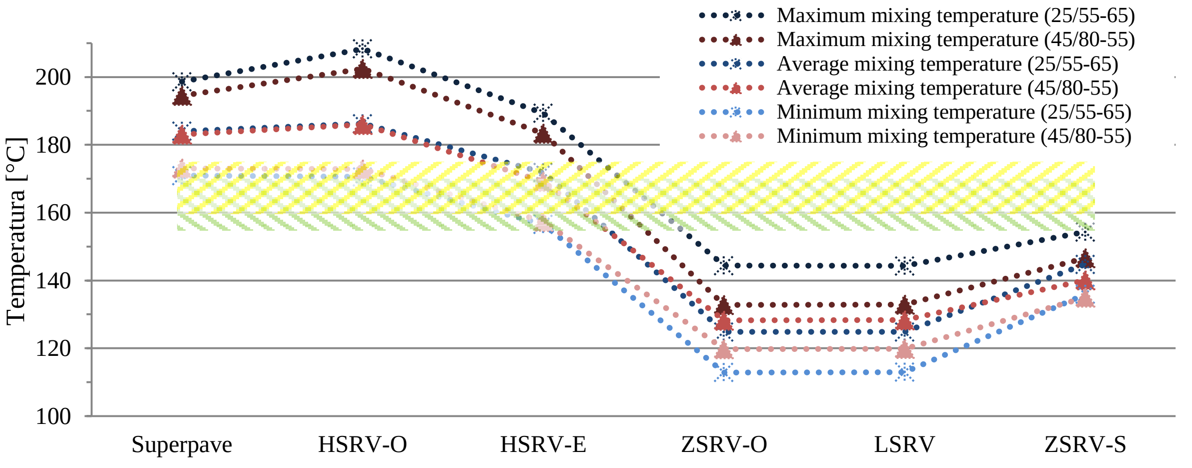


Figure 6: Mixing (a) and compaction (b) temperatures of modified bitumens grouped according to original penetration

a) Mixing Temperature



b) Compaction Temperature

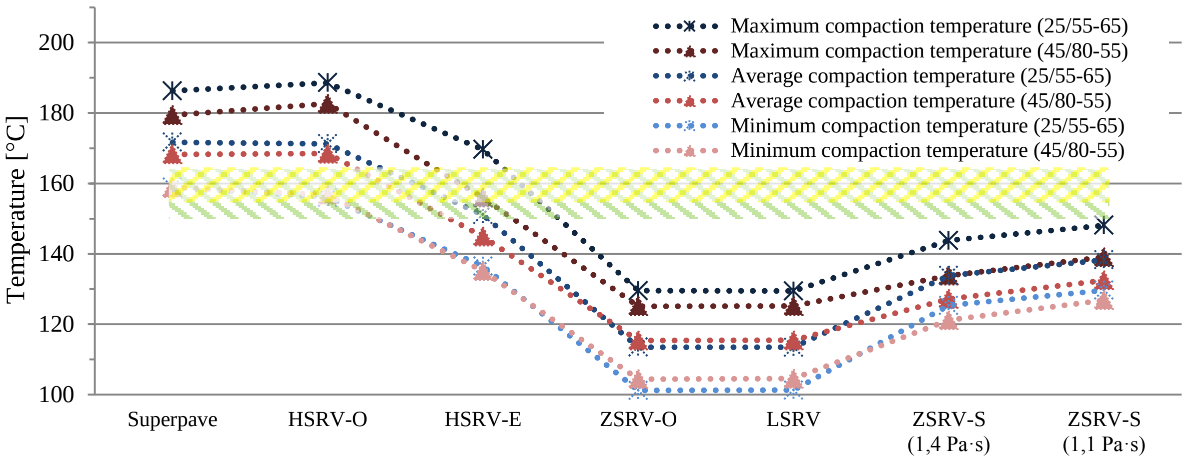


Figure 7: Mixing (a) and compaction (b) temperatures of modified bitumens grouped according to final penetration

5. CONCLUSIONS

Construction technical guides do not specify any methodology to determine mixing and compaction temperatures of modified bitumens, or it simply defines as EN 12697-33 does: “When using modified binder or hard grade bitumen binder or additives, the temperature may be adjusted“. Many studies have confirmed that the increase of temperature have serious consequences to modified bitumens (oxidation, breakdown of long chain polymers, volatile loss, emissions, odor-causing compounds) [8].

This paper presents an experimental study on mixing and compaction temperatures of SBS polymer modified bitumens. Two different classes of paving grade bitumens, from 2 suppliers, were modified in lab with SBS contents from 2% to 4%, and the rheology at high temperatures (above 100 ºC) evaluated with a rotational viscometer. Four different methods, and three variants, proposed by several authors were applied and the results compared.

Regarding the rheological behaviour, at high temperatures, it was concluded that:

- SBS polymer modified bitumens have non-Newtonian behaviour, i.e. viscosity is shear rate dependent, in opposition to the Newtonian behaviour of non-modified bitumens; viscosity decreases as the shear rate increases, with constant temperature conditions, which is designated as “shear thinning”;
- The more SBS the bitumen has, the more the viscosity values and shear rate dependency increases;
- The thermal susceptibility of modified bitumens decreases with SBS polymer content increase;
- SBS polymer modified bitumens have higher viscosity than the neat bitumen used to create it, at equal temperature and shear rate test conditions;
- Shear rate dependency decreases with temperature reduction;
- For the bitumens obtained from 50/70 paving grade bitumens, and for the same SBS content, the bitumen from Huelva refinery produces the highest viscosity values;

- For the bitumens obtained from 35/50 paving grade bitumens, and for the same SBS content, the bitumen from Porto refinery produces the highest viscosity values;

Regarding mixing and compaction temperatures obtained with the selected methods, it was concluded that:

- The Superpave method determines reasonable temperatures for non-modified bitumens, i.e. within the recommended ranges specified by suppliers, European Standards and industry, and in agreement with industry experience;
- Using the Superpave and the HSRV-O methods result very high temperatures, above 180 ºC, which may jeopardize SBS polymer modification benefits and add risks to workers and the environment; both methods are not advised to estimation of mixing and compaction temperatures for modified bitumen asphalt mixtures;
- The HSRV-E determines mostly mixing temperatures within the suppliers recommended range; compaction temperatures are below the minimum recommended temperature;
- The ZSRV-O and the LSRV methods determine very low mixing and compaction temperatures, below 140 ºC; the new version, ZSRV-S, finds higher temperatures but below minimum temperatures considered adequate for asphalt production, inclusively if 1.4 Pa.s is used for compaction temperature calculation.

The High Shear Rate Viscosity (evolution) method determined production temperatures that are closer than any other method to suitable considered temperatures. Authors consider that this method should be deeply investigated with mixing and compaction testing on different asphalt mixtures and polymer modified bitumens.

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