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ORIGINAL ARTICLE

Improvements on asphalt mixtures rutting performance characterization by the use of low shear viscosity

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Abstract The relationship between the rutting performance of dense asphalt concretes and the low shear viscosity (LSV) of different asphalt binders was analysed in a previous work. A LSV limit was found for the original asphalt to prevent the rutting of the mixtures, and in addition, a model to predict the rutting performance based on the LSV of the asphalt binder was validated. With the aim of amplifying the criterion previously found, the performances of micro and stone mastic asphalt mixtures are studied in this work. Conventional, multigrade and polymer modified asphalts were used as binders. Considering that the properties of original and aged asphalts must be taken into account for a better asphalt binder characterization, LSV measurements on aged asphalts were also done in order to analyse their relationship to the mixtures rutting performance. The micro and stone mastic asphalt mixtures showed a similar behaviour as the dense grade asphalt concrete in the previous study. Regarding the control of rutting, a LSV limit of 500 Pa.s was found for original asphalts, while 2,000 Pa.s was the limit for aged asphalt binders. The model to predict the rutting performance of asphalt mixtures was amplified, incorporating both original and aged asphalt LSVs as appropriate input data.

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Keywords Low shear viscosity (LSV) · Rutting performance · Aged asphalts

1 Introduction

The permanent deformations of asphalt mixtures are usually studied in the laboratory through the wheel tracking test (WTT). The WTT measures the mixture rut depth over time under extreme temperature and load traffic conditions. This test is widely used around the world, although recent research explores different testing alternatives for the WTT in order to find a better quantification of the rutting performance or to compare the advantages of diverse asphalts mixtures and materials [8, 11, 12]. The test temperature is normally 60 °C, which is representative of the highest pavement temperature that can be found. Not all asphalt mixtures lead to a good rutting performance at this temperature; however, in practice the pavement temperatures are not always so extreme and mixtures with poor performance in the WTT can show acceptable rutting behaviour at lower temperatures.

The prediction of mixture performance is important during the design process, so it is useful to better understand how the asphalt properties influence that performance. The ASTM D 6373 standard classifies the asphalt binders considering the temperature conditions that would happen in pavements based on their rheological properties. These properties are associated to the most common pavement failures (rutting and cracking). Regarding rutting, the parameter G*/sin is used and original and aged asphalt conditions are considered for a proper asphalt binder selection. It has been proved that the G*/sin is not appropriate to classify all binders, particularly the modified ones [2, 7, 13], nevertheless the idea of characterization of rutting performance from the asphalt rheological properties (original and aged) is an important concept in the standard.

Nowadays other rheological properties are used to characterize permanent deformations. For example, the low shear viscosity (LSV) has been recognized as a parameter strongly related to the asphalt rutting resistance [6]. The LSV measurement is specified in [4] however, a criterion using this rheological property for rutting mixture designs was not developed.

In a previous work [10], the rutting performance of dense grade asphalt concretes and their relationship to the LSV of the used binders was studied. A rutting performance limit related to the original asphalt LSV value was found and drastic changes in rutting resistance were observed when asphalt binders had LSVs lower than 500 Pa.s. Besides, a model to predict the rutting performance based on the original asphalt LSV was validated for this kind of mixture.

The effect of temperature on the rutting performance of asphalts mixtures is recognized. In the mentioned paper [10], it was demonstrated that by plotting original LSV versus temperature curves, the temperature at which each asphalt binder presents a LSV of 500 Pa.s. can be found. This temperature can be associated with the maximum temperature at which each asphalt mixture can be submitted without compromising its rutting resistance. The CEN 15324 standard follows a similar criterion. It must be noted that this standard specifies a LSV of 2,000 Pa.s to obtain the Equi-viscous temperature (EVT) and indicates that this LSV value can be applied on original as well as aged asphalts. Nevertheless, it is not explained why the same limit can be used for both asphalt conditions.

The performance of most widely applied types of asphalt mixtures, including dense, micro and stone mastic asphalts (SMA), were studied in this work. The main objective was to amplify the LSV limit criterion related to rutting resistance previously found for dense grade asphalt concretes. The relationship between asphalt mixture rutting performances obtained from WTT and LSV measurements for both original and aged asphalts was analysed.

2 Experimental

2.1 Materials and mixtures

Three aggregate gradations were studied in this work: micro asphalt (M-10), stone mastic asphalt (SMA-10) and the dense grade mixture (D-20) previously study [10]. Micro asphalt is a discontinue mixture gradation with the objective to obtain a macro-texture surface. These are commonly used in the top surface of pavements to offer better condition to traffic. The micro asphalts present a similar aggregated gradation to SMA but without fibres and in consequences this mixture are made with minor asphalt contents. The SMA and dense grade mixture are asphalt mixture types well known in the road field.

Three asphalt binders currently used in Argentina [conventional (C), multigrade (M) and polymer modified (PM)] were used in each aggregate gradation to make different asphalt mixtures. Table 1 presents their main characteristics including penetration, softening point (R & B), Brookfield viscosity at 60 °C, torsional recovery test results as well as their performance grades (PG) according to the ASTM D 6373 standard (1999). The different mixtures are identified by gradation and type of asphalt binder used.

Table 2 shows the main characteristics of the studied gradations, which were made using different proportions of two coarse aggregates (6–20 and 6–12 mm), two crush sands (0–6 and 0–3 mm), hydraulic lime, filler and cellulose fibres. Table 2 also

Table 1 Asphalt binder properties

Asphalt	C	M	PM
Modification	–	Multigrade	SBS
Argentinian standard type	CA-30	–	AM3-C
Penetration to 25 °C [dmm]	55	60	64
Softening point [°C]	51.8	58.3	95.5
Brookfield viscosity to 60 °C [Pa.s]	297.6	1,224	–
Torsional recovery [%]	–	–	77.2
Performance grade (PG)	64–16	70–22	70–22

Table 2 Properties of gradation

	M-10	SMA-10	D-20
Aggregate proportions [%]			
6–20 mm	–	–	40
6–12 mm	75	75	12
0–6 mm	–	–	45
0–3 mm	16	15.5	
Filler	8	8	2
Hydraulic lime	1	1	1
Cellulose fibres	–	0.5	–
Design properties			
OAC [%]	5.3	6.0	5.0
D [gr/cm^3]	2.380	2.400	2.437
AV [%]	4.9	3.3	3.5

OAC optimal asphalt content, *D* density, *AV* air voids

presents the main design characteristics of the mixtures including optimal asphalt content (OAC), density (D) and air voids (AV). Figure 1 shows the aggregate gradations.

2.2 Testing program

For each aggregate gradation the performance of different asphalt mixtures were studied in the WTT at 50, 60, 70 and 80 °C (the temperature range in which rutting occurs). For each gradation, eight samples, 300 mm wide and 50 mm high, were cast. They were compacted to the design Marshall density using roller compactor equipment [15] and controlled to verify a minimum of 98 % of the design density. The specimens were then tested in pairs at each temperature.

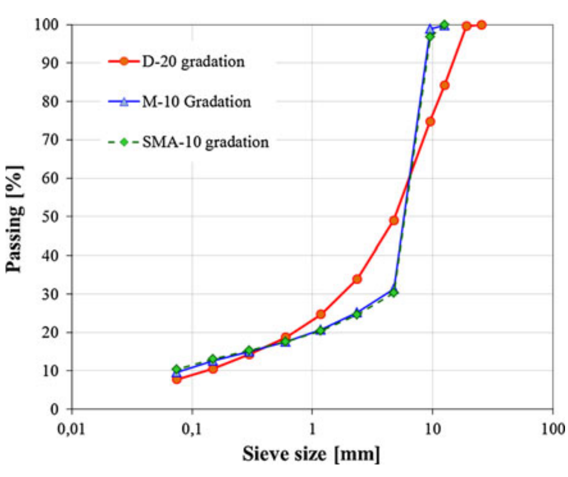

Fig. 1 Mixtures gradations

In addition, the LSV of each asphalt binder, for both original and aged conditions, was measured at the same temperatures (50, 60, 70 and 80 °C). The rolling thin film oven test (RTFOT, ASTM D 2872) was used to generate the asphalt binder ageing. A modified RTFOT (at 180 °C) for the PM asphalt was also done, considering that the ageing of this asphalt by the standard method was not necessarily enough. Different studies show how the standard RTFOT (ASTM D 2872) produces an inadequate ageing for some polymer modified asphalts [1, 9]. One of the main problems is that this kind of asphalt does not roll inside the bottle during the test due to a higher viscosity at the test temperature (163 °C). In this condition, the thin asphalt film is not generated and, therefore, the ageing is inadequate and unlike what happens in the mix plant. Furthermore, modified asphalts are usually exposed to higher temperatures during the mix process, adding another reason for a modified RTFOT.

2.3 Test procedures

2.3.1 *Frequency sweep test*

A dynamic shear rheometer (DSR) Paar Physica SM-KP with a Rheolab MC-100 was used to evaluate the rheological behaviour of the asphalts. The equipment has a thermo stabilizer which circulates water around the asphalt sample and allows the temperature to be controlled in a range from 0 to 90 °C.

The frequency sweep test method was used to obtain the asphalts LSV. The frequency sweeps were done at 10 °C steps between 40 and 80 °C. The Plate-plate configuration, 25 mm diameter and 1 mm gap sample geometry, was used in all DSR tests. The frequency sweeps were done from 1 to 10 Hz inside the linear viscoelastic region of the studied asphalts.

Master curves for reference temperatures of 50, 60, 70 and 80 °C were built using the frequency-temperature superposition principle through the frequency sweeps at different temperatures. The cross model was used to fit the complex viscosity data as Eq. 1 indicates.

$$\eta' = \eta'_\infty + \frac{\eta'_0 - \eta'_\infty}{1 + (k.f)^n} \tag{1}$$

where η' is the viscosity data; $\eta_0{}'$ is the ZSV; $\eta_\infty{}'$ is the limiting viscosity; K and n is the model constants; f is the frequency in Hz. As recommended by [5], the LSV was calculated at a frequency of 0.001 Hz for each reference temperature.

2.3.2 Wheel tracking test (WTT)

The WTT [3] was used to characterize the asphalt mixture rutting performance. The device consists of a solid rubber wheel, 207 mm in diameter and 47 mm wide, loaded with 520 ± 5 N. The loaded wheel describes a simple harmonic motion with a total travel distance of 230 mm and a frequency of 21 cycles per minute over a sample of asphalt concrete. Rutting depth was measured at 1 min intervals by an LVDT for a total period of 120 min. The collected data were fitted with the potential model as Eq. 2 indicates. The first ten data collected were not taken into account because they significantly affected the fit.

$$\varepsilon_p = a.t^b \qquad (2)$$

where ε_p is the permanent deformation data; t is the time; a and b is the model constants. The rutting performance was evaluated through the rutting rate (Rr); this parameter represents the rate of chance in rut depth determined over the last part to the rut depth-time curve. It is calculated as Eq. 3 indicates, where $D_{120\ min}$ and $D_{105\ min}$ are the deformations at 120 and 105 min respectively.

$$Rr = \frac{D_{120} - D_{105}}{15min}\left[\frac{\mu m}{min}\right] \qquad (3)$$

In Europe takes the proportional rut depth (PRD) as WTT result. However this parameter is affected by the initial deformation of mixture at the beginning of the test. This period is characterizing with changes in volume and not depends on the materials shear resistant in mixture. In addition the PRD represent a single value at the end of the test. On the other hand the Rr is calculated from a period of time that represent the shear resistance behaviour of mixture in front of rutting. In consequences this parameter (the Rr) is considering a better characterization parameter for the rutting performance of mixture.

3 Analysis of results

Table 3 shows the Rr of each asphalt mixture studied (D-20, SMA-10, M-10) and the corresponding LSV measurements on the original and aged (in RTFOT) asphalts, performed at temperatures of 50, 60, 70 and 80 °C.

It must be noted that the LSV of aged PM asphalt, indicated in Table 3, corresponds to modified RTFOT performed at 180 °C, while in other binders (C and M) the standard temperature of 163 °C was used. To validate the use of a higher temperature, a PM asphalt mixture was made at 180 °C, the temperature at which all subsequent PM mixtures were made. The asphalt was then recovered following the ASTM D 1856 (2003) methodology in order to compare with both aged PM in standard (163 °C) and modified (180 °C) RTFOT. Table 4 compares the LSV values of aged PM asphalts with those recovered from the PM asphalt

Table 3 Test results

Asphalt	T [°C]	LSV		Rr		
		Original [Pa.s]	Aged [Pa.s]	D-20 [µm/min]	M-10 [µm/min]	SMA-10 [µm/min]
C	50	1012.4	2674.5	3.9	4.2	3.4
	60	252.5	559.3	9.6	14.8	11.2
	70	83.2	159.5	23.4	37.9	24.0
	80	34.3	58.4	*	*	*
M	50	3631.1	15267.4	2.4	1.8	2.1
	60	947.5	3199.4	3.4	3.2	3.3
	70	308.1	863.9	6.7	10.4	8.4
	80	120.5	288.5	14.1	30.0	16.7
PM	50	7669.9	21881.6[a]	2.3	1.4	1.8
	60	2459.3	6471.5[a]	3.0	1.8	1.9
	70	911.3	2220.4[a]	3.5	2.6	3.0
	80	383.1	867.9[a]	4.9	4.1	3.8

*Not measured

[a] Obtained by means of modified RTFOT

Table 4 LSV [Pa.s] of PM aged asphalt

T [°C]	RTFOT[a]	RTFOT[b]	Mix recover[c]	a/c[%]	b/c[%]
50	24952.9	21881.6	35824.8	69.7	61.1
60	5169.0	6471.5	9103.7	56.8	71.1
70	1367.7	2220.4	2766.8	49.4	80.3
80	445.0	867.9	982.5	45.3	88.3

[a] RTFOT at 163 °C—85 min

[b] RTFOT at 180 °C—85 min

[c] Asphalt recover of mixture according to ASTM D 1856

mixture. As expected, the LSV values for aged PM in standard RTFOT are lower than those for the recovered PM, while the LSV values of aged PM at 180 °C are closer to those for the recovered PM. Thus, the modified RTFOT gives a better representation of the real ageing that occurs in the PM mixture process, mainly as temperature increases (see last columns in Table 4).

Figure 2 shows the variation of Rr versus temperature for the mixtures (D-20, M-10 and SMA-10) made with each one of the binder types. Beyond the type of mixture, the response to rutting is similar with respect to asphalt type and thermal susceptibility. As expected, it is clearly seen that the rutting rates (Rr) increase as the temperature increases when considering one type of asphalt. With respect to the rutting susceptibility, it is observed that this clearly depends on the asphalt binder, independent of mixture type. Higher rutting susceptibility is observed for conventional asphalt mixtures than for M and PM mixtures. Also, it is important to mention that, depend of asphalt binder; it seems modify the temperature threshold for which a fast increase in rutting takes place. The threshold is below 50 °C for C asphalt, close to 60 °C for M and higher than 80 °C for PM.

The M-10 mixtures with C and M asphalts (see Fig. 2b) show a greater thermal rutting sensitivity than the SMA-10 and D-20 mixtures with the same asphalts; however, no such differences are observed when the PM asphalt is considered. It is observed in former ones a major instability with a fast increase of rutting once the temperature threshold indicated abode is exceeded.

Figure 3 shows the aspect of samples after the WTT of D-20 and M-10 with C asphalt tested at 60 °C and SMA-10 with PM asphalt tested at 70 °C. The effect of the type of gradation and kind of asphalt on rutting behaviour can be verified. It is interesting to note how

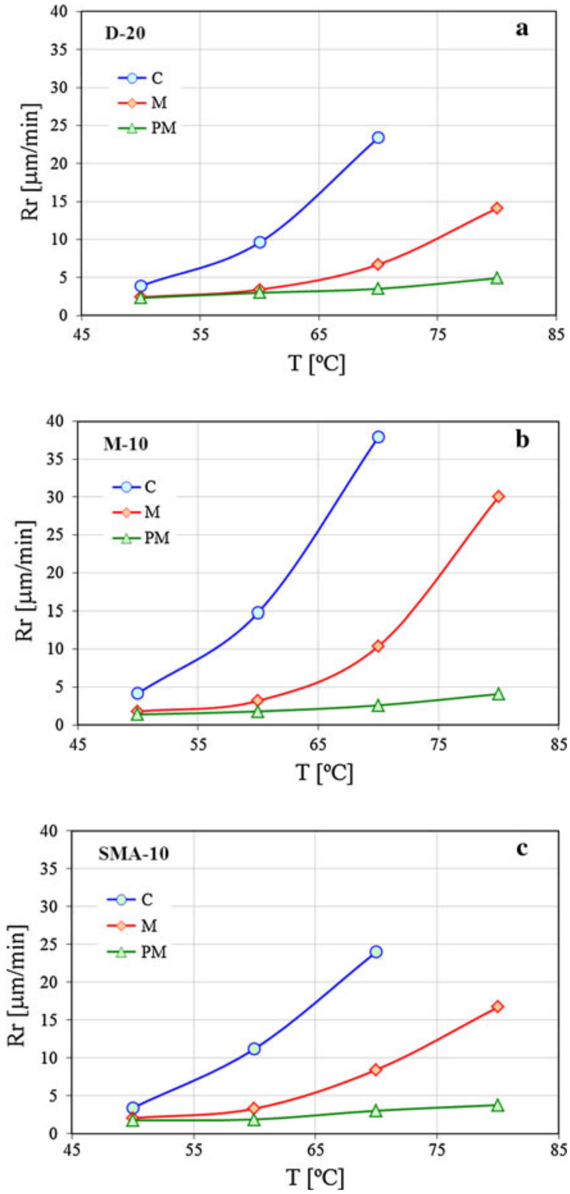

Fig. 2 Rr-Temperature relationships for the different asphalts (conventional, multigrade, polymer modified) and mixtures (D-20, M-10, SMA-10) studied

mixtures with different rutting responses had a similar behaviour with respect to one type of asphalt and thermal susceptibility.

In work previous to this [10], a relationship was found between the Rr determined in the WTT and the LSV of the original asphalt measured at the same temperatures for dense mixtures. Figure 4 shows the Rr test results as a function of original asphalt LSV considered at the same temperatures for D-20, M-10 and SMA-10. A similar behaviour is observed in the three mixtures; the rutting performance improves in the WTT (minor Rr) as the LSV is increased.

By plotting together the Rr-LSV relationships of the different types of mixtures studied (D-20, M-10 and SMA-10), it appears that they all follow the same tendency, see Fig. 5. Besides, the figure shows that Rr drastically changes in the region of low LSV values. Within the constraints of the studied temperature range, asphalt types and gradations, it is confirmed that notable changes in rutting resistance appear when the original asphalt binder has LSV values lower than 500 Pa.s, as it was previously found for D-20 mixtures [10].

Similarly, Fig. 6 shows the variation of Rr (WTT result) as a function of aged asphalt LSV determined at the same temperatures. As expected, the same tendency is observed for all the mixtures; strong changes in the rutting behaviour take place for aged asphalt LSV values lower than 1,000 Pa.s. Based on this observation, the CEN 15324 LSV value of 2,000 Pa.s can be taken as a safer threshold for the aged asphalt condition.

4 Discussion

From the analysis of results, it is interesting to note that the sudden drops in rutting performance (Rr) observed along the lower region of LSV values were independent of gradation and type of asphalt for both original and aged asphalts. The obtained results indicate that the LSV values of 500 and 2,000 Pa.s represent reasonable limits related to the partial contribution of binder in the mixture rutting resistance for the original and aged asphalt conditions respectively. However, it must be kept in mind that each original asphalt binder (C, M or PM) has a LSV value of 500 Pa.s at different temperatures; similar for the 2,000 Pa.s in the aged asphalts (see Fig. 7). By means of LSV-Temperature curves it is possible to obtain each temperature associated to a LSV of 500 and 2,000 Pa.s for the original and aged asphalts, respectively (T500 and T2000). Table 5 shows the T500 and T2000 values for the asphalts studied. This temperature can be associated with the maximum pavement temperature at under which each mixture can be submitted without compromising its rutting resistance.

The [4] uses the LSV to obtain a temperature, called equi-viscous temperature (EVT), associated to rutting resistance. A LSV value of 2,000 Pa.s is used to calculate the EVT. However, the standard uses the same LSV value for both original and aged asphalt. Considering the results obtained in this work, it is not logical to take the same limit for both conditions. If the limit of 2,000 Pa.s is applied in Fig. 5 (Rr vs. original asphalt LSV), in most cases the test results fall outside; thus, this limit appears as a rigorous threshold for original asphalt.

Fig. 3 Samples after WTT; **a** D-20 C at 60 °C, **b** M-10 C at 60 °C, **c** SMA-10 PM at 70 °C

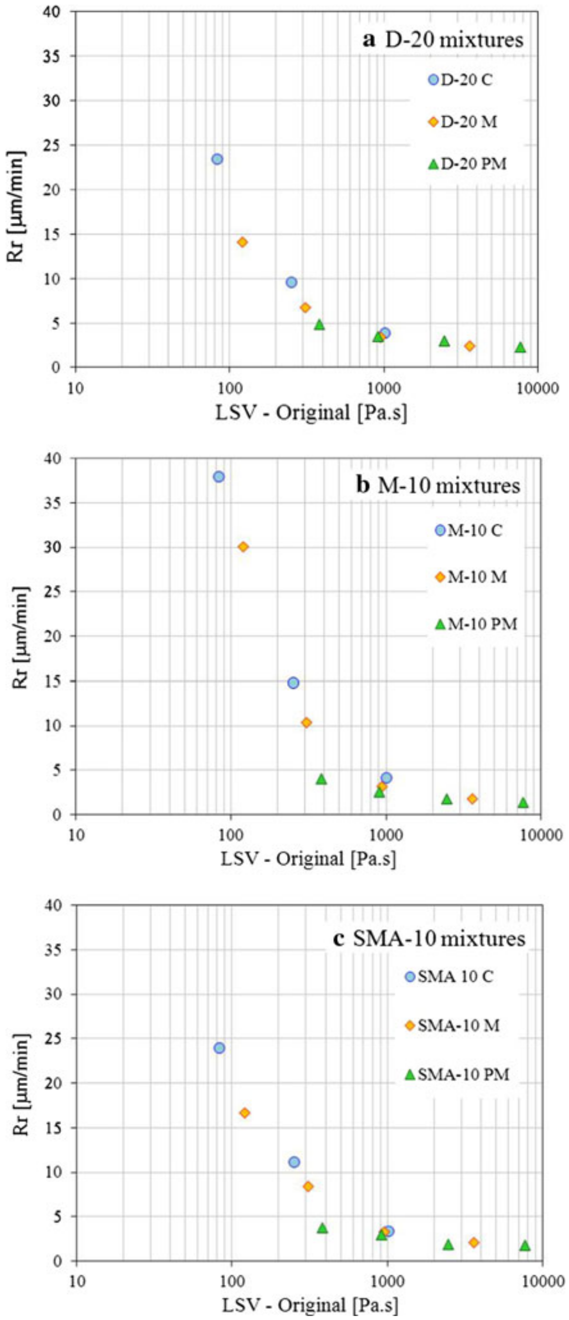

Fig. 4 Mixture Rr vERSUS asphalt LSV; **a** D-20, **b** M-10, **c** SMA-10

The relationships between Rr and the original and aged asphalt LSVs represent a powerful tool to estimate the mixture rutting resistance at a specific temperature, if the asphalt's LSV in the same condition is known. Thus, the Rr-LSV relationships were

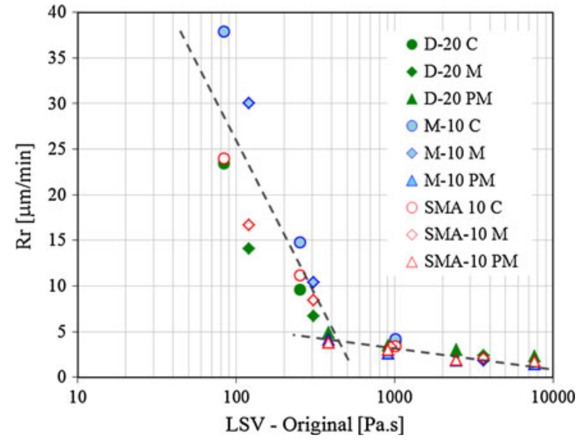

Fig. 5 Rr of D-20, M-10 and SMA-10 mixtures versus original asphalt LSV

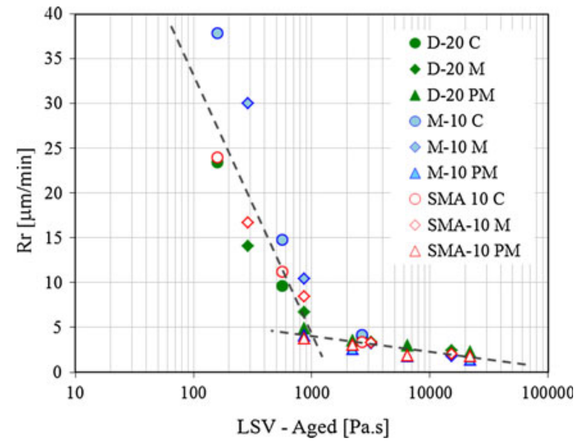

Fig. 6 Rr of D-20, M-10 and SMA-10 mixtures versus aged asphalt LSV

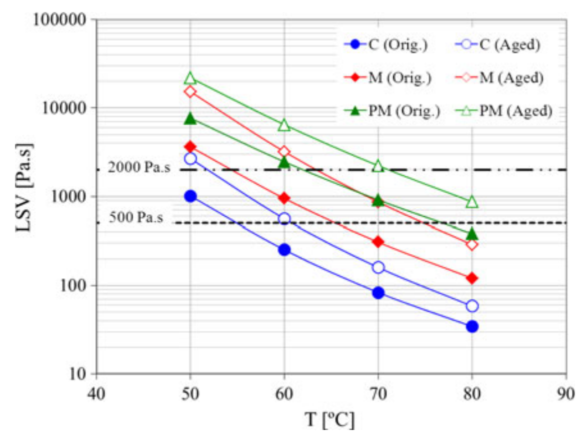

Fig. 7 Asphalt's LSV versus temperature (*Filled dots* original, *void dots* aged)

Table 5 High temperatures related to T_{500} y T_{2000} concepts

Criterion	Asphalt		
	C	M	PM
T_{500} (original) [°C]	54.8	65.5	76.8
T_{2000} (aged) [°C]	51.7	63.4	73.0

obtained fitting the data by a non-lineal regression as Eqs. 4 and 5 indicate. Figure 8 shows the fit curves for both original and aged conditions.

$$\mathrm{Rr}[\mu\mathrm{m/min}] = 1.06 + \frac{2287.9}{\mathrm{LSV}_{\mathrm{original}}}\left(R^2 = 0.87\right) \qquad (4)$$

$$\mathrm{Rr}[\mu\mathrm{m/min}] = 2.04 + \frac{4494.5}{\mathrm{LSV}_{\mathrm{aged}}}\left(R^2 = 0.86\right) \qquad (5)$$

This paper shows that the original and aged asphalt properties must be taken into account for a correct asphalt binder characterization. Note that in many practical situations it is not possible to obtain a sample of the original asphalt and only a pavement or mix plant sample is available for the analysis. As a consequence, it is relevant to relate the mixture rutting performance to the aged asphalt properties.

The rutting curve obtained in WTT can be interpreted as a creep test of mixture; in this interpretation the Rr can be assimilated to the creep rate. In rheology the Burger's model, indicates in Eq. 6, is used to explain the creep behaviour of asphalt and any viscoelastic materials; the asphalt mixture at high temperature behaves like one and then the Burger's model can be used to fit the permanent deformation data measured in the WTT.

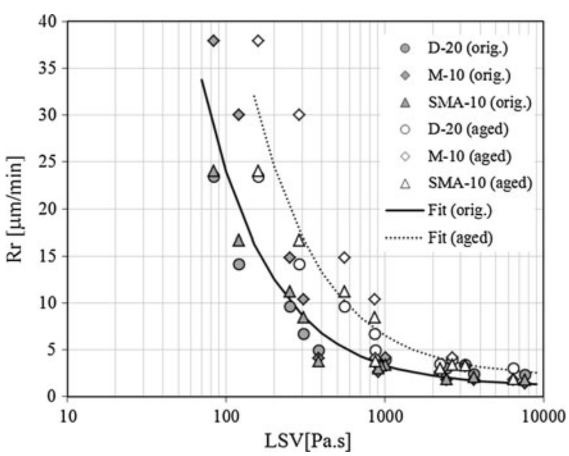

Fig. 8 Rr versus LSV (original and aged asphalts)

$$J = \frac{\varepsilon(t)}{\sigma_0} = \frac{1}{G_0} + \frac{1}{G_1}\left(1 - e^{-t.G_1/\eta_1}\right) + \frac{t}{\eta_0} \qquad (6)$$

where J is the creep compliance, t is time and G_0, G_1, η_0 and η_1 are model parameters.

Figure 9 shows the rutting test of mixture D-20 with C asphalt and its fit by the Burger's model. In the figure, the permanent deformations measured were converted into compliance. It can be seen how the model satisfactorily explains the mixture rutting behaviour ($R^2 = 0.99$).

In the Eq. 6 the parameter t/η_0 represents the material viscous behaviour; it is related to the creep rate. The term η_0 in asphalt or polymer is known as the zero shear viscosity (ZSV) and is related with the mixture rutting resistance [14] in asphalt mixture can

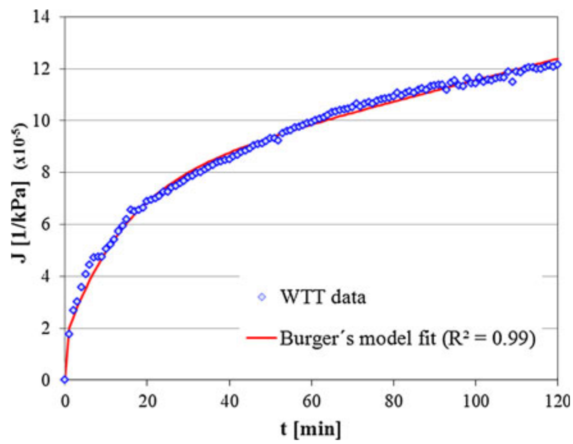

Fig. 9 Fitting of a rutting test by means of Burger's model

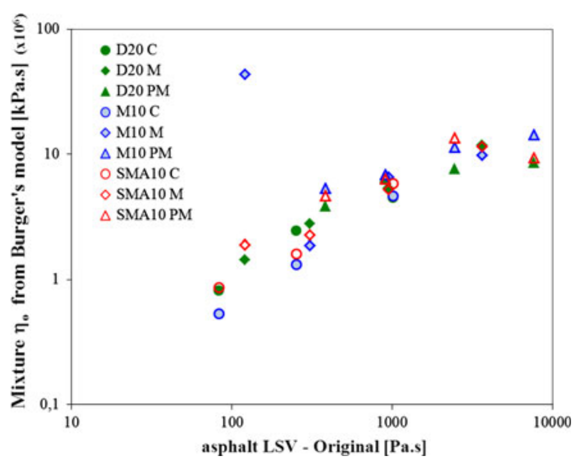

Fig. 10 Mixture η_0 versus original LSV

be taken as a kind of mixture viscosity associated to the viscous flow. It is important to remind that the LSV concept derives from the ZSV one and both are related for most asphalt types (except some polymer modified asphalts that not present a clear ZSV).

Figure 10 shows the relation between the mixture η_0 obtained from Burger's model fitting and the asphalt LSV measured at the same temperature at mixture were tested in WTT. It can be seen a good correlation; only a data for one of M-10 with M asphalt is out of general trend without an explanation. As it was expected, while the asphalt LSV increases the mixture η_0 increases.

From the rheology analysis is concluded that the correlation between mixture η_0 and the asphalt LSV support the relationships Rr-LSV previously founded.

5 Conclusions

The rutting performances of three mixture gradations (dense, micro and SMA), incorporating conventional, multigrade and polymer modified asphalts, were studied at different temperatures ranging between 50 and 80 °C through the wheel tracking test (WTT). The LSV of original and aged asphalts was also evaluated in order to relate this rheological property with the rutting behaviour. The main conclusions are indicated as follows:

A change to a worse performance (fast increase in rutting) was observed in mixtures when were tested beyond a temperature threshold; this threshold depend on the asphalt binder used. This temperature represents an upper limit until which the mixture can be submitted offering an adequate rutting performance.

The rutting performance of mixtures studied presents different temperatures susceptibilities depends on the asphalt binder type, independent of mixture gradation.

A worse mixture rutting performance in WTT (minor Rr) was observed when decreases the asphalt LSV measured at the same temperature of the rutting test. In addition, within the conditions of the temperatures, gradations, and binder types studied, similar relationships were observed for all mixes between rutting performance and the asphalt's LSV (original or aged) measured at the same temperature.

Strong drop offs in rutting performance (measure by Rr) were found when the asphalt binder achieved LSV values lower than 500 and 2,000 Pa.s for original and aged asphalts, respectively. Considering that the changes in performance were observed independently of mixture type and kind of asphalt, these LSV values represent limits of the partial contribution of the binder in mixture rutting resistance.

The temperature thresholds at which the rutting performance of mixtures drastically changes were associated to the LSV limits.

A model to estimate the asphalt mixture rutting performance at different temperatures based on the LSV (original or aged) at the desired temperature was proposed. The Rr-aged LSV relationship can be specifically used when only in situ pavement samples are available.

By mean of rheology approaches, the rutting performance measures in WTT were fitted with the Burger's model. A relation between LSV and mixture viscoelastic parameters obtained from the model was found. These result support the Rr-LSV relationship founded.

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